HIGH ENERGY COOLING

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Objectives and Outline

- Proton beam cooling for ep-collider represents one of most challenging problems in modern accelerator physics
- The talk shortly reviews the present status and analyses possible ways for further developments
- The request is to cool dense proton bunches in a wide energy range
  - Up to ~300 GeV protons => 150 MeV electrons
- Other requirements
  - good cooling of high amplitude particles
- Cooling methods discussed for bunched proton beam at collisions
  - Electron cooling
    - Based on the energy recovery linac
    - Based on a cooling ring with injection from induction linac
    - Cooling ring with SR cooling for electrons to suppress IBS
  - Stochastic cooling
    - OSC
    - Coherent electron cooling: (1) FEL based, (2) micro-bunch instability based, (3) based on plasma cascade instability

Electron Cooling Rate Estimates

- There is considerable controversy in the cooling rate calculations
  We assume: Gaussian distributions in both beams, uniform n_e, $B=0$.

$$\lambda_\parallel \approx \frac{4\sqrt{2\pi}\, n_e r_e r_p L_c}{\gamma^4\beta^4\left(\Theta_\perp + 1.083\Theta_\parallel/\gamma\right)^{3/2}\sqrt{\Theta_\perp\Theta_\parallel}} L_{cs} f_0 \;, \qquad \Theta_\parallel/(\gamma\Theta_\perp) \le 2,$$

$$\Theta_\parallel = \sqrt{\theta_{\parallel e}{}^2 + \theta_{\parallel p}{}^2}\;, \qquad \theta_{\parallel p,e} \equiv \sqrt{\overline{\Delta p_{p,e}{}^2}}\,/\,p_{p,e}$$

$$\lambda_\perp \approx \frac{\pi\sqrt{2\pi}\, n_e r_e r_p L_c}{\gamma^5\beta^4\Theta_\perp{}^2\left(\Theta_\perp + \sqrt{2}\Theta_\parallel/\gamma\right)} L_{cs} f_0 \;. \qquad \Theta_\perp = \sqrt{\theta_{\perp e}{}^2 + \theta_{\perp p}{}^2}, \quad \theta_{\perp p,e} \equiv \sqrt{\overline{\Delta p_{\perp p,e}{}^2}}\,/\,p_e$$

⇨ The best-case estimate:

(*) $L_{cs}=2\beta_x^*=2\beta_y^* \equiv 2\beta^*$; (*) uniform density of e-beam;

(*) e-beam radius is twice larger than the rms ion beam size in the center;

(*) zero temperature of e-beam

$$\lambda_\parallel = \frac{2\sqrt{2}\, r_e r_p \beta^* L_c}{\sqrt{\pi}\,\gamma^2\beta^2\varepsilon_{pn}{}^2\theta_{\parallel p} C}\frac{I_e}{e}\,, \qquad \lambda_\perp = \sqrt{\frac{\pi}{2}}\,\frac{r_e r_p \beta^{*3/2} L_c}{\gamma^{5/2}\beta^{3/2}\varepsilon_{pn}{}^{5/2} C}\frac{I_e}{e}\,,$$

$$\Theta_\parallel \ll \gamma\Theta_\perp . \quad <=> \quad \begin{pmatrix} \lambda_x \\ \lambda_y \\ \lambda_p{}^2 \end{pmatrix}_{IBS} \approx \frac{N_p r_p{}^2 c L_{cp}}{8\sqrt{\gamma}\,\sigma_z \varepsilon_{pn}{}^2} \begin{pmatrix} \sqrt{R_0/\left(\varepsilon_{pn}\nu_x{}^5\right)} \\ 0 \\ \left(\sqrt{\nu_x\varepsilon_{pn}/R_0}\right)/\left(\gamma\theta_{\parallel p}{}^2\right) \end{pmatrix}.$$

- With energy, cooling rate decays much faster than IBS heating

⇨ Fast increase of e-beam current with energy

Electron Cooling Rate Estimates (continue)

- eRHIC parameters [1]
  - the proton beam beta-functions in the cooling section center - 60 m,
  - the total cooling section length - 120 m,
  - the proton beam energy - 275 GeV,
  - the rms normalized emittance - 2.7 μm,
  - ring circumference - 3.8 km,
- The best-case estimate for the e-beam of 100 A yields:
  - the transverse emittance cooling time - 50 minutes
  - For the rms momentum spread of $5 \cdot 10^{-4}$ the cooling time - 5 minutes
- Accounting the momentum and angular spreads in e-beam increases the cooling times by at least 2 times.
  - It needs to be done to avoid overcooling!!!
- Magnetized cooling does not help if e-beam velocity spread can be made smaller than the spread in p-beam
- e-bunch has to be longer than p-bunch to get to these rates
- Getting 100 A peak current at 150 MeV is extremely challenging

