APS | DIVISION OF PARTICLES & FIELDS

DPF 2017

Bunched Beam Cooling for Hadron Colliders

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U.S. DEPARTMENT OF ENERGY

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Talk Objectives

- Beam cooling at collision energies is required for future hadron colliders with energies below a few TeV – It is the only way to achieve the required luminosities
  - The LHC & FCC are exceptions due to sufficiently fast SR cooling at very high energy
  - Next generation hadron colliders
    - NICA @ Dubna: an ion-ion collider at 1-5 GeV/u/beam
      - Construction started
      - Both electron and stochastic cooling are planned
    - Electron Ion Collider (EIC)
      - CM energies 20-150 GeV/u
      - Broad range of ion species: p to heavy ions
      - Fast hadron cooling required

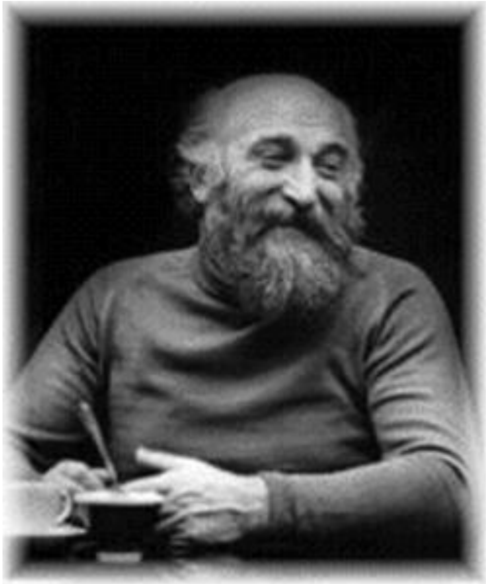
Objectives (continued)

- Which cooling method to use?
- What cooling rates are achievable?

- Demonstration of required cooling rates is one of the greatest challenges for the accelerator physics

Particle Cooling in Accelerators and Storage Rings

- Two basic methods
  - Electron cooling – Gersh Budker, Novosibirsk, 1967
    - Tested experimentally at BINP in NAP-M, Novosibirsk, 1974-79
    - Many installations based on the same technology since then, up to 2 MeV electron beam (COSY, Juelich)
    - Highest energy cooling: at Fermilab Recycler: E=4.3 MeV (8 GeV –pbars) – the only e-cooler used for HEP colliders
    - Never used for cooling at collider top energy



  - Stochastic cooling - Simon van der Meer, CERN, 1969
    - Tested experimentally in CERN at ICE, 1977-78
    - Used for pbar accumulation at CERN & Fermilab
      - ⇒ The foundation of p-pbar colliders (SppS, Tevatron)
    - Used for ion bunched beam cooling at the top energy in RHIC; bunched beam cooling of protons in both Tevatron and RHIC was not successful.

Technology gap

- The present electron cooling technology is not scalable to energies above ~10 GeV/u
- Conventional bunched beam stochastic cooling did not work for protons (RHIC and Tevatron experience)

- The EIC R&D report has identified Bunched-Beam cooling of hadrons in the collider rings as on the highest-risk elements

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

2017

Electron Cooling

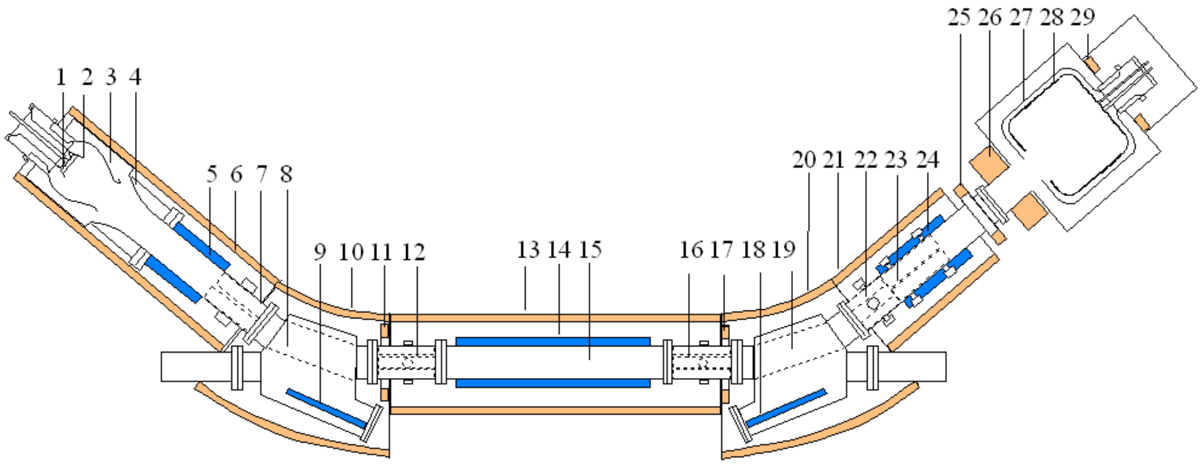
- Electron cooling – friction force in electron gas

