Cooling & Friends

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Mitigation Approaches for Hadron Storage Rings and Synchrotrons

Virtual Workshop

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U.S. DEPARTMENT OF ENERGY
Fermilab

Our Great Challenge

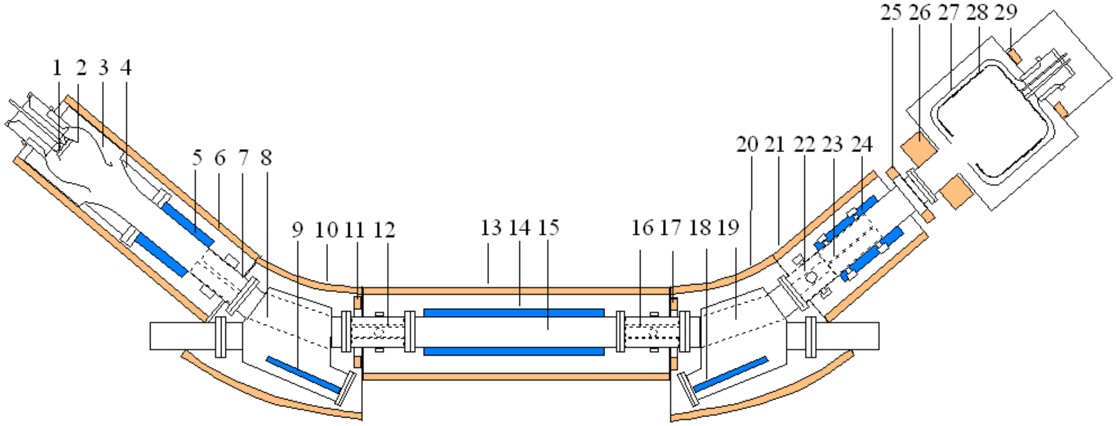
- Presently, cooling at collision energy in e-p collider is one of the most challenging problems in accelerator physics and technology
- Possible candidates
  - Electron cooling
    - Ring based cooler based on an energy recovery SRF linac: Jlab
    - Ring based cooler based on an induction linac: Fermilab
  - Stochastic cooling
    - Optical stochastic cooling (OSC), Zolotarev, Zholentz, Michailichenko, 1994
      Passive (to be tested with electrons in IOTA this year)
      Active (coming at IOTA in 3-4 years)
    - Coherent electron cooling, Derbenev, ~1980
      FEL based: Derbenev, Litvinenko, ~2007
      Micro-bunched Electron Cooling (MBEC), Ratner, 2013
      Plasma cascade instability, Litvinenko, 2018
- This talk discusses some details of this challenge
  & how ideas elaborated for cooling can be applied to other areas
  - But it should not be considered as a review of any kind

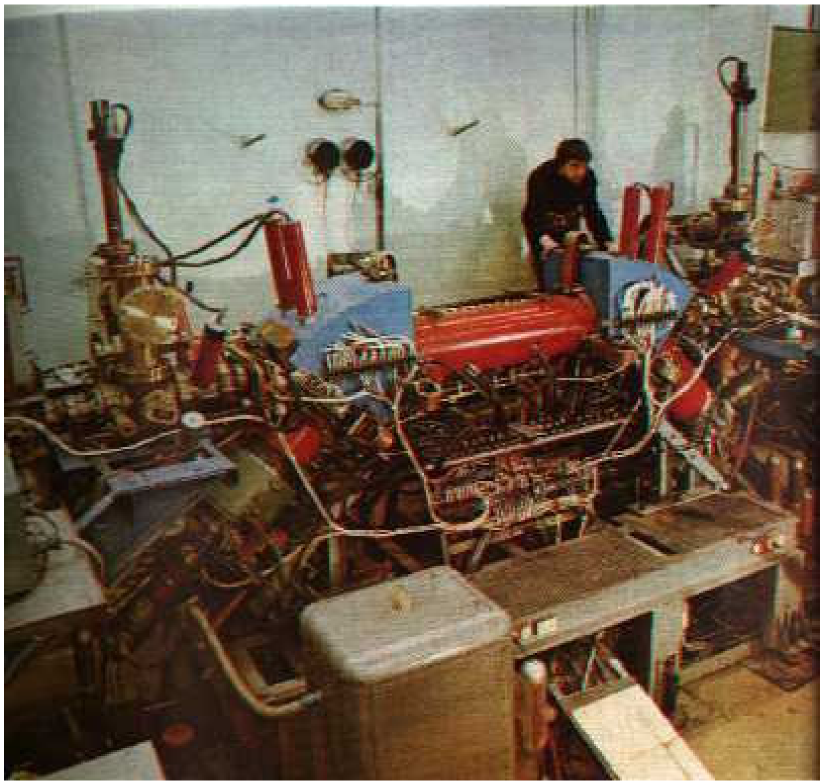
Outline

- Cooling
  - Electron cooling
  - Stochastic cooling
    - OSC
    - CEC
    - Micro-bunched electron cooling
- Friends
  - Strongly X-Y coupled optics by design and circular modes
  - Optimization of kicker waveform to reduce excitation of head-tail modes
  - Dampers with GHz bandwidth
  - Electron lens for transverse stabilization

Electron Cooling

- Suggested by A. M. Budker in 1966
  - In the beam frame: heavy particles come into thermal equilibrium with cold electron gas
- Tested experimentally at NAP-M in BINP, Novosibirsk, 1974-79
  - 35 MeV electron beam (65 MeV protons)
  - Magnetized electron cooling





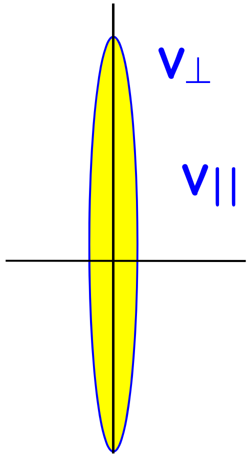
- Many installations since then, up to 300 kV electron beam (GSI, Darmstadt)
- FNAL 4.3 MeV, peletron based, 2005
- 2 MeV cooler in COSY, Julich
- BNL 1.6 MeV, SRF linac based, 2019

Physics of electron cooling

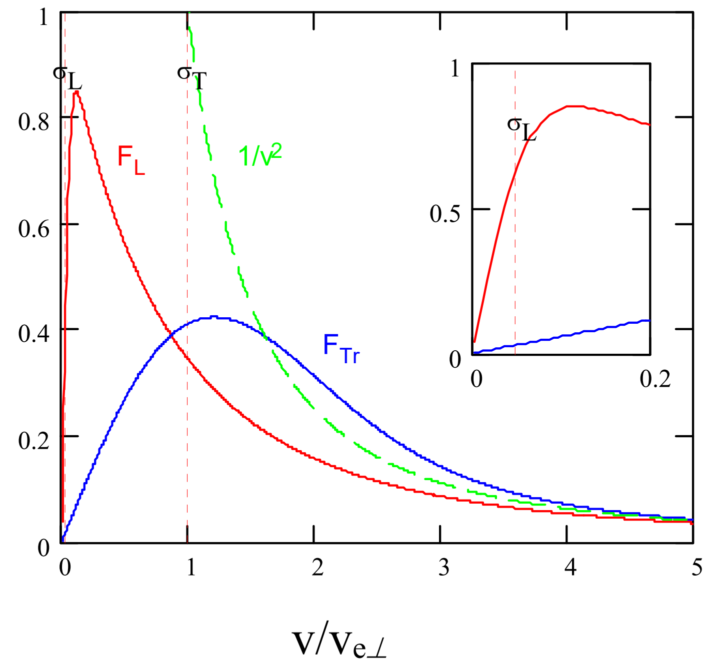
- Friction force

$$F(\mathbf{v}) = \frac{4\pi n_e e^4 Z^2}{m} L_c \int \frac{\mathbf{v}-\mathbf{v}'}{\left|\mathbf{v}-\mathbf{v}'\right|^3} f(\mathbf{v}') d\mathbf{v}'^3$$

B = 0, plasma perturbation theory ($L_c >> 1$ or $\rho_{max} >> \rho_{min}$)

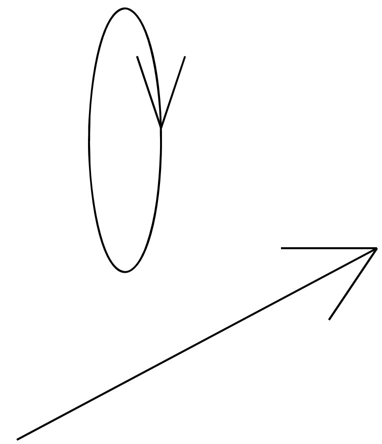


- Flattened el. distribution due to particle acceleration
- Maximum cooling force is achieved for v about $v_{e\perp}$ and $v_{e||}$ for transverse and longitudinal forces, respectively
- $F_{max\perp} \sim 4\pi n_e e^4 Z^2 L_c / T_\perp$ is set by $T_\perp$



Dependence of || and ⊥ friction forces on velocity for non-magnetized electron cooling, $\sigma_L/\sigma_{Tr} = 0.05$

Magnetized electron cooling



- Magnetic field switches off $T_\perp$
  - For $r_L < (r_{max} = v/\omega_p)$ the transverse temperature is magnetized out

    => an increase of force for small velocities, $v < v_\perp$
- Longitudinal temperature of electrons is set by long.-longitudinal relaxation (el. static acc., B=const)
  - The acceleration in Pierce electron gun is fast and initial random position of electrons are not changed by acceleration => $T_{||} = T_c^2/2W_e$
    - After a quarter of plasma period, interaction of electrons => $T_{||} \approx \dfrac{T_c^{\,2}}{2W_e} + 1.9 e^2 n_e^{\,1/3}$
- Maximum cooling force, $F_{max} \approx e^2 n_e^{\,2/3}$, is achieved at $v_p \approx \sqrt{\overline{v_{||e}^{\,2}}} \approx \sqrt{e^2 n_e^{\,1/3}/m}$ when L_c~1.
- Magnetization does not help for cooling at collision energy because
  - proton velocities are large and are comparable to ⊥ electron velocities in a small emittance gun.
  - <u>An absence of magnetization prevents overcooling !!!</u>