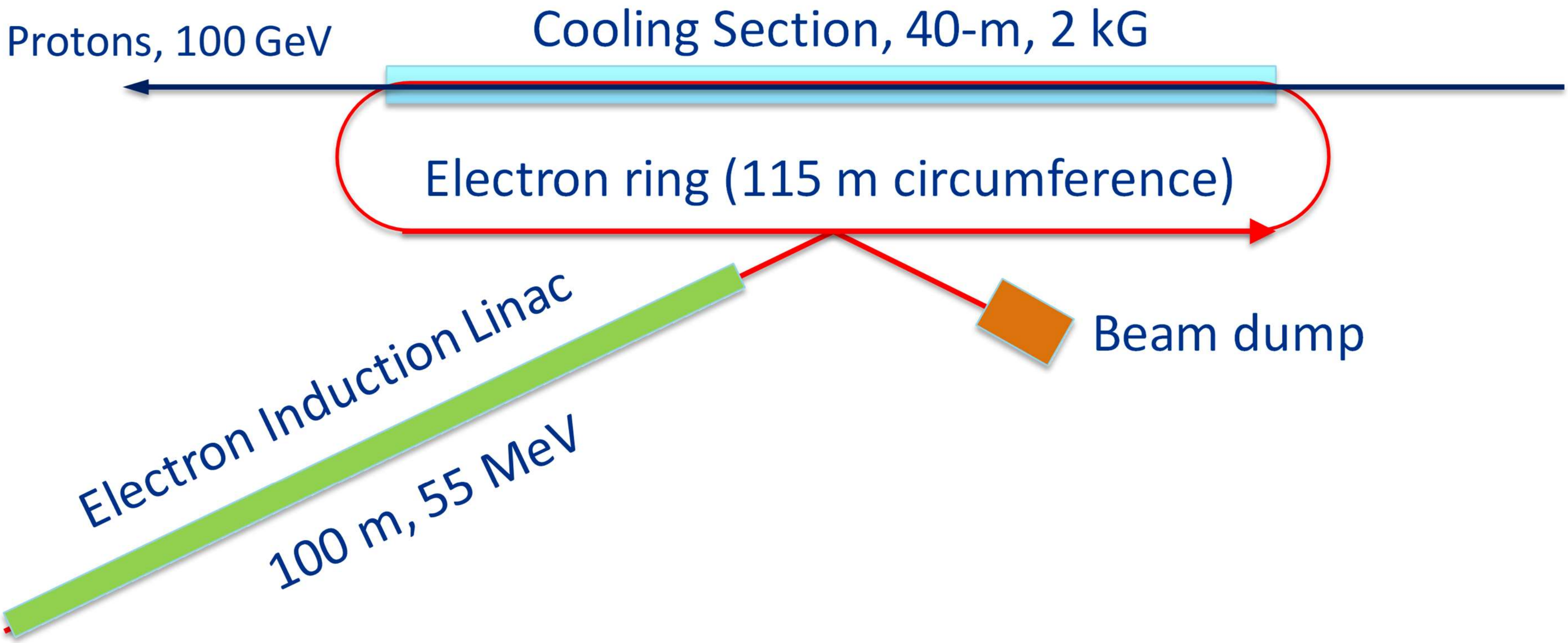
[1] C. Montag, et.al., "eRHIC design overview", IPAC2019, Melbourne, Australia, (2019).

Choice of Practical Scheme for e-cooling

- 100 A * 150 MeV = 15 GW
  - If pulsed beam is used: $6\sigma_s$ = 30 cm, s_{bb} = 3.3 m => 1.4 GW
- The beam power loss limit < 1 MW

  => energy recovery: minimum 10^3; better 10^4
- How to get the energy recovery
  - Energy recovery linac – cannot achieve required recuperation
  - e-beam storage in a ring
    - frequent reinjections from induction linac to mitigate excessive heating by IBS (FNAL)
    - low-rate reinjections with strong SR damping to suppress IBS (BNL)
  - Combination of energy recovery linac and ring (JLAB)