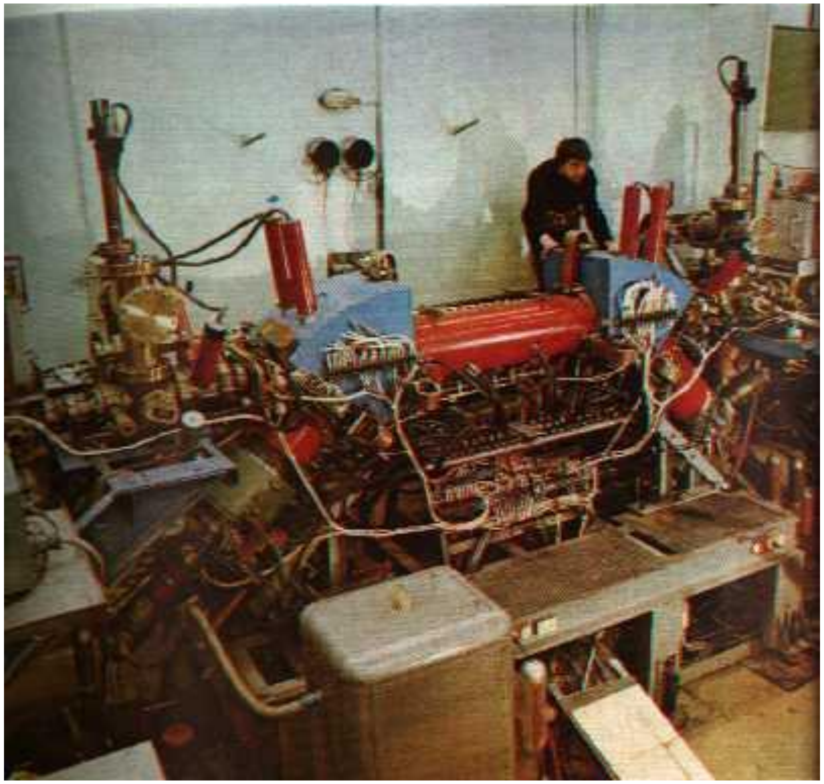
$$F(\mathrm{v}) = -\frac{4\pi n_e Z^2 e^4}{m_e \mathrm{v}^2} L_c \xrightarrow[\text{electron temperature}]{\text{For finite}} \mathbf{F}(\mathbf{v}) = -\frac{4\pi n_e Z^2 e^4}{m_e} L_c \int \frac{\mathbf{v}-\mathbf{v}'}{|\mathbf{v}-\mathbf{v}'|^3} f(\mathbf{v}') d\mathbf{v}'^3$$

- ♦ Does not directly depend on number of cooled particles
- ♦ Cools to the equality of temperatures in the rest frame

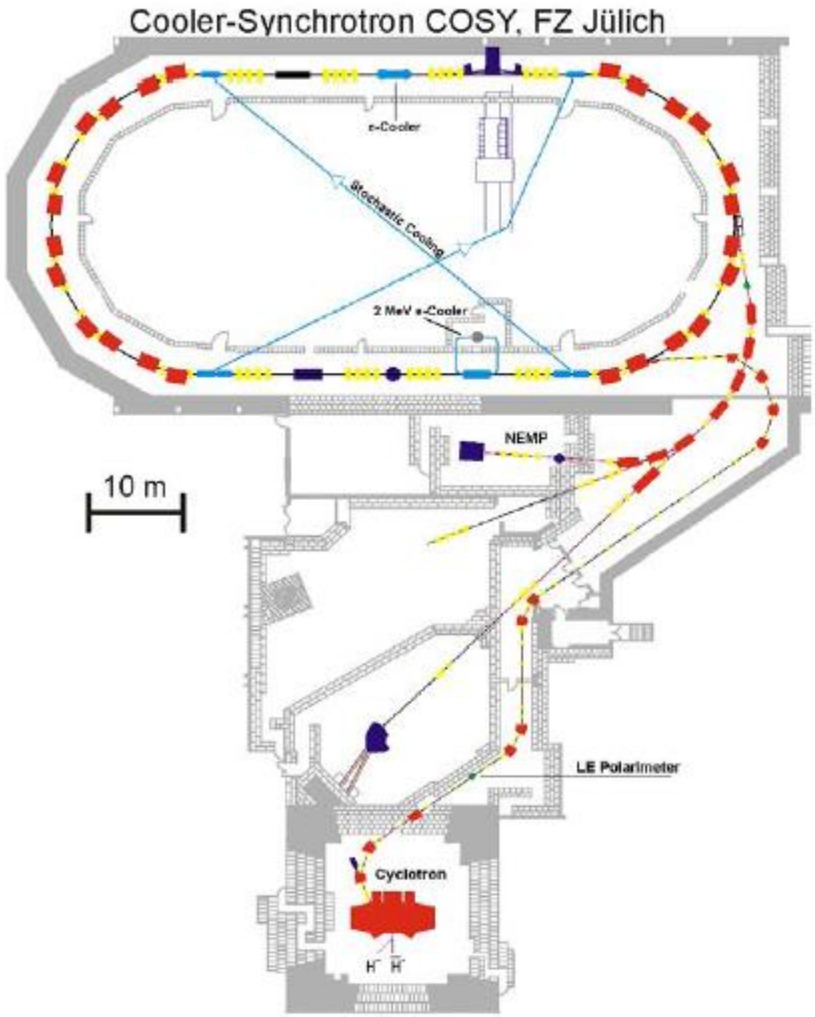
=> $\overline{\mathrm{v}_p{}^2} \approx \frac{m_e}{m_p} \overline{\mathrm{v}_e{}^2}$

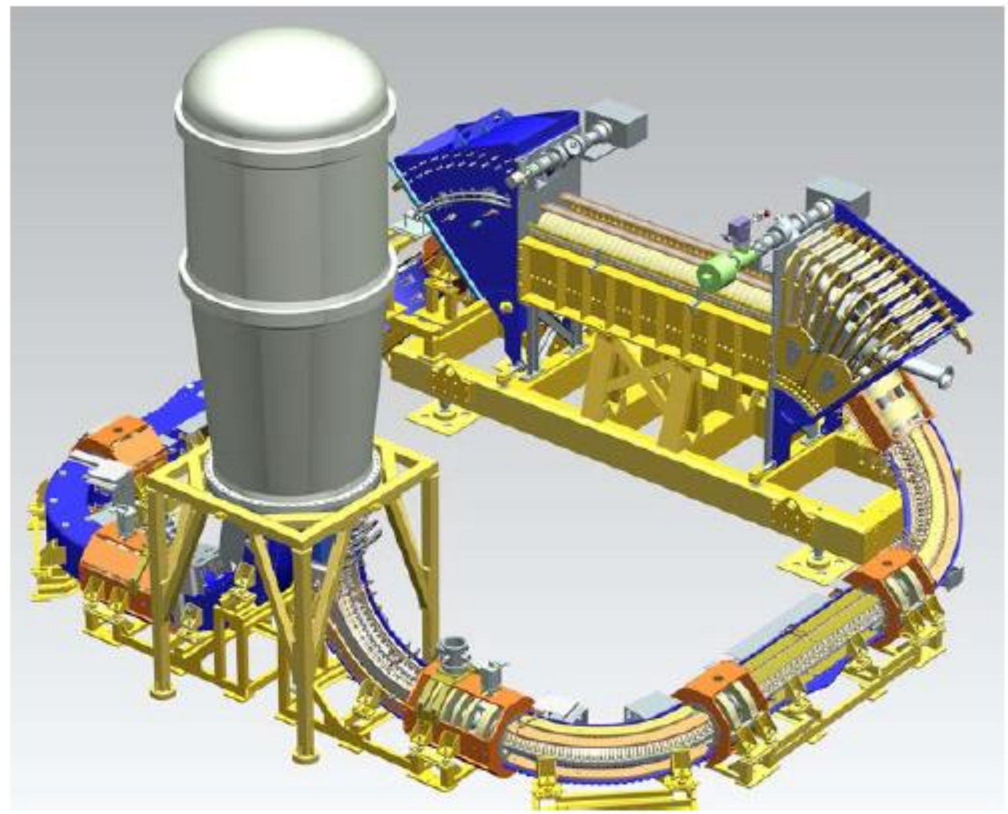
- ♦ $T_{||} \ll T_{\perp}$ for electrostatic acceleration
  - $T_{\perp}$ can be frozen out by strong continuous longitudinal magnetic field