Cooling at relativistic energies

- Cooling rates for non-magnetized cooling

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

$$\lambda_\perp \approx \frac{\pi\sqrt{2\pi} n_e r_e r_p L_c}{\gamma^5 \beta^4 \Theta_\perp^{\ 2} \left(\Theta_\perp + \sqrt{2}\Theta_\parallel / \gamma\right)} L_{cs} f_0 \ ,$$

$$\frac{\Theta_\parallel}{\gamma\Theta_\perp} \le 2 \,. \qquad \Theta_\parallel = \sqrt{\sigma_{pe}^{\ 2} + \sigma_{pp}^{\ 2}} \ , \qquad \Theta_\perp = \sqrt{\theta_e^{\ 2} + \theta_p^{\ 2}} \ ,$$

- Pane-cake distribution, ideal magnetic field ($B_\perp$=0) and $\gamma \gg 1, \quad \beta_f = L_{cs}, \quad a_e = 2\sqrt{\beta_f \varepsilon}, \quad \Theta_\perp = \sqrt{\varepsilon / \beta_f}, \quad \varepsilon = \varepsilon_n / \beta_f \gamma$

$$\lambda_\perp \approx \sqrt{\frac{\pi}{8}} \frac{r_e r_p L_c}{\gamma^{5/2} \varepsilon_n^{\ 3/2}} \left(\frac{I_e}{e}\right) L_{cs}^{\ 3/2} f_0$$

- IBS

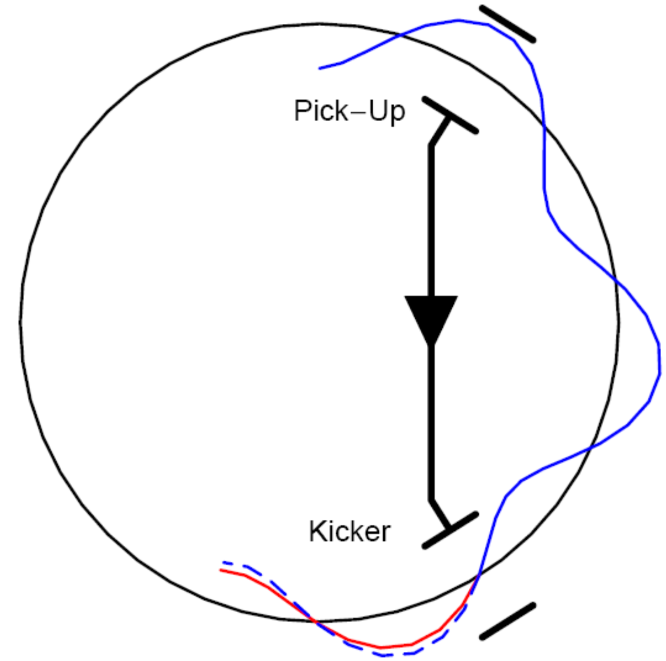
$$\lambda_x \approx \frac{N_p r_p^{\ 2} c L_c}{4\sqrt{2}\sqrt{\gamma}\,\varepsilon_n^{\ 5/2} \sigma_z} \left\langle \frac{D_x^{\ 2}}{\beta_x^{\ 3/2}} \right\rangle_s \ , \quad \gamma \gg Q_x, \quad Q_x \gg 1, \quad \varepsilon_x = \varepsilon_y = \frac{\varepsilon_n}{\gamma}$$

- Relative to IBS rate the cooling rate drops with γ as:

$$\lambda_{cool} / \lambda_{IBS} \propto 1 / \gamma^2$$

  - It has to be compensated by growth in I_e and L_{cs}

Stochastic Cooling



- Invented in 1969 by Simon van der Meer
- Naïve cooling model
  - 90 deg. between pickup and kicker

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

Averaging over betatron oscillations yields

$$\delta\overline{\theta^2} = -(1/2)\,2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

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 for maximum cooling rate

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

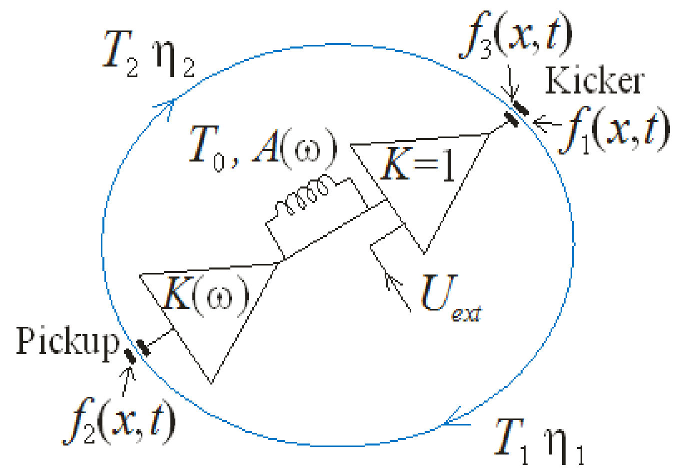
- In accurate analytical theory the cooling process is described by Fokker-Planck equation
  - The theory is built on the same principle as plasma theory – which is a perturbation theory (large number of particles in the Debye sphere versus large number of particles in the sample)

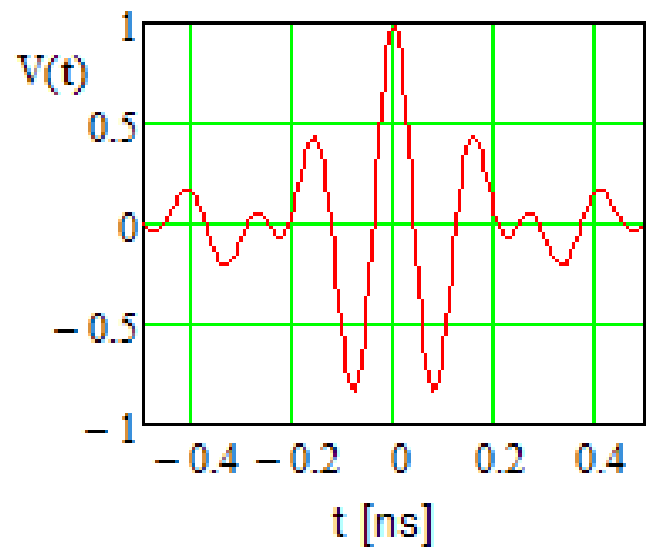
Methods of longitudinal (microwave) stochastic cooling

- Palmer cooling
  - Diff. pickup signal is proportional to particle momentum. It is measured by 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
- Transient time cooling
  - No signal treatment
  - The same expression for kick as for FC
  - Larger diffusion => less effective than FC
  - Examples: OSC, CEC

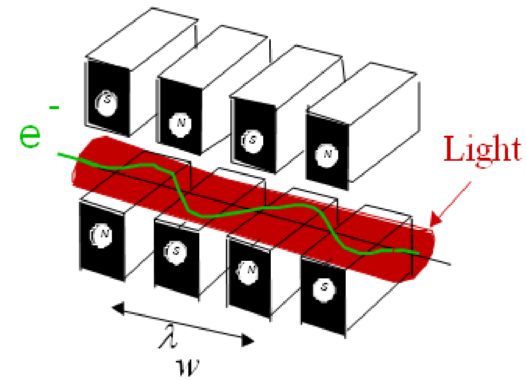


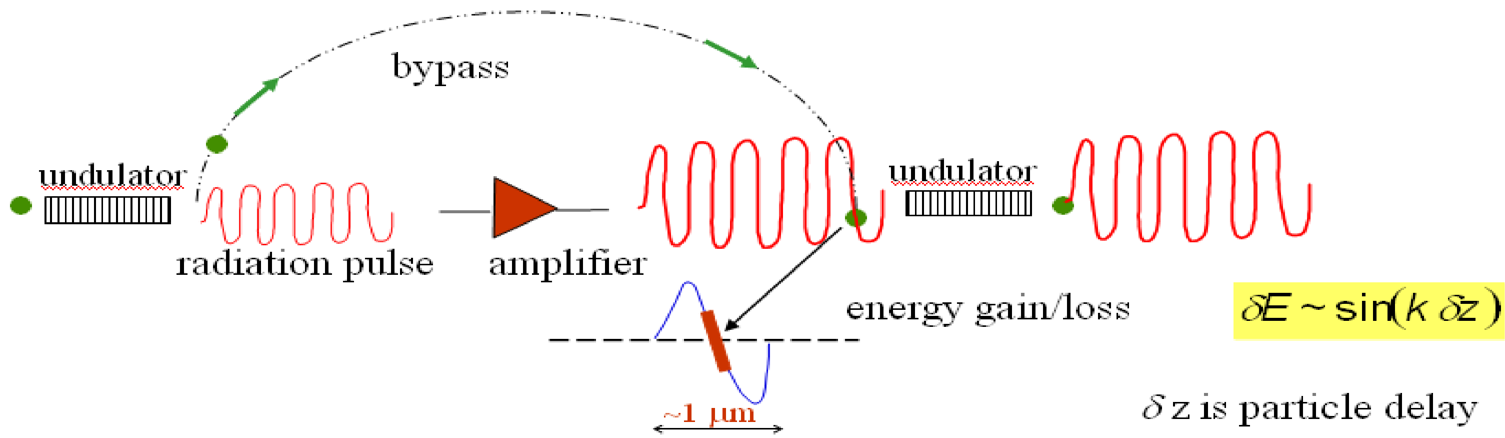


particle in a system with constant gain in 4-8 GHz band

Optical Stochastic Cooling (OSC)