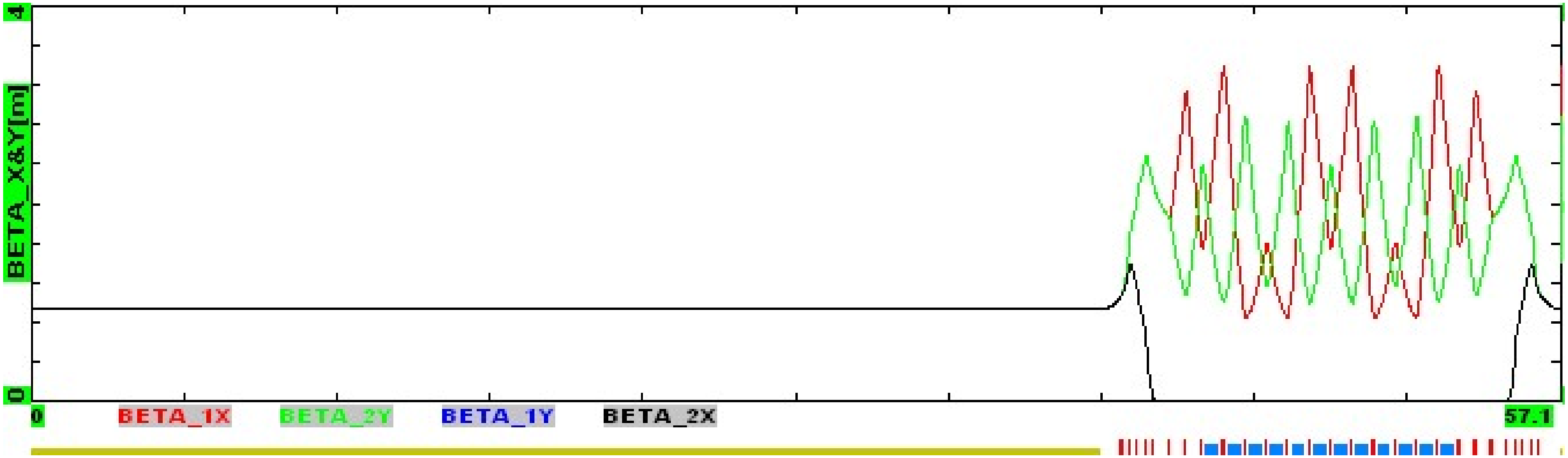
FNAL Suggestion for the Ring Electron Cooler



- Thermionic gun is emersed in magnetic field, circular modes
- Acceleration is performed in an induction linac
- Beam energy recuperation (<0.1%) is achieved by a usage of large number of turns in the electron storage ring (5,000 – 10,000)
- 100 A unbunched beam to achieve the longitudinal cooling time less than 1 hour

Beam Optics for Electron Storage Ring

- 100% coupled optics
- The Derbenev transform with 5 skew-quads is used to convert rotational modes in solenoids to flat modes in the arcs
  - Reduced IBS and beam space charge
  - Large ratio of mode emittances
- Relatively small magnetic field in arc bending dipoles and small beam energy result in small energy loss on SR
  - No energy correction is required for energy loss due to SR



4D beta-functions for one half of electron ring

Tentative Parameters of Ring Electron Cooler

Proton beam energy	270 GeV
Proton ring circumference	3834 m
Cooling length section	80 m
Normalized rms proton beam emittances (x/y)	3/0.5 μm
Proton beam rms momentum spread	$<3\times10^{-3}$
β-functions of proton beam at the cooling midpoint	80 m
Proton beam rms size (hor/ver)	0.9/0.4 mm
Electron beam energy	147 MeV
Electron beam current	100 A
Cathode diameter	25 mm
Cathode temperature	1050ºC
Longitudinal magnetic field in cooling section, B_0	780 G
Electron beam rms momentum spread, initial/final	$(1.0/1.25)\cdot10^{-3}$
Rms electron angles in cooling section	4.8 μrad
Rms electron beam size in cooling section	2.2 mm
Electron beam rms norm. mode emittances at injection, $\varepsilon_{1n}/\varepsilon_{2n}$, μm	220/0.042
Number of cooling turns in the electron storage ring	6,000
Longitudinal cooling time (emittance)	23 min
Transverse cooling time (emittance)	30 min

- Solid proposal (gun, induction linac, transfer line optics, ring optics, IBS, instabilities, sensitivity to errors, cooling time dependence on amplitude)
- Only known not-addressed problem – chromaticity of Derbenev's adapters

Other Possibilities for Ring Cooler

- SR radiation damping compensating IBS enables to reduce frequency of reinjection (BNL)
  - Requires bunched beam => problems with CSR and beam stability (100 A peak current @ 150 MeV)
- Usage of energy recovery linac to reduce beam power loss (JLab)
  - Relatively small number of turns limited by CSR
  - Photocathode lifetime
  - Reinjections at very high frequency