The 2 MeV electron cooler at COSY



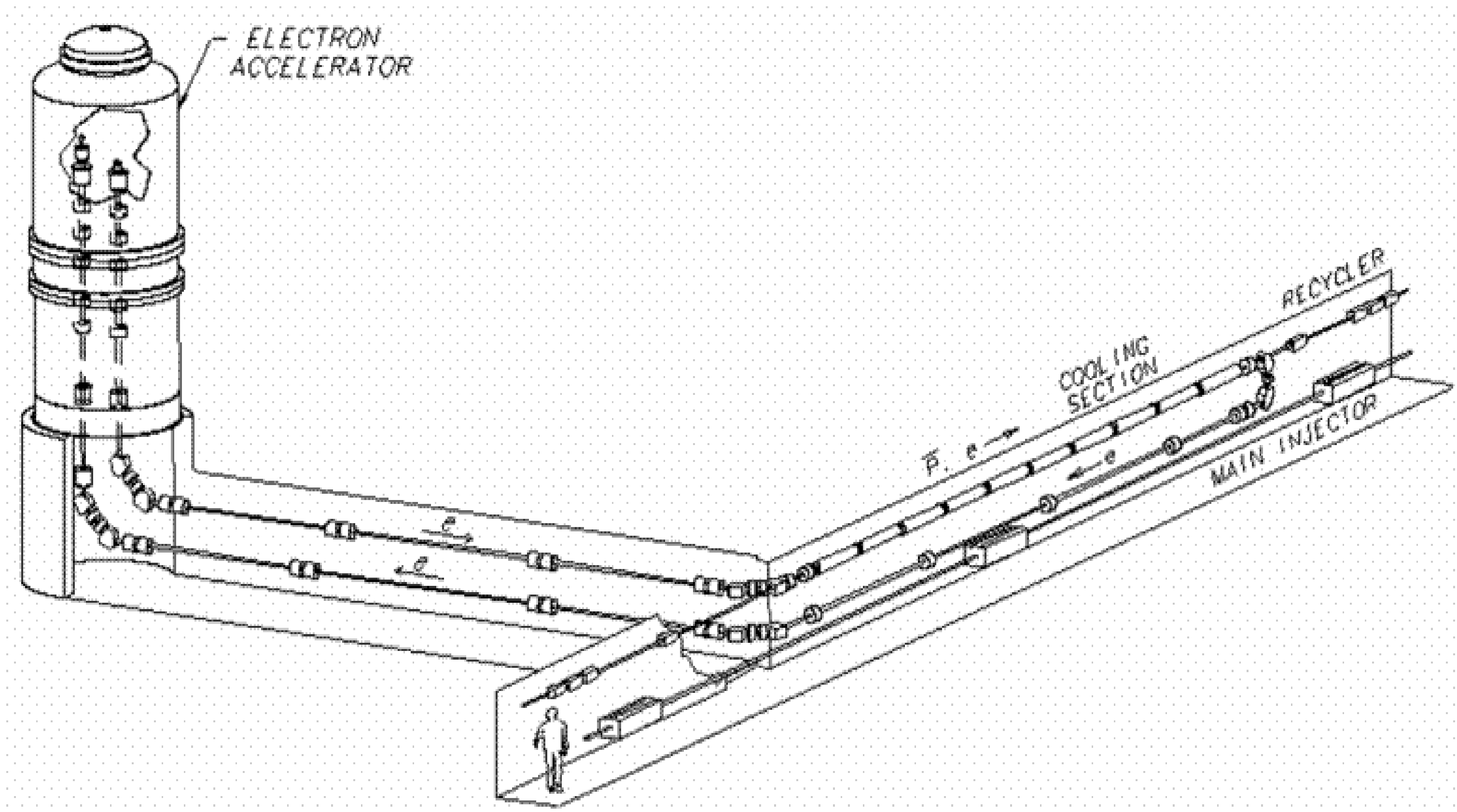


Electron Cooling at FNAL

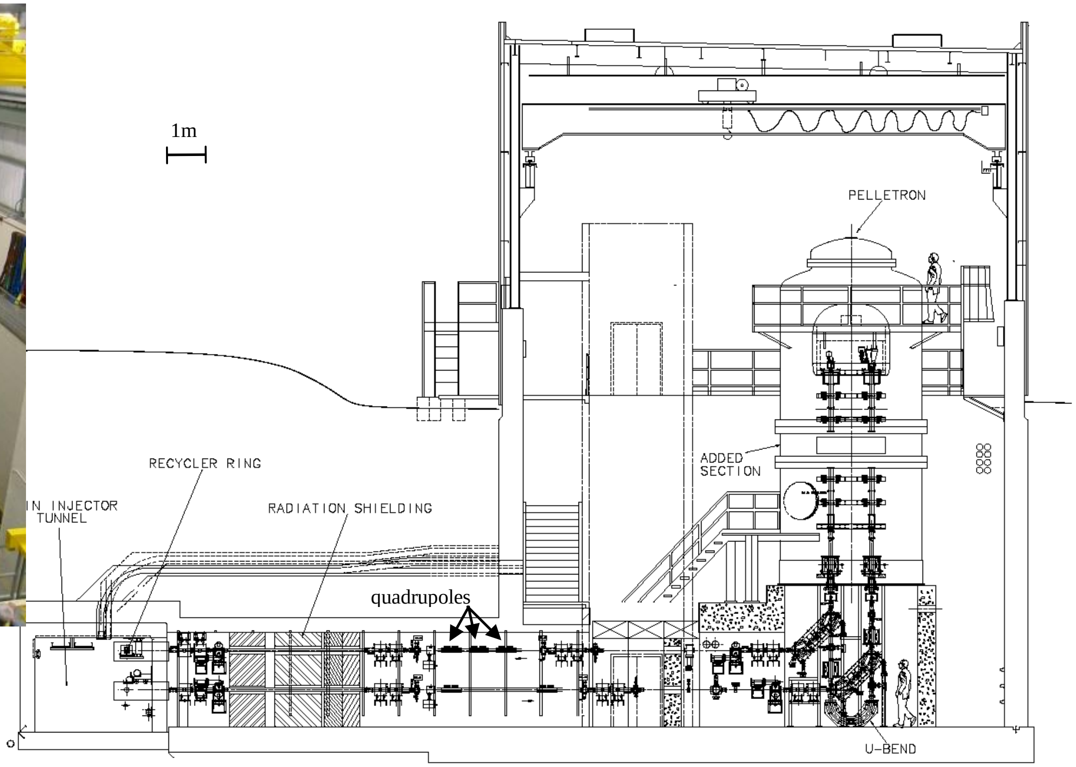
- Fermilab made the next step in the e-cooling technology (1992-2011)
  - Longitudinal magnetic field is not present on the entire transport

Main Parameters

- 4.34 MeV Pelletron (Van de Graaff – type 5-MV accelerator)
- 0.5 A DC electron beam with radius of about 4 mm
- Magnetic field in the cooling section - 100 G
- Interaction length – 20 m (out of 3319 m of Recycler circumference)

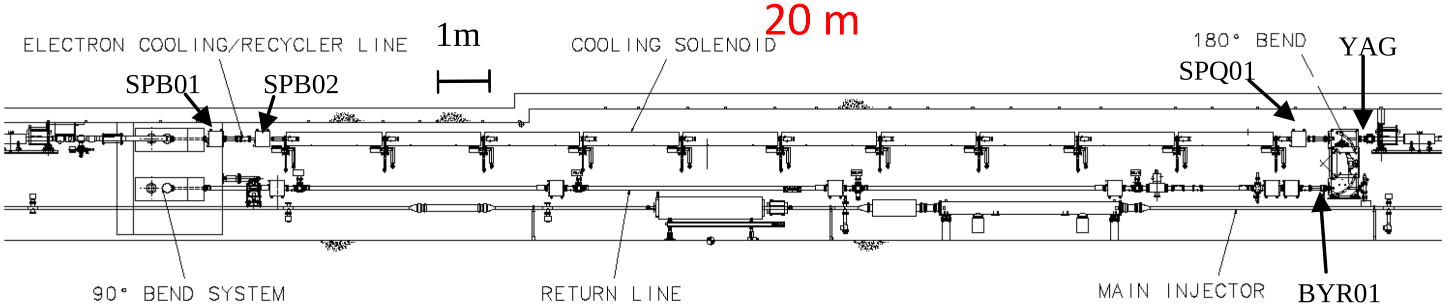


E-cooler in the Recycler Ring

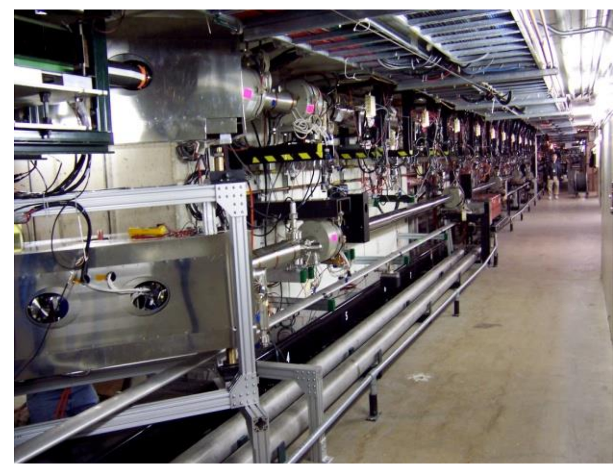


February, 2005-
beginning of commissioning

The Pelletron and beam “supply” and “transfer” lines



The Main Injector/Recycler tunnel containing the cooling section and the “return” line.



High-Energy Electron Cooling

- Cooling rates at relativistic energies
  - Consider the optimistic case when everything is optimized: thermionic cathode, non-magnetized cooling, $\overline{v_{p\perp}^{2}} \approx \overline{v_{e\perp}^{2}}$:

$$\lambda_{\perp} \approx 5 \frac{r_p r_e \Lambda_c}{\gamma^{2.5}} \frac{L_{cool}}{C} \sqrt{\frac{\beta_x}{\varepsilon_{np}}} \frac{j_{catode}}{e} \frac{m_e c^2}{T_{cathode}}$$

where: $\Lambda_c = \ln \dfrac{\rho_{\max}}{\rho_{\min}}, \quad \beta_x \cong L_{cool}$

The electron beam current is set by $j_{cathode}$ and the rms norm. emit. of p beam:

$$I_e \approx 8\pi\varepsilon_{np}^{2}\left(1+\frac{L_{cool}^{2}}{4\beta_x^{2}}\right)\frac{m_e c^2}{T_{cathode}} j_{cathode}$$