- 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
- Pickup and kicker must work in the optical range and support the same bandwidth as the amplifier
  - ♦ Microwave pickups cannot be scaled to μm
    - Distance to the beam is 10^3-10^4 λ
  - ♦ Undulators were suggested as pickup & kicker



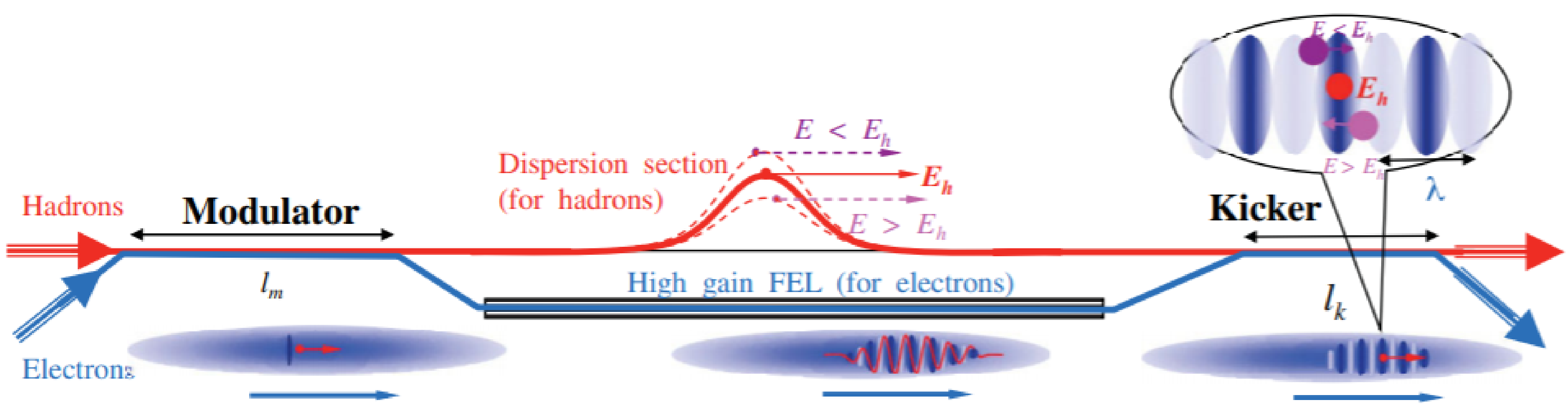


- ⊥ cooling is due to coupling between different degrees of freedom
- Passive cooling can amplify SR cooling by 1-2 orders of magnitude

Coherent Electron Cooling (CEC)

- Initially suggested by Ya. Derbenev (~1980)
  - Perturbation in electron beam introduced by a proton is amplified by an instability excited in the electron beam
- The idea became realistic in 2006 with proposal to use FEL as an amplifier

PRL **102,** 114801 (2009) PHYSICAL REVIEW LETTERS



- Same as OSC it is a high frequency version of stochastic cooling which in general terms is described by the same equations as SC
- Only transient time cooling is possible at OSC and CEC frequencies
  - No notch filters, differential amplifiers, etc.

Stochastic Cooling Rate at Optimal Gain

- Obtained above formula is frequently used for estimates. It implies continuous beam, optimal slip factor and optimal gain but does not account for ratio of cooling acceptance to the rms particle spread. $\lambda_{opt} \le W / N$
  - For filter cooling we have: $$\lambda_{opt} \approx \frac{8\sqrt{\pi}}{3}\frac{W}{Nn_\sigma}$$ (rectangular band W) $W = 2\sqrt{\pi}\sigma_f$
- In transient time cooling a signal of zero amplitude particle is not canceled => larger diffusion and less effective cooling $$\lambda_{opt} \approx \frac{2\pi^2 W}{N{n_\sigma}^2}$$
- Beam bunching further reduces the rate $$\lambda_{opt} \approx \frac{2\pi^2 W}{N{n_\sigma}^2}\frac{\sqrt{\pi}\sigma_s}{C}$$
- In both OSC and CEC getting amplification at the entire length of proton bunch may represent a challenge
  ⇨If electron bunch is shorter than the proton bunch, we have: $$\lambda_{opt} = \frac{2\pi^2 W}{{n_\sigma}^2 N}\frac{\sqrt{\pi}\sigma_s}{C}\frac{\sigma_g}{2\sigma_s}, \quad \sigma_g \ll \sigma_s$$
  Here σ_g is the gain length

Limitations following from of the OSC theory

- Let's make the best-case cooling estimate for BNL PoP experiment
- n_σ=5, relative bandwidth = 3%, λ_0 = 13 μm, σ_p/σ_e = 200

⇨ Total bandwidth: $W_{tot} = 3\%*c/\lambda_0$ = 685 GHz

Effective bandwidth: $W_{tot}*(\sigma_p/2\sigma_e)$ = 1.7 GHz

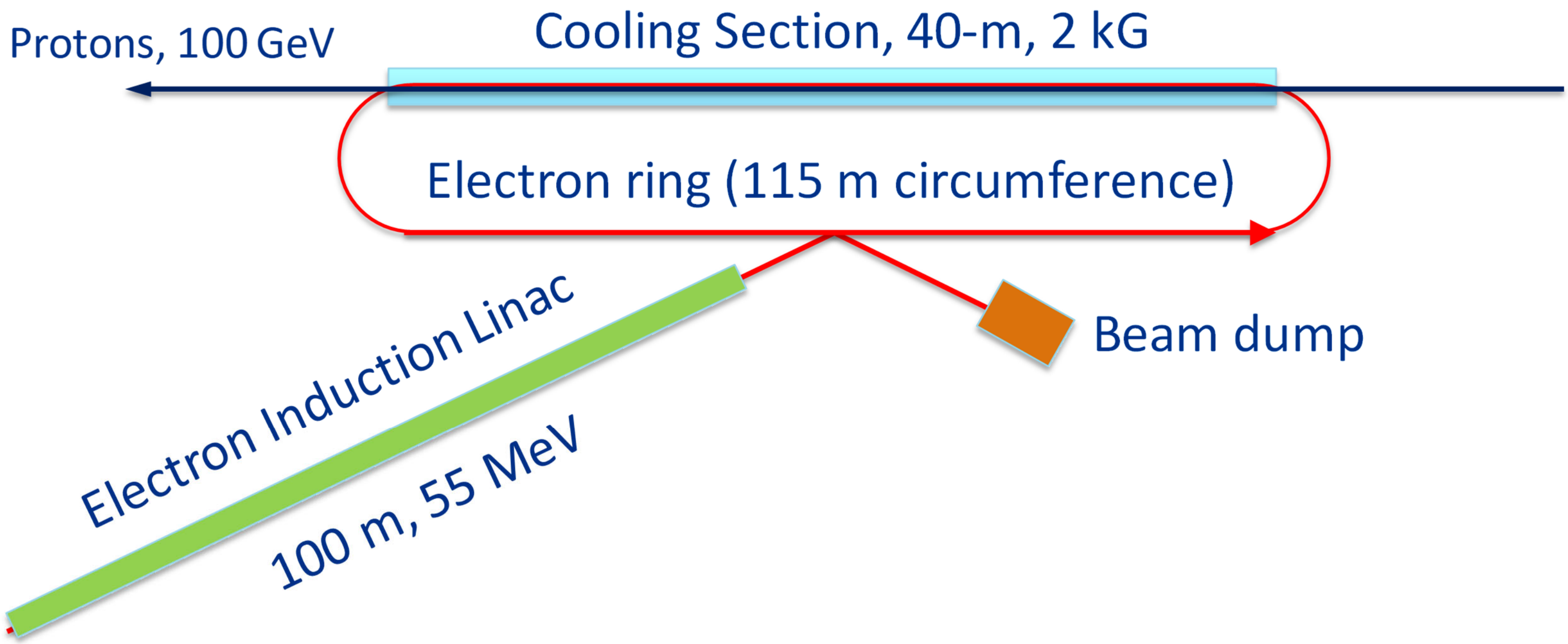
  - That is the same bandwidth as for the microwave bunched beam stochastic cooling already available at RHIC

- The original CEC proposal for RHIC has significantly larger effective bandwidth but still has insufficient cooling (cooling time ~10 hour)
- That is the reason while two other schemes are presently investigated
  - CEC based on plasma cascade instability [1]
  - CEC based on micro-bunched electron cooling [2]
- They are expected to have larger bandwidth
  - Length of el. bunch is still much shorter than the proton bunch

[1] V.N. Litvinenko, et.al. "Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams", https://arxiv.org/ftp/arxiv/papers/1802/1802.08677.pdf

[2] G. Stupakov & P. Baxevanis, "Microbunched electron cooling with amplification cascades", Phys. Rev. Accel. Beams 22, 034401, (2019)