- Both ideas require much more detailed proposals

- Energy recovery linac looks feasible at low energy

Stochastic Cooling at Optical Frequencies

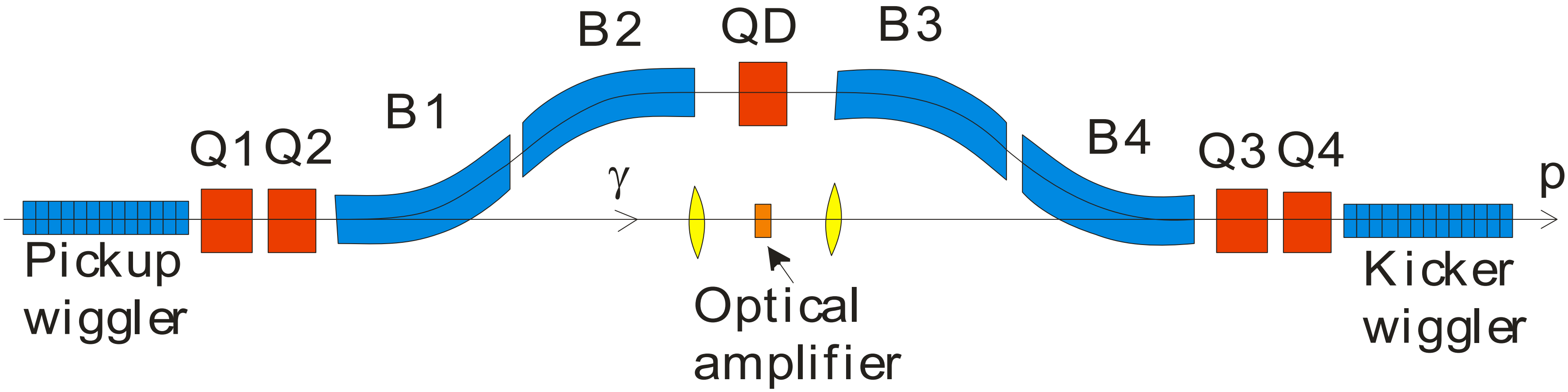
- Transition to optical frequencies leaves the transient-time cooling as the only possibility
- Only longitudinal kicks
  - Transverse cooling is achieved through x-s coupling
- For gaussian bunched beam the emittance cooling rate at the optimal gain is:

$$\boxed{\lambda_{\max} \approx \frac{\pi^2}{n_\sigma^{\ 2}} \frac{2\sqrt{\pi}\sigma_t}{T_0} \frac{W_{eff}}{N_p} \frac{\sigma_g}{\sqrt{\sigma_g^{\ 2} + \sigma_{sp}^{\ 2}}}}$$

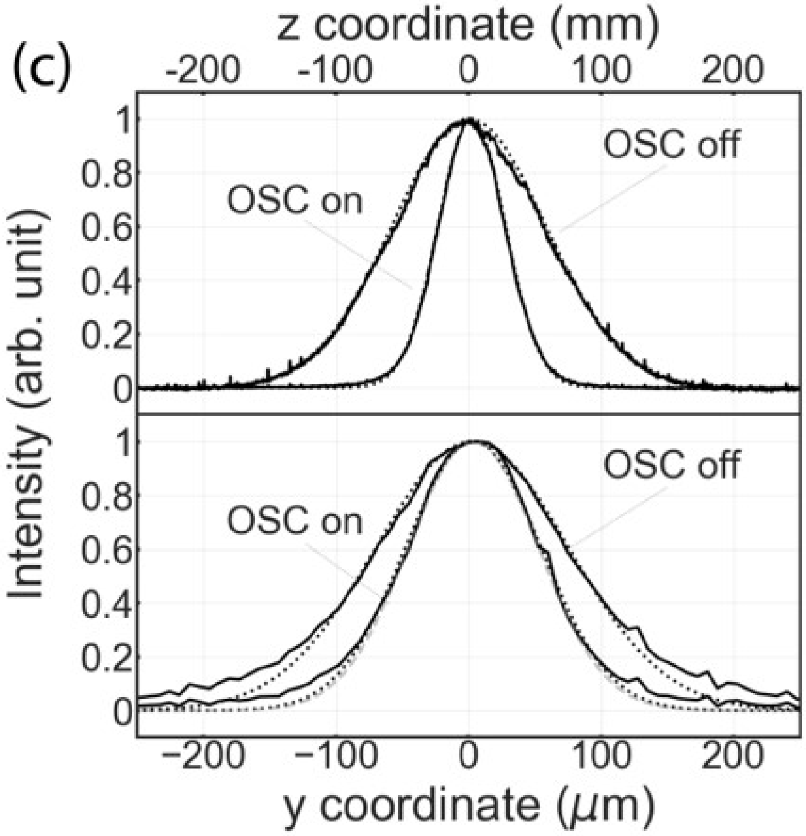
$$W_{eff} = \frac{\left(\int_0^\infty \mathrm{Re}\left(G(f)\right) df\right)^2}{\int_0^\infty \left|G(f)\right|^2 df} \xrightarrow[band]{\text{Rectangular}} f_{\max} - f_{\min}$$