- The reduction of IBS rates with energy enables the attainment of required cooling rates with increased energy:

$$\lambda_{IBS\perp} \approx 0.3 \frac{r_p N_p c \Lambda_c \sqrt{C}}{\gamma^{1.5} \sigma_s \varepsilon_{np}^{1.5} \nu_x^{2.5}}$$

- To achieve such cooling rates one needs the longitudinal magnetic field with very high accuracy: $\Delta B / B \ll \sqrt{\varepsilon_{np} / (\gamma\beta_x)}$,

  i.e. $\Delta B/B \lesssim 10^{-5}$ for E_p=100 GeV

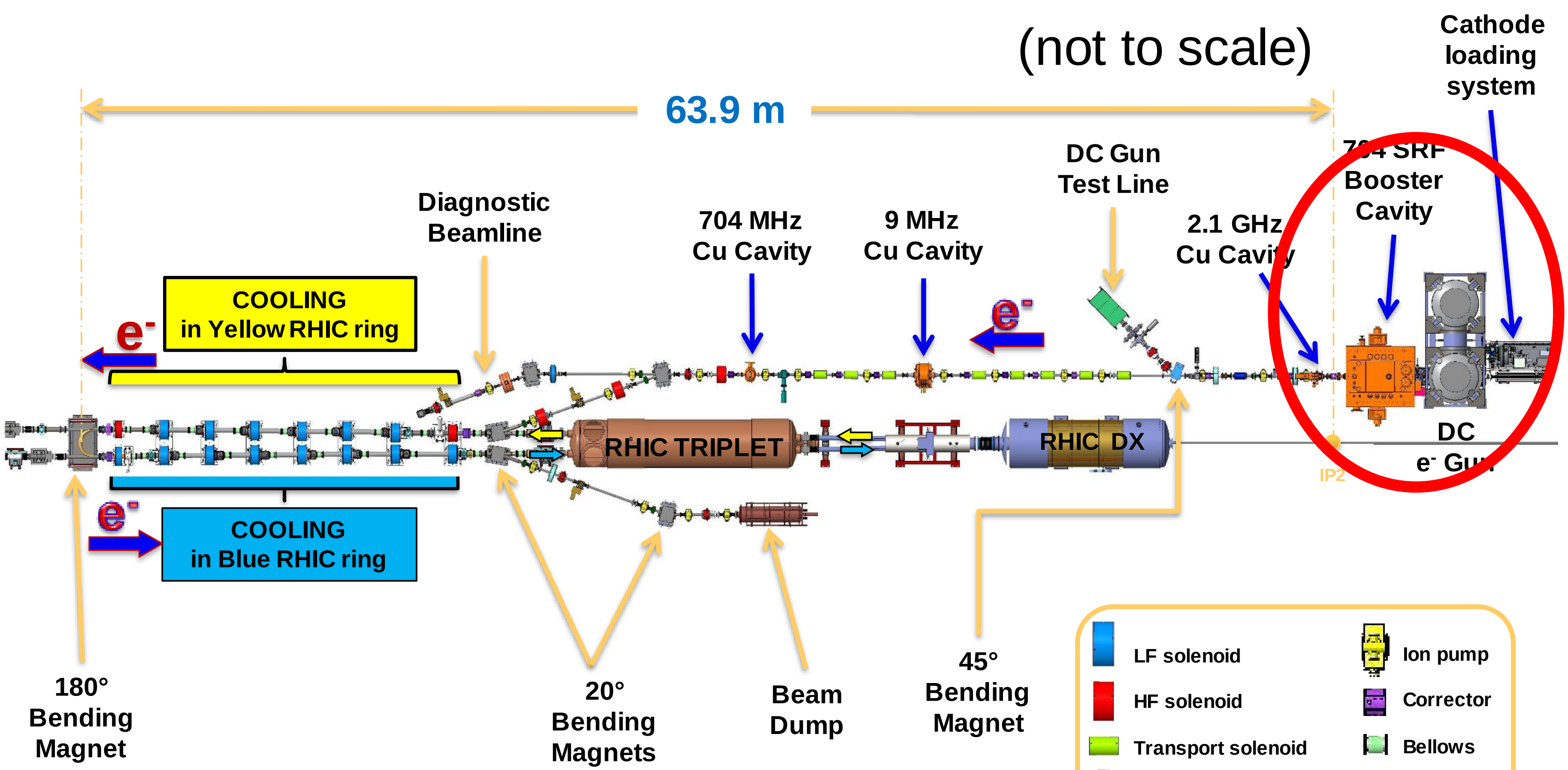
Practical Implementation of Collider E-Cooling

- High energy of colliding beams => high energy of electron beam
  - Electrostatic acceleration looks unfeasible for E_e > 10 MeV
- Two possibilities: RF acceleration or an Induction linac
  - To reduce beam power both can be used with
    - A ring for e-beam recirculation or
    - Energy recuperation (deceleration of "spent" beam)
- SC RF linac (BNL ep-collider proposal LEReC)

  – a cost effective way to get high e-beam energy: 10–100 MeV
  - Difficulties to create a bunch with sufficient length, number of particles and required ⊥ emittances: ~1 ns, 10^{11}, $\varepsilon_n \approx 1$ μm
    - Potential issue: electron energy spread increase due to long. impedance

Low Energy RHIC electron Cooling (LEReC)

A. Fedotov et al.



Energies E : 1.6, 2.0 (2.65) MeV

Avg. current I_{avg} : 27 mA

Momentum $\delta p/p$: 5×10^{-4}

Luminosity gain : 4×

1st bunched beam electron cooler

planned operation in 2019/2020

- An induction linac can create long bunches with required charge. Technology is similar to a DC gun. In combination with a recirculating ring, it can create e-beams required for cooling.
  - Quite complicated optics for the ring
  - Less investigated option. However, to us it looks as a preferred option for now.