Ring based electron cooling



Main Parameters of the Cooler

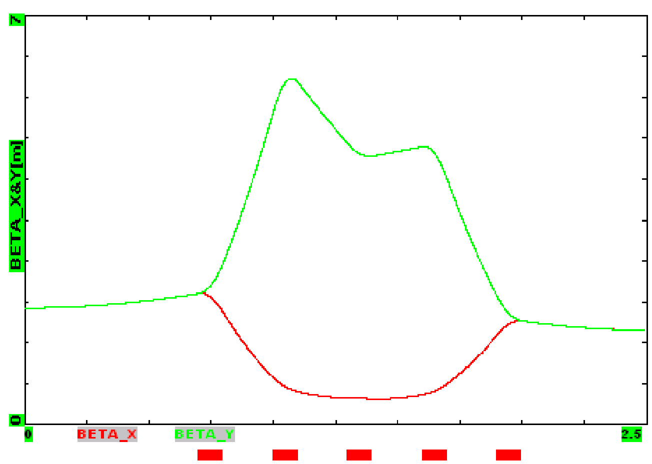
Proton ring circumference (used for cooling rate computation only)	~3,000 m
Normalized rms proton beam emittance	1 µm
Proton beam rms momentum spread	$<3\cdot10^{-3}$
Electron ring circumference	114.2 m
Cooling length section	40 m
Electron beam current	50 A
Longitudinal magnetic field in the cooling section, B_{cs}	1.848 kG
Initial rms electron beam size in the cooling section, r_{cs}	1.47 mm
Cooling time (emittance)	~0.5 - 1 hour

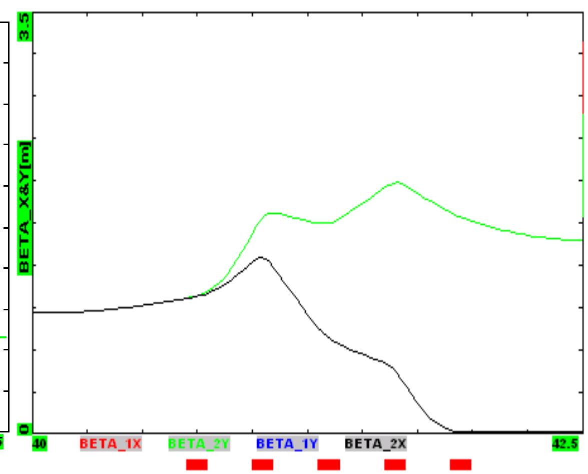
Friends

Optics Choice for the Ring-based Electron Cooler

- Solenoid strongly couples hor. & vert. motions
- Two natural circular modes inside solenoid:
  - One is responsible for the transverse beam size $\sigma_{\perp} \approx \sqrt{\varepsilon_1 \beta_0}$
  - Another one for the el. beam temperature $\theta_{\perp} \approx \sqrt{\varepsilon_2 / \beta_0}$

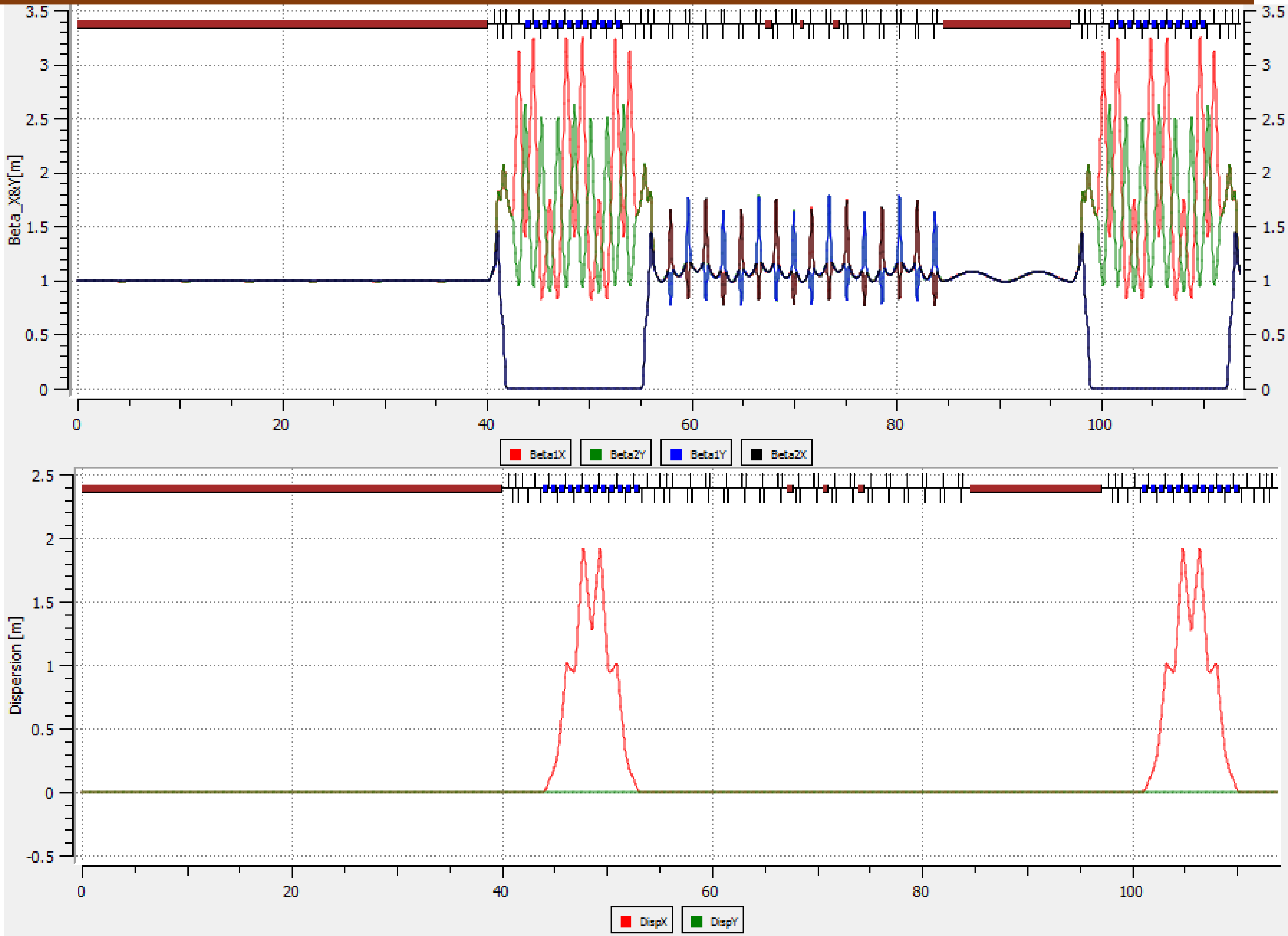
    => Very large ratio of mode emittances
- Usage of circular modes in arcs would result in unacceptable emittance growth for the small emittance mode
- Derbenev's adapters are used for transform the beam between arcs and straights





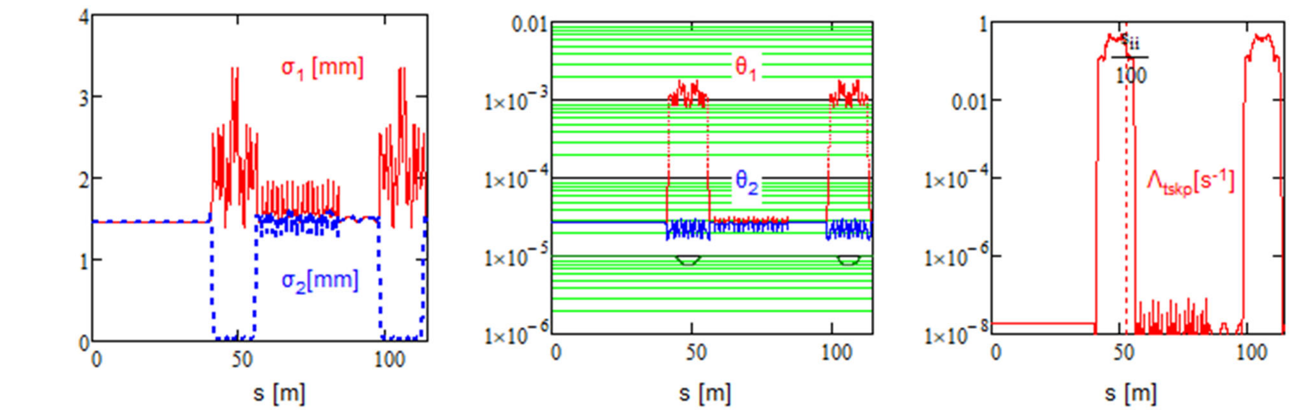
Receipt: Make 90 deg. difference in phase advances, rotate by 45 deg.