  - The cooling rate decreases if the gain length, σ_g, is smaller than the bunch length, σ_{sp}

Optical Stochastic Cooling in IOTA



- Passive OSC was demonstrated in Fermilab IOTA at 2021
  - 100 MeV electrons
  - 0.95 μm basic wave length
  - 3D cooling
  - Sum of cooling rates 18.4 s^{-1}
    - ~30% below prediction
- The only successful cooling demonstration at optical frequencies



Optical Stochastic Cooling

Tentative parameters of OSC for ep-collider

Basic wavelength of forward radiation	5.5 μm
Band of optical amplifier, μm	5.4-6.6
Number of undulator periods	20
Peak undulator magnetic field	10 T
Length of undulator period	90.7
Undulator parameter	0.46
Angle subtending KU outgoing radiation	1.6 mrad
M_{56} (PU-to-KU transfer matrix element)	3.3 mm
Gain in optical amplifier, dB	50
Emittance cooling times, $\tau_x/\ \tau_y/\ \tau_s$, min	30/30/30
Cooling time at optimal gain	14 min
Power of OA	< 500 W

- Delay and M56 are bound an IOTA type chicane as: $\Delta s = M_{56}/2$

  ⇨ Δs = 1.65 mm
  - That may be insufficient for 50 dB gain
  - In this case a chicane with more complicated optics is required. It will be more difficult to tune, but still has to be within reach

Coherent Electron Cooling

- CEC was suggested in 1980's to address the fast decrease of electron cooling force with increase of proton velocity
  - There was not practical scheme for long time.
  - The breakthrough happened at the end of 2000's with transition to relativistic energies and a suggestion to use FEL as an amplifier.
- Examination revealed that FEL narrow band (~0.5%) & short e-bunch length (~1/100 of p-bunch) limit cooling rate to the same level as the bunched beam microwave SC operating at RHIC.
  - 2 other schemes with wider bandwidth (up to ~50%) were suggested:
    - the micro-bunched electron cooling and
    - the cooling based on the plasma-cascade instability
- All mentioned above cooling schemes operate at the same principle as the SC and therefore can be described within the same theoretical framework.
- Similar to the OSC the CEC is based on the longitudinal kicks. The $\perp$ cooling is achieved by coupling $\perp$ and || planes.

Coherent Electron Cooling

- All CEC proposals are based on the energy recovery linacs, which can deliver required transverse emittances and momentum spreads, but cannot deliver required number of particles in the bunch.
- To create a desired amplification, one need to have large peak current. As result the electron bunch length is much shorter than the proton bunch length. That reduces the cooling rates in proportion of bunch length ratio
- Major CEC problems
  - Large loss of cooling rate due to short e-bunch
  - Operation at the boundary of saturation ($\Delta n/n$~15-20% rms)
  - It is unclear if desired bandwidth (>10-20%) can be achieved
    - 1D model says OK.
    - 3D?
  - Noise/perturbations in the electron beam were neglected but $n_e \sim n_p$
    - Effects of impedances at bunch with very small $\Delta p/p$ may increase Δn_e
    - Experimental study required (BNL & FNAL have needed infrastructure)

Conclusions

- Beam cooling of protons in high energy hadron colliders is one of the most challenging problems in the modern accelerator physics.
  - Considerable progress has been achieved in recent years but a number of problems still need to be addressed
- The electron cooling looks as a possible technology for the proton beam energy below ~250-300 GeV
  - Presently, only ring-based cooling looks feasible for the proton energies above ~100 GeV.
  - With lower energy a cooler based on an energy recovery linac looks as a possibility
- OSC looks as extremely promising technology for proton energy above ~250-300 GeV.
  - It needs ~10 T undulators & OA with small signal delay and large gain
- The CEC development is still at its initial stage. Considerable work has been done in recent years. CEC potential and reach need to be understood better before real implementation can be considered