Tentative Parameters for ep-collider e-cooling

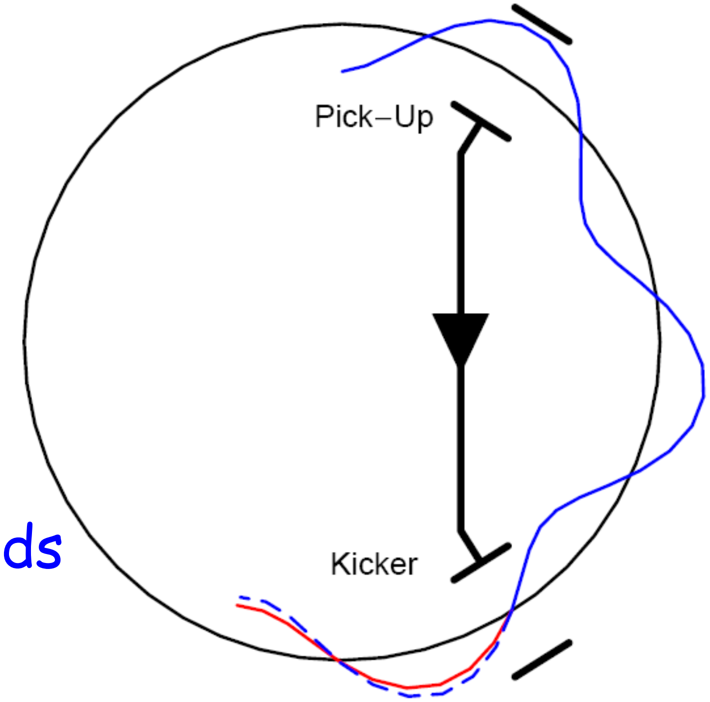
Proton energy	100 GeV
Proton ring circumference	3000 m
Electron energy	54 MeV
Electron beam current	70 A
Rms e-beam size at cathode	2 cm
Cathode radius	4 cm
Rms e-beam size in cooling section	1.4 mm
Rms proton normalized emittance	1 μm
Cooling length	40 m
Proton beta-function at the cooling section center	40 m
Rms proton angles in the cooling section	15 μrad
Magnetic field in the cooling section	5 kG
Limitation on transverse magnetic field, $\Delta B_{\perp}/B$	<10 μrad
Cooling time	~0.5 hour

Time of beam recirculations in the e-ring is determined by IBS and can be up to 10 ms.

- 1 ms (1 kHz rep rate) looks relatively conservative

Stochastic Cooling

Transverse stochastic cooling



- Naïve model for transverse cooling
  - 90 deg. between pickup and kicker

$$\delta\theta = -g\theta$$

  - Averaging over betatron oscillations yields

$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

  - Adding noise of other particles yields

$$\delta\overline{\theta^2} = -g\overline{\theta^2} + N_{sample}g^2\overline{\theta^2} \equiv -\left(g - N_{sample}g^2\right)\overline{\theta^2}$$

That yields optimal gain

$$\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}$$

⇨ Cooling rate:

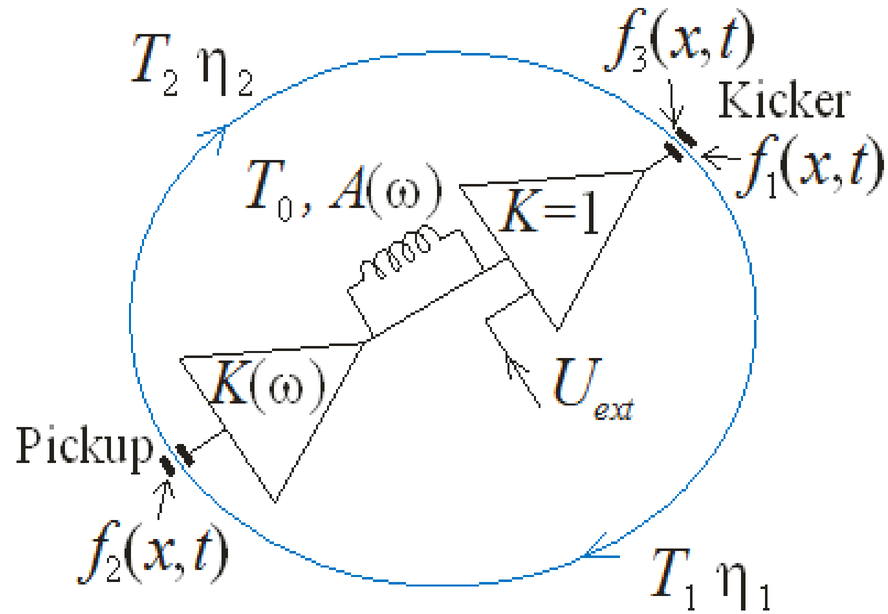
$$\lambda_{opt} = \frac{1}{2}g_{opt}f_0 = \frac{W}{4N}$$

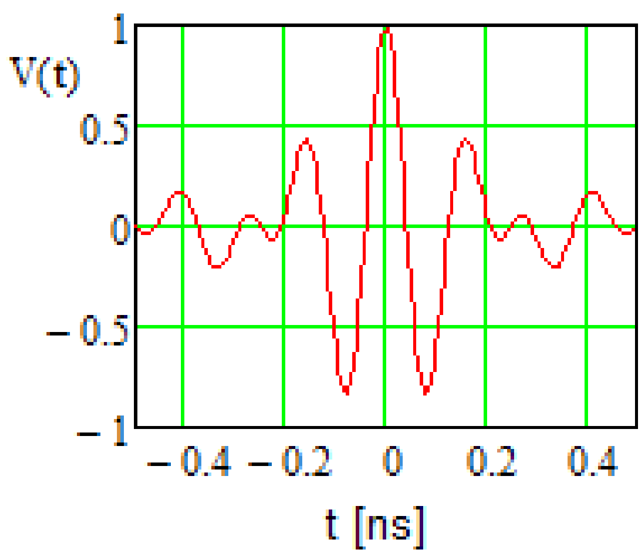
Longitudinal Stochastic Cooling

- Palmer cooling
  - Signal is proportional to particle momentum. It is measured by a pickup at high dispersion location
  - Example: FNAL Accumulator
- Filter cooling
  - Signal proportional to particle momentum is obtained as difference of particle signals for two successive turns (notch filter)

$$U(t) = u(t) - u\left(t - T_0\left(1 + \eta\frac{\Delta p}{p}\right) + T_0\right) \approx \frac{du}{dt} T_0 \eta \frac{\Delta p}{p}$$