Beam optics in the cooling ring: 4D Twiss parameters

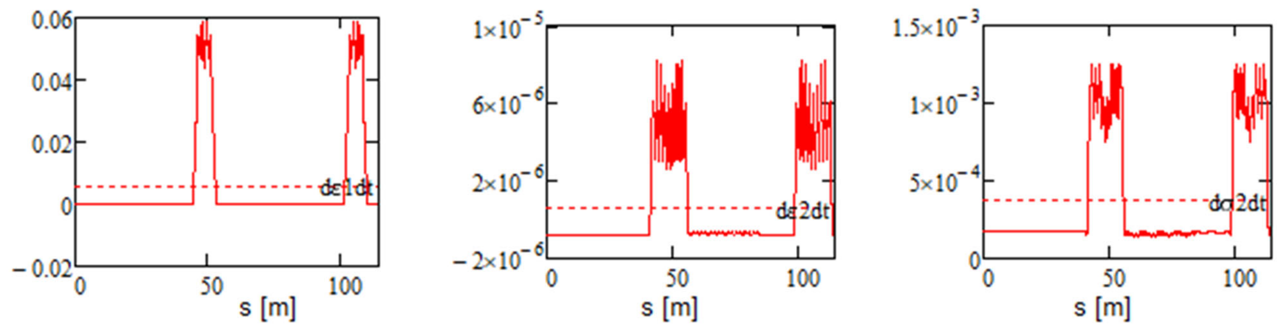


Advantages of optics with circular modes

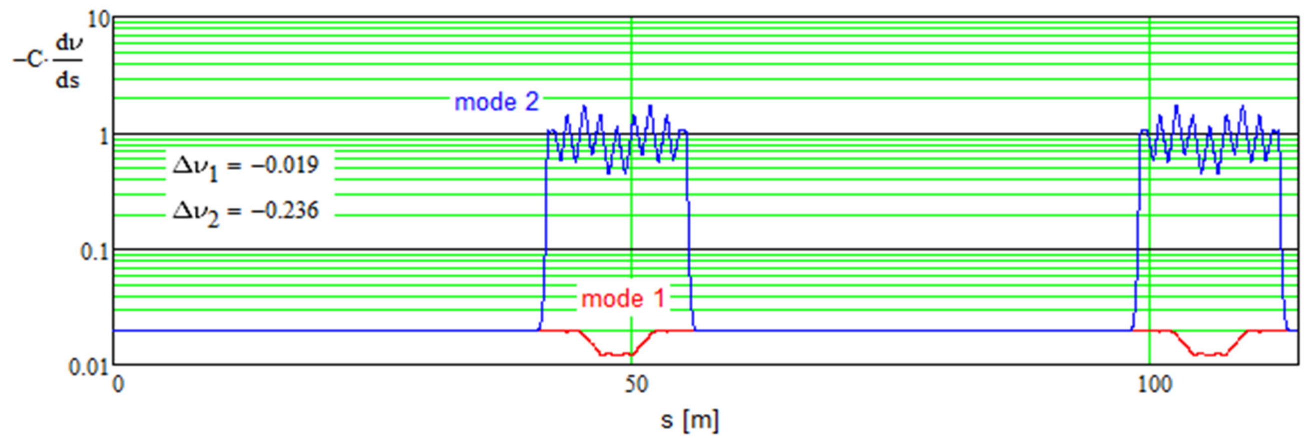
- Reduced Touschek scattering



- Reduced IBS



- Reduced space charge tune shifts

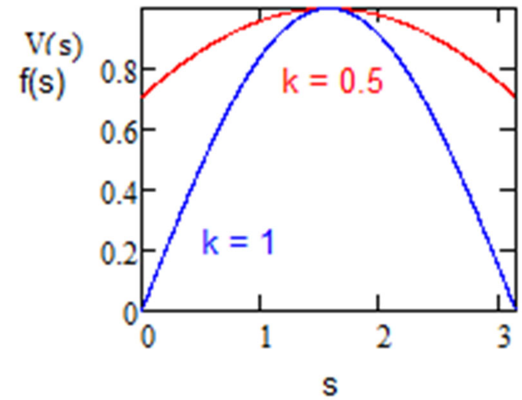


Excitation of Head-tail Modes by Transverse Damper

- Zero order perturbation theory yields damping rates of HT modes

$$\lambda_n \equiv \frac{1}{2x_0^{\,2}}\frac{d}{d\tau}\left|x_0^{\,2}\right| = -\frac{G}{2}\mathrm{Re}\left(R_n(k_p,\phi_p)\overline{R(k_k,\phi_k)}\right)$$

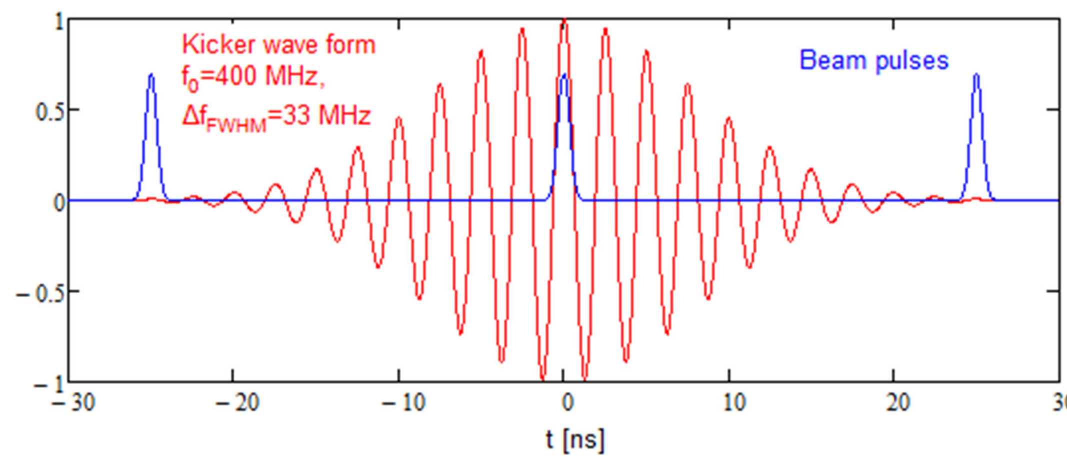
$$R_n(k_x,\phi_x) = \frac{1}{\pi}\int_0^{\pi} e^{i\chi\psi} r_x(\psi)\cos(n\psi)d\psi\ , \quad x = k, p$$



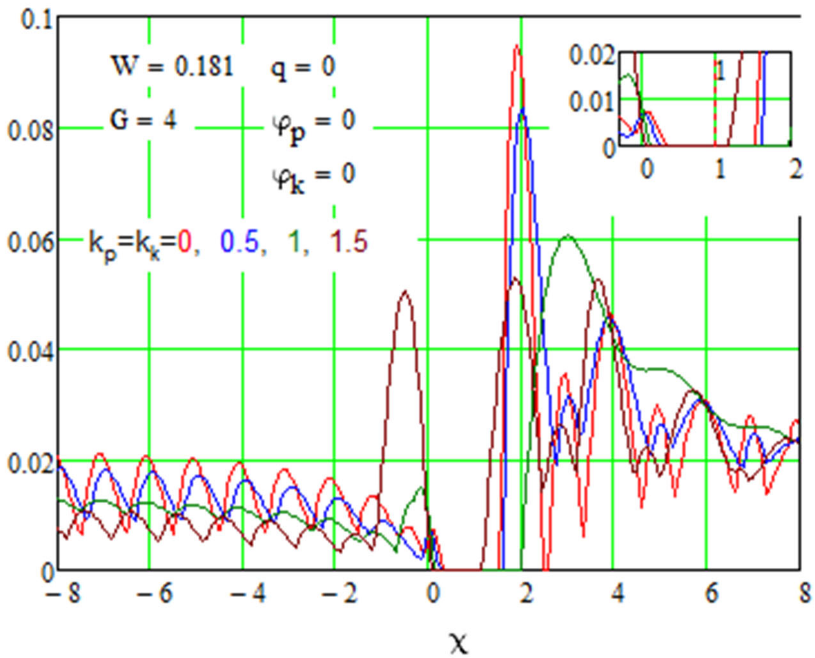
  - ♦ If response functions of pickup and kicker, $r_x(\psi)$, are equal, there are no modes undamped by damper
    - Harmonic response is the most straightforward choice

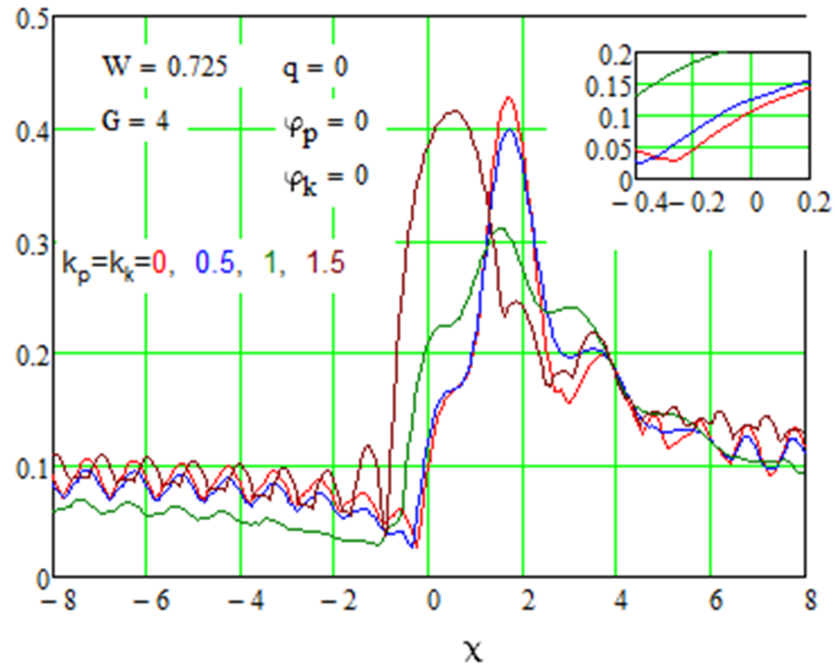
$$r_k(\psi) = r_p(\psi) = \cos\left(k(\psi - \pi/2)\right)$$

- The LHC damper pickup response is already harmonic at 400 MHz
- New kicker is required



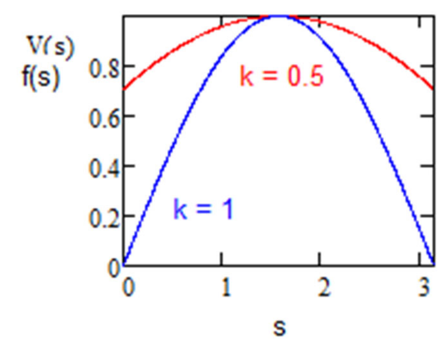
Dependence of HOMs excitation on damper response (SBM)



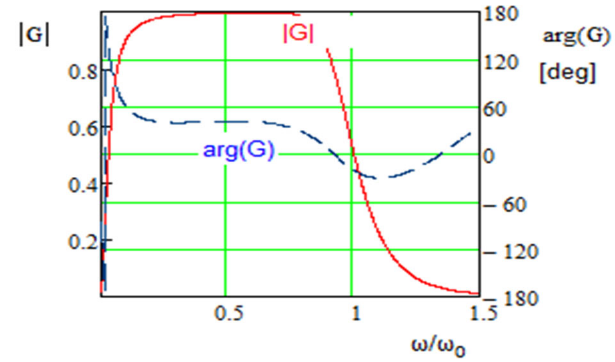


Growth rate of the most unstable mode on head-tail parameter χ for different damper responses for the cases of the beam intensity of twice less (left) or twice more (right) than the strong head-tail threshold.