  - Examples: FNAL Debuncher and Recycler
- Transit time cooling
  - No signal treatment
  - The same expression for kick as for FC
  - Larger diffusion => less effective than FC
  - Examples: OSC, CEC





Kicker voltage excited by single particle in a system with constant gain in 4-8 GHz band

Bunched-beam Cooling

- The optimal gain is determined by the longitudinal density

$$\frac{N}{C} \xrightarrow[\text{beam}]{\text{Bunched}} \frac{N}{\sqrt{2\pi}\sigma_s}$$

⇨ An estimate of maximum cooling rate: $$\lambda_{opt} \cong \frac{W}{4N} \frac{\sqrt{2\pi}\sigma_s}{C}$$

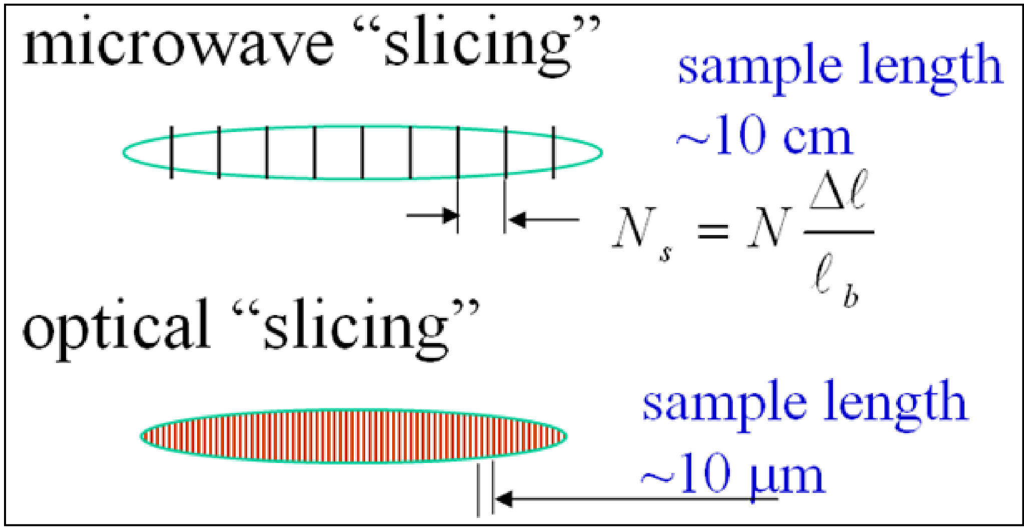
- An accurate result for the transit-time cooling with rectangular band

$$\lambda_{opt} \approx \frac{2\pi^2 W}{N n_\sigma^{\,2}} \frac{\sqrt{\pi}\sigma_s}{C} \qquad W = \frac{n_{\max} - n_{\min}}{T_0}, \quad n_\sigma = \frac{(\Delta p / p)_{\max}}{\sigma_p}.$$

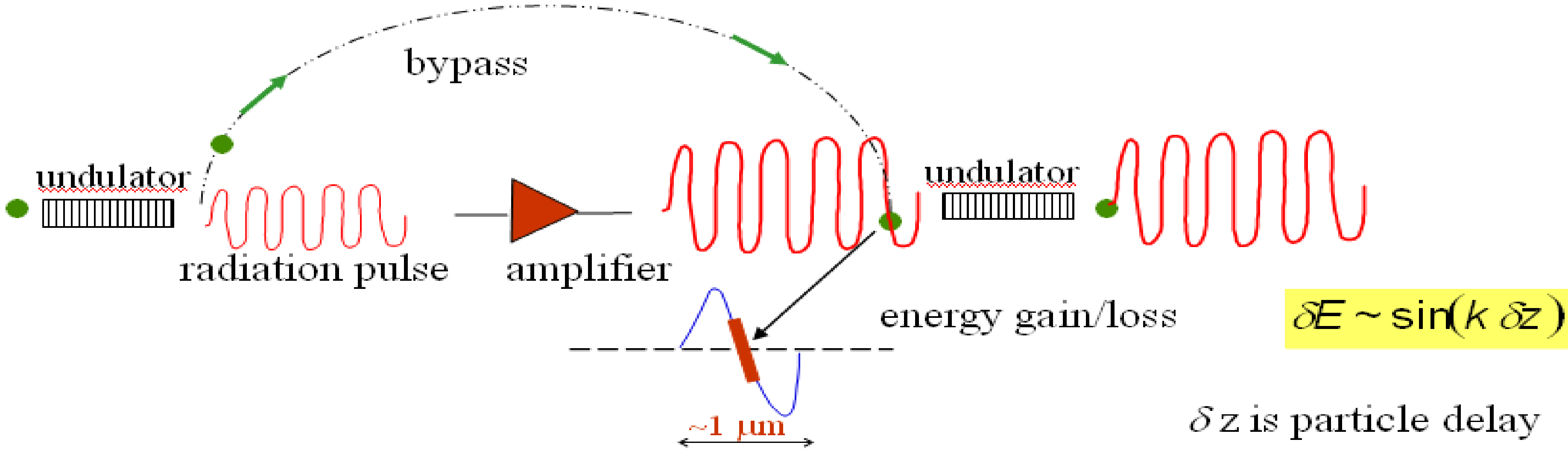
♦ The cooling rate is decreasing with an increase of cooling range (n_σ) expressed in cooling acceptance $(\Delta p/p)_{max}$

Principles of Optical Stochastic Cooling

- OSC was suggested by Zolotorev, Zholents and Mikhailichenko (1994)
- OSC obeys the same principles as the microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~ 10^{14} Hz
  - can deliver damping rates ~3 orders of magnitude larger than usual (microwave) stochastic cooling



- Pickup and kicker must work in the optical range and support the same bandwidth as the amplifier
  - Undulators were suggested for both pickups and kickers



Optical Stochastic Cooling in IOTA

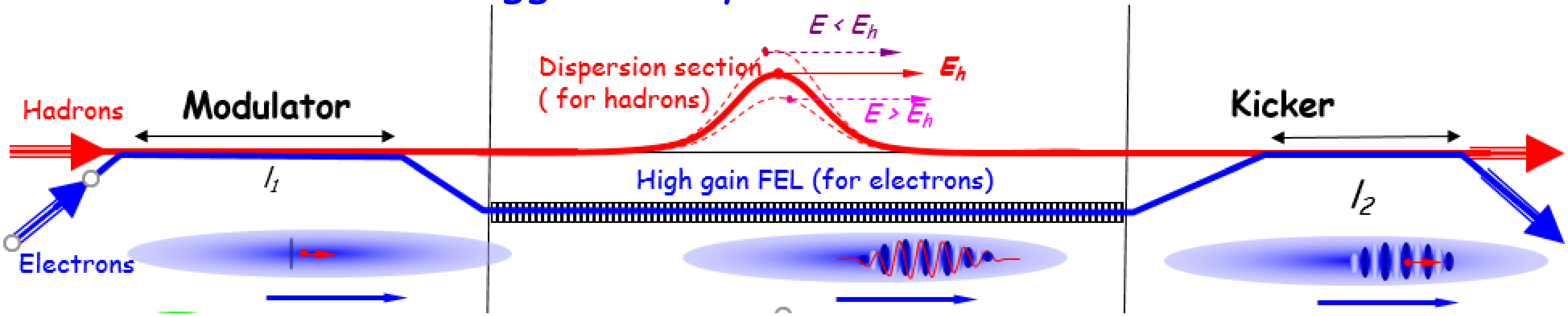
- Test of OSC will be carried out at IOTA ring in Fermilab
  - Its results and developed technology can be scaled to a real hadron collider

Major parameters for the IOTA OSC and tentative parameters for eRHIC OSC

	IOTA	RHIC
Particle type	electrons	protons
Energy	100 MeV	250 GeV
Relativistic factor, γ	196.7	267.5
Rms momentum spread, σ_p	$1.06\cdot10^{-4}$	$1.5\cdot10^{-4}$
Hor. rms emittance, ε, nm	2.62	0.6
Delay in the cooling chicane, Δs, mm	2	2.7
Cooling ranges measured in rms sizes, $n_{\sigma x} / n_{\sigma s}$	10 / 4.4	5.7/4
Basic radiation wavelength, $2\pi/k$, μm	2.2	2.2
Cooling type	Passive	Active
Number of wiggler periods, n_w	7	50
Wiggler length, $L_u = \lambda_w n_w$ [m]	0.774	15.46
Peak magnetic field of the wiggler, B_0 [kG]	1.005	120.8
Optical amplifier gain [dB]	0	30
Power of optical amplifier	N/A	≤1 W
Hor. emittance cooling time, λ_x	0.05 s	0.28 hour
Longitudinal emittance cooling rate, λ_s	0.06 s	0.57 hour

Coherent Electron Cooling (CEC)

- Initially suggested by Ya. Derbenev in the 1980s
- Practical scheme suggested by V.Litvinenko and Ya.Derbenev in 2007

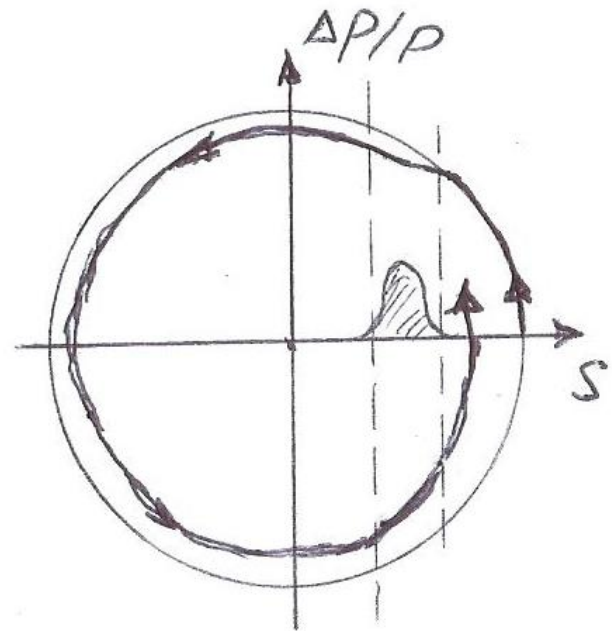


- In operational principle, the CEC is a stochastic cooling system.
  - The signal is excited in the electron beam in modulator (pickup)
  - Then it is amplified in an FEL
  - And, finally, the perturbation in the electron beam makes a longitudinal kick in the kicker.

CEC Challenges

- It has an additional source of diffusion due to random fluctuations in the electron beam
- In the BNL proposal for CEC test e-bunch is much shorter than p-bunch
  - In an optimal configuration, it reduces the cooling rate proportionally to the ratio of electron to hadron bunch lengths (σ_g/σ_{sp})

$$\lambda_{opt} = \frac{2\pi^3 \sigma_f}{n_\sigma^{\ 2}} \frac{1}{N_p \dfrac{C}{\sigma_{sp}} + N_e \dfrac{C}{\sigma_{se}}} \frac{\sigma_g}{\sigma_{sp}}$$



- Compared to the microwave stochastic cooling the CEC proposal loses two orders of magnitude in relative bandwidth (50% -> 0.5%) and two orders of magnitude due to the electron bunch being much shorter than the proton bunch
  - It makes the CEC cooling rates similar to the cooling rates of microwave stochastic cooling
  - It might be challenging to resolve in an actual collider

Conclusions

- Electron cooling has a potential to cool protons/ions in a collider at the top energy at energies up to a few hundreds GeV
  - No obvious show stoppers for now. More work is required to prove the feasibility
- Optical stochastic cooling looks like an interesting possibility
  - Getting required optical gain with a short delay can be a problem
    - Optical parametric amplifiers and FELs do not represent a valuable choice due to too short amplification length
  - OSC is tied to a single energy ($\omega \propto 1/\gamma^2$)
    - Energy change requires change of undulators or OA or both
  - Test of OSC will be carried out at the IOTA ring
- BNL is carrying out a CEC demonstration experiment. Expecting first results soon.