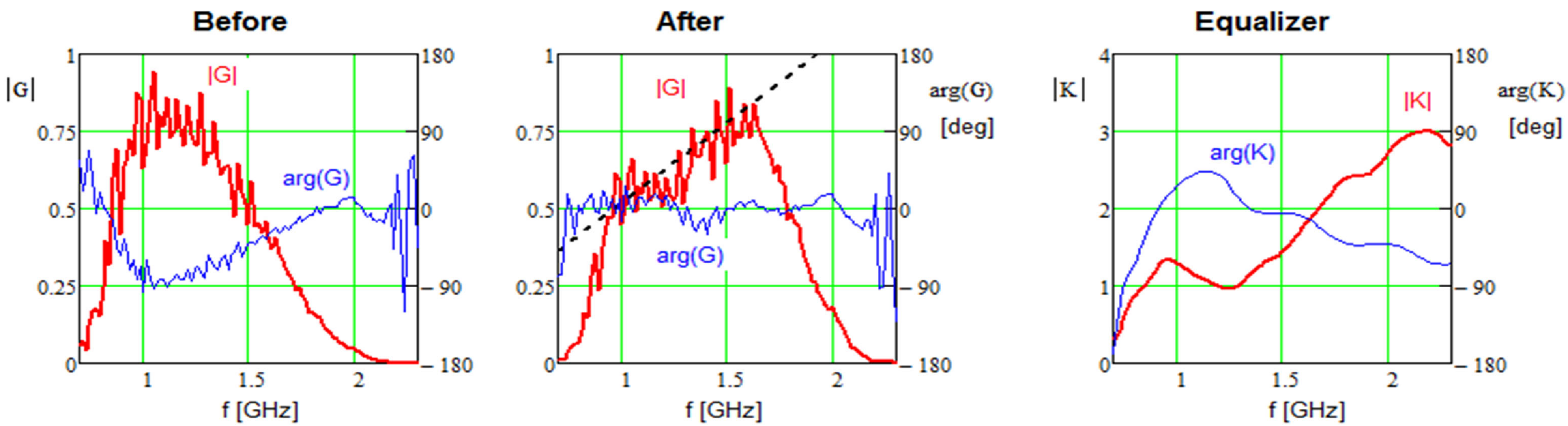
- Optimal responses improve damping of HOMs by about 2 times for negative χ
  - Optimum is achieved at $k_p=k_k$ ~ 1-1.5 (half oscillation on L_b)
- New kicker is responsible for the beam stabilization only!!!
  ⇨ Great reduction in the maximum kick value
- Old kicker should be used for injection damping



Equalizers in Stochastic Cooling

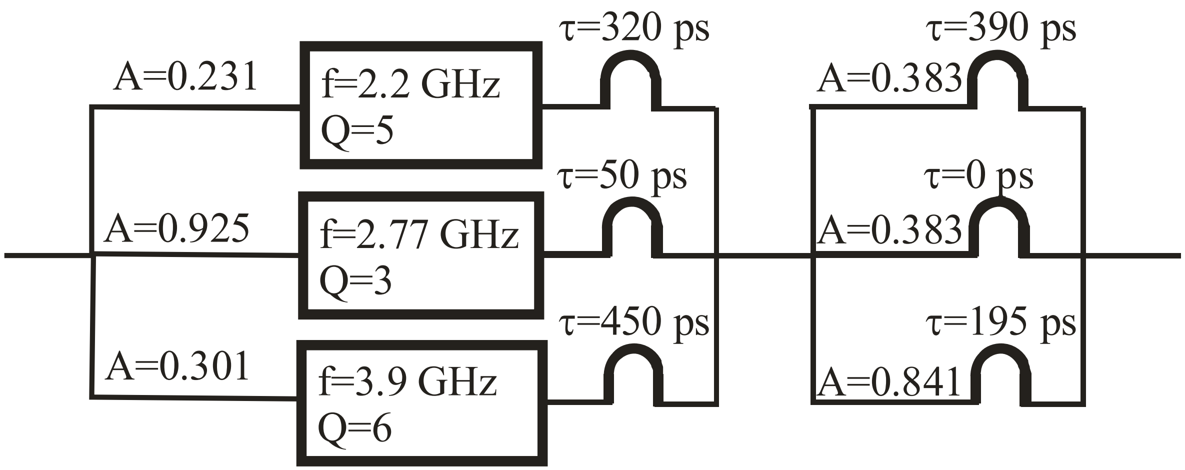


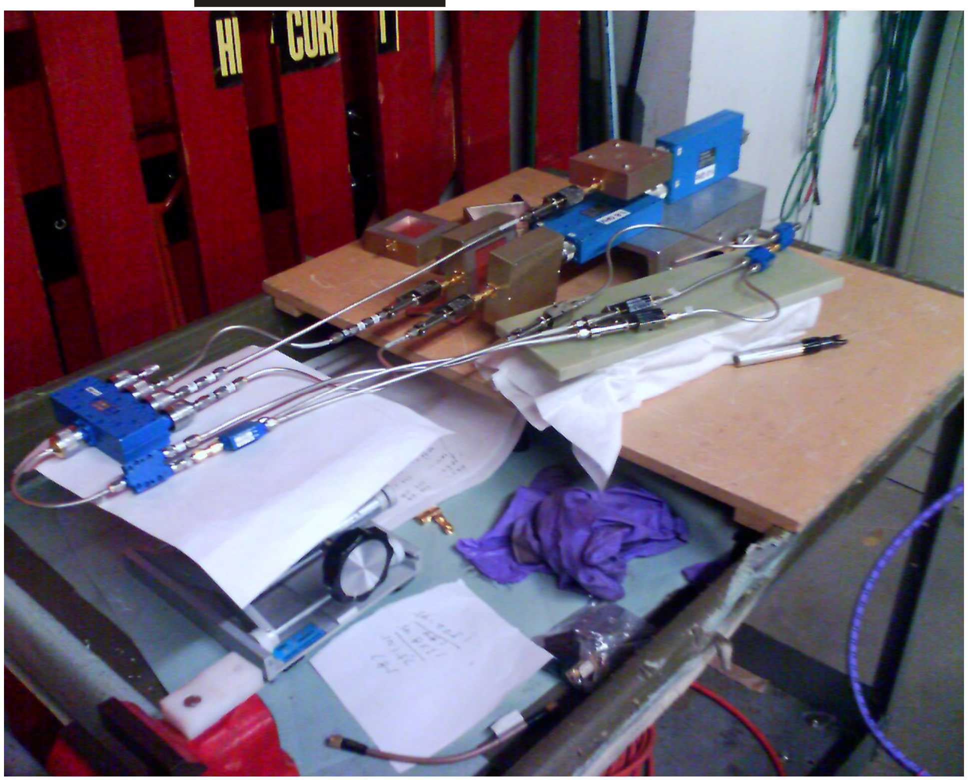
- For typical amplifier the amplitude and phase responses are bound by causality
  - There is no causality limitation in a damper
  - Cable shortening => signal comes earlier
- ⇨ Amplitude and phase responses can be controlled independently
- Limitations for digital filter are the same
  - Digital filtering adds additional flexibility to a system but is not available at very high frequencies

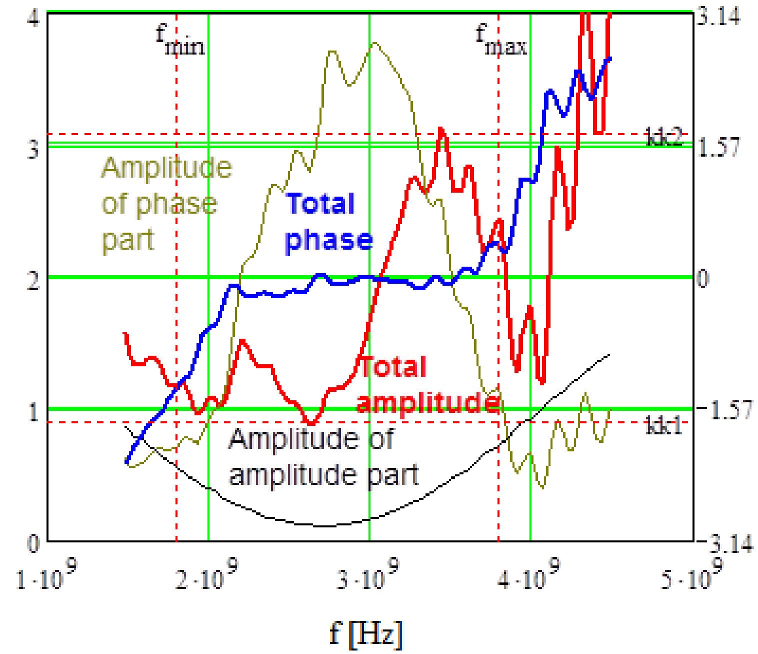


Correction of transfer function for Recycler

Equalizers in stochastic cooling (2)



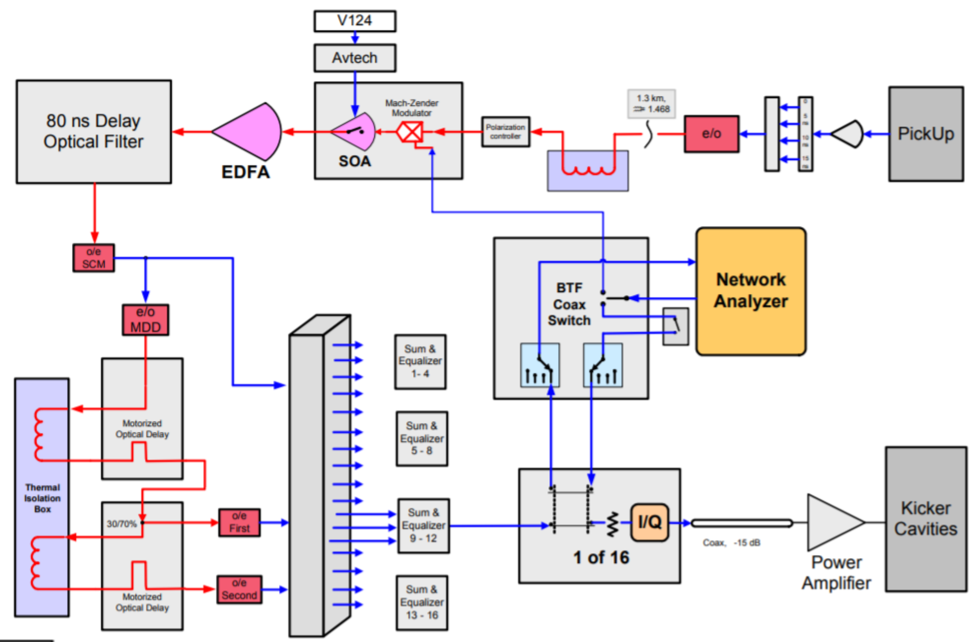


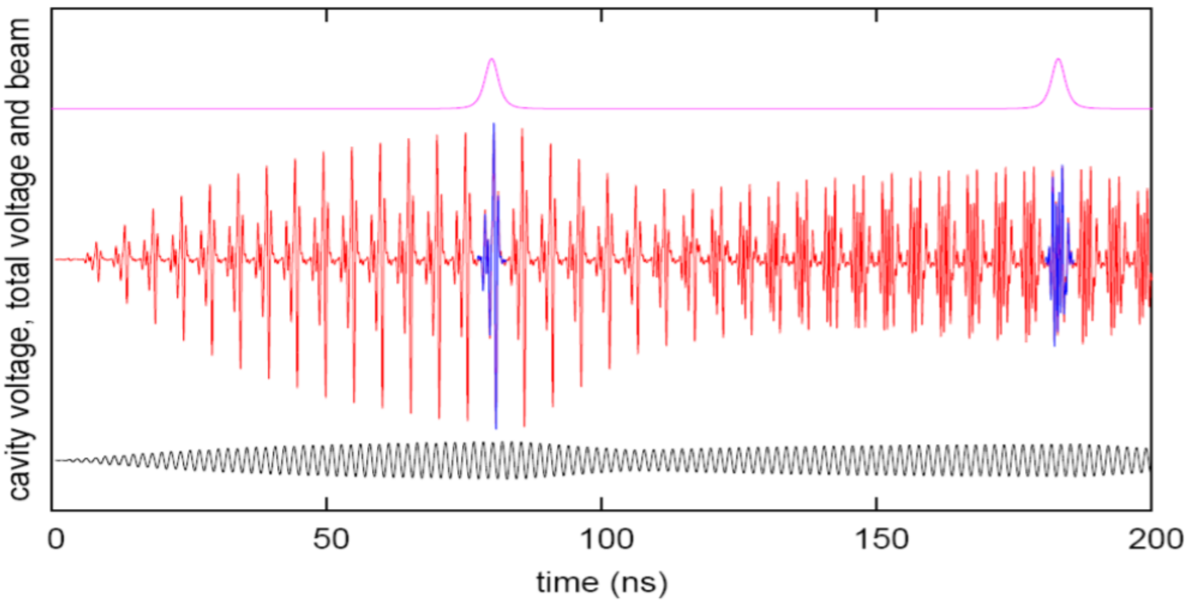


Bunched Beam Stochastic Cooling (Brennan, Blaskiewicz)

- BNL demonstrated the bunched beam stochastic cooling system
- 5-8 GHz (16 bands × 200 MHz)
- Major components of LL circuits:
  - Notch filter (correct offset)
  - traversal filter (delayed copies)
  - I/Q modulators.
- Effective power management

Stochastic Cooling Low Level Block Diagram

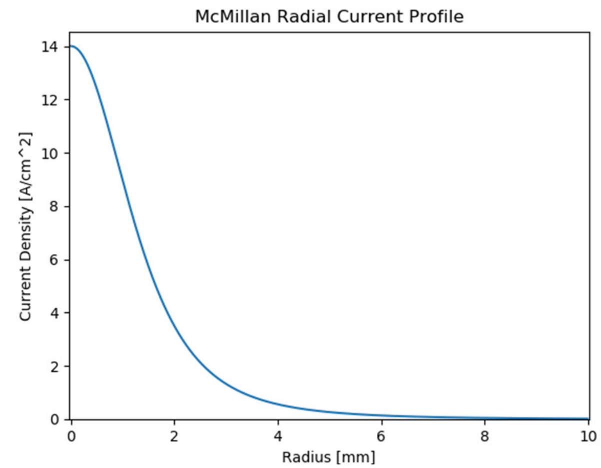


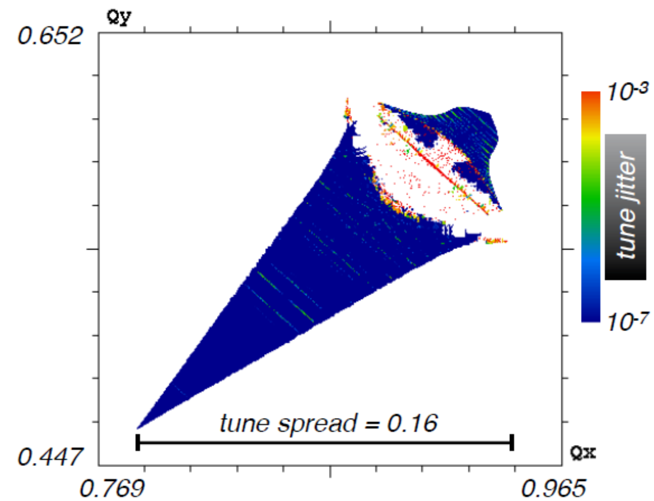


- Almost ready-to-go intra-bunch damper for the LHC
  - 10 times longer delay is manageable with present fiber technology: 5dB/30km
- It easily bits digital system in the bandwidth

Electron Lens for Transverse Beam Stabilization

- In difference to octupoles the electric field of e-lens does not grow at large amplitudes
  - ⇨ i.e. it represents much better means to introduce betatron tune spread into the beam than octupoles
    - For same dynamic aperture limitations, it results in much larger tune spread and, consequently, much larger area in stability diagram [4]
- If required, a creation of a special current distribution can make particle motion integrable [5]
- This study is part of the IOTA program





Left: The radial current function of the McMillan Lens.
Right: The tune spread seen from simulating the McMillan lens.

[4] V.Shiltsev,Y.Alexahin,A.Burov&A.Valishev, "Landau Damping of Beam Instabilities by Electron Lenses", Phys. Rev. Lett. 119, 134802 (2017) https://arxiv.org/ftp/arxiv/papers/1706/1706.08477.pdf

[5] A. Valishev, talk at this conference

Proton Beam in IOTA

- Studies of Non-linear Integrable Optics with protons and electron lens create a wide field of research
- Electron lens can additionally operate as an electron cooler
- Effects to study
  - Beam loss due to overcooling of high intensity proton beam
  - Electron heating observed in Celsius [3]
  - Beam storage with repeated injection
  - Electron cooling in an NIO system
  - …
- The program is under discussion. Experiments will start in 2-4 years
- Your ideas, proposals and collaboration are welcomed

- Additional details can be found in A. Valishev talk at this conference

[3] D. Reistad, Measurements of electron cooling and "electron heating" at Celsius", Workshop on Beam Cooling and Related Topics, Montreux, 1993, pp.183-187 (CERN-1994-003); http://cds.cern.ch/record/398595/files/

Summary

- Beam cooling was one of major constituents resulting in the Tevatron Run II success and the steady luminosity growth for the ion collisions in RHIC

- Beam cooling looks as a promising technology for the electron-ion collider to be built in BNL

- Many techniques developed especially for cooling may be used in other fields of accelerator technology

- Fermilab is working on
  - OSC experimental test on IOTA
  - Proposal for the ring-based electron cooling (DoE grant)

Backup slides

Single Pass Electron cooling (very low energy)

- "Solenoid model" installation, BINP, 1979 - 1989
  - Next step in understanding of magnetized cooling
  - Low energy single pass device
  - Magnetic field non-uniformity has negligible effect on cooling due to small velocities of electrons

- Cooling section length – 2.4 m
- Electron energy – 460 eV
- Magnetic field – 1-4 kGs
- Measured longitudinal cooling length - ~20 m

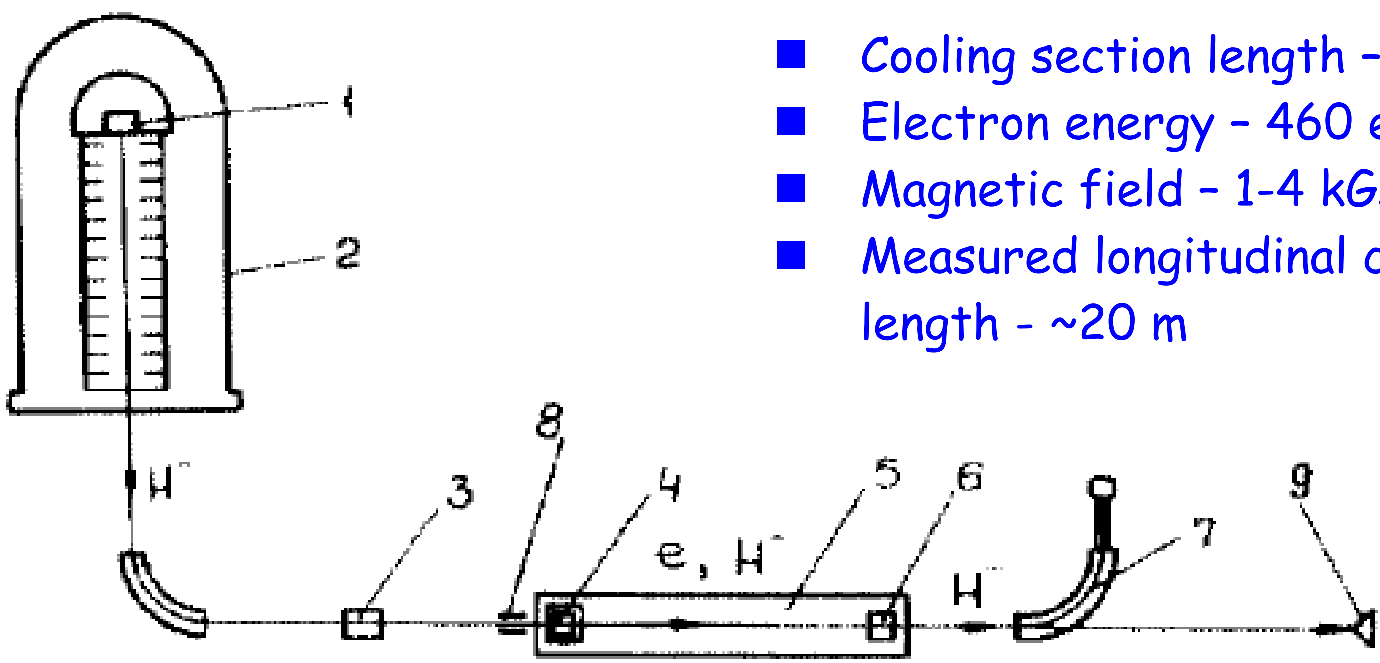


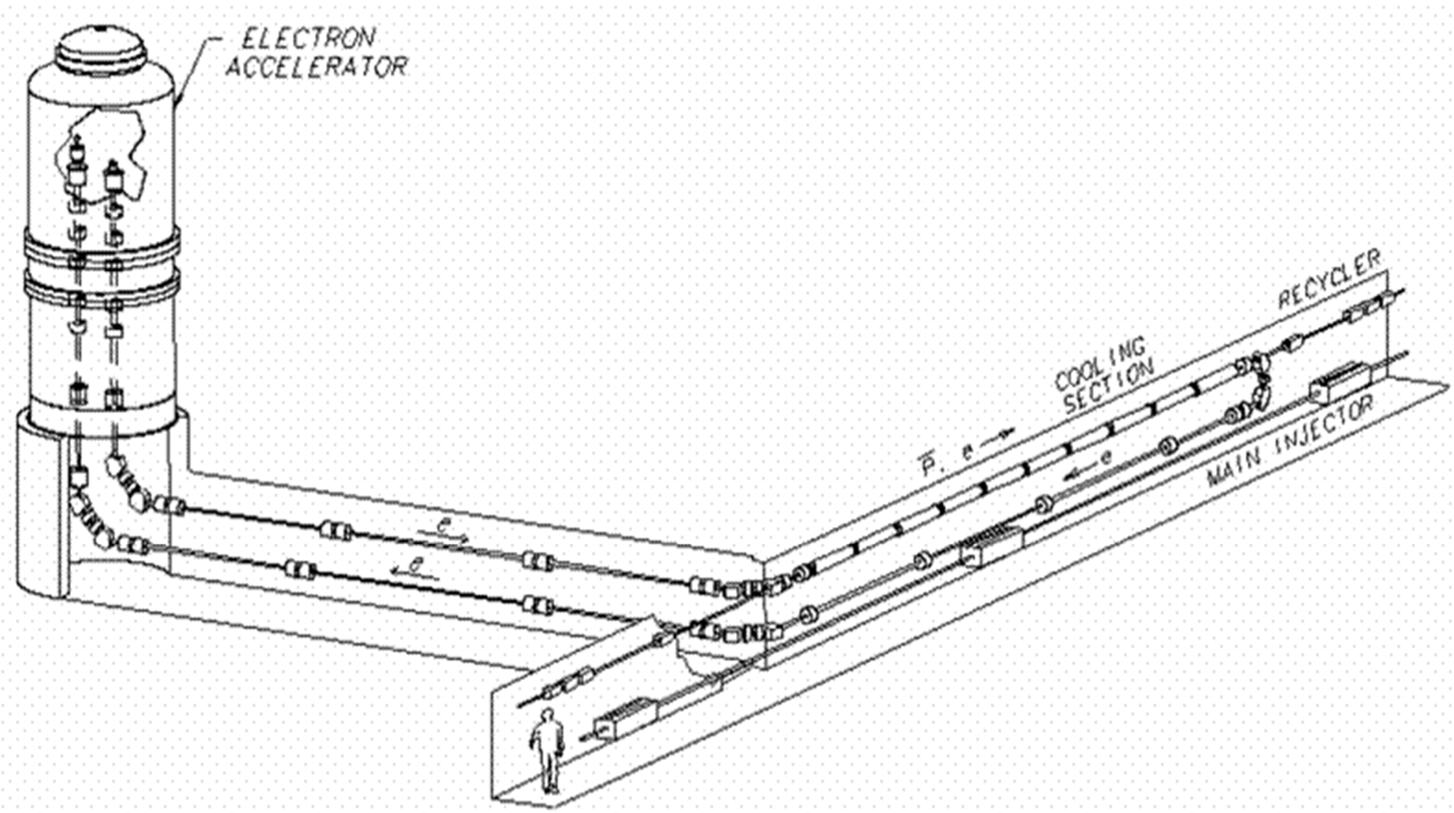
Fig. 1. Layout of the device:
1 — source of H^- ions; *2* — electrostatic accelerator; *3* — magnesium vapor target; *4* — electron gun; *5* — solenoid; *6* — collector of electrons; *7* — spectrometer; *8* — plates of transverse ion spread; *9* — two-coordinate position-sensitive detector.

Electron Cooling at FNAL (Highest energy up to now)

Fermilab made next step in the electron cooling technology

Main Parameters

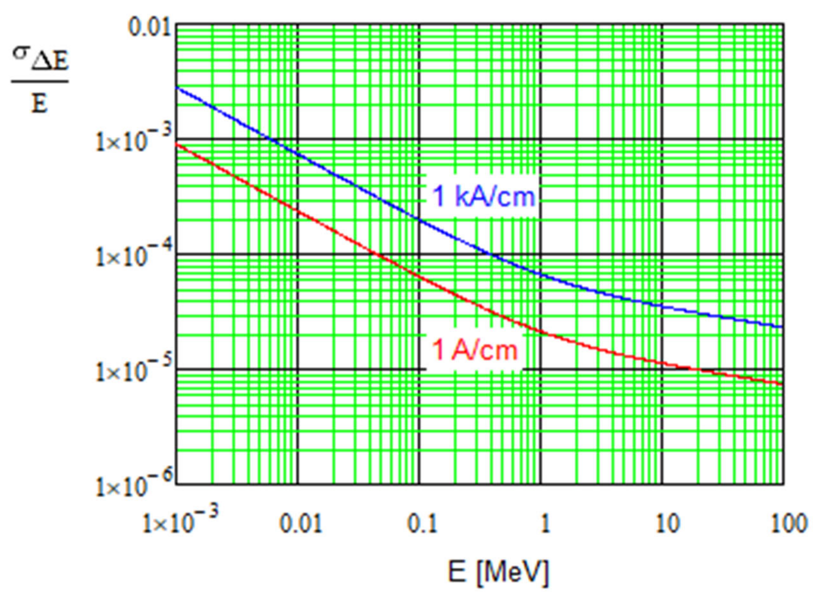
- 4.34 MeV pelletron
- 0.5 A DC electron beam with radius of about 4 mm
- Magnetic field in the cooling section - 100 G
- Interaction length – 20 m (out of 3319 m of Recycler circumference)

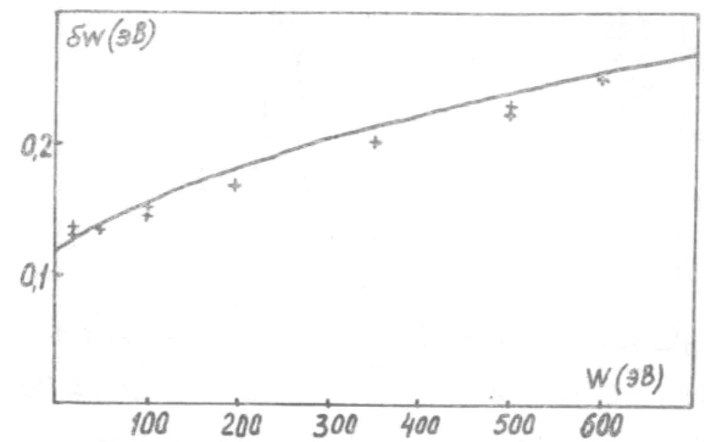


Dependence of Electron Temperature on Beam Energy

- Acceleration in DC gun does not change the energy spread but results in a reduction of $T_{||}$ in the beam frame
- Additionally, fast acceleration in el. gun (even in space charge limited regime) leaves random positions of electrons at the accel. start untouched.

  ⇨ Additional growth after ¼ of plasma per.





Energy spread of electrons after acceleration: I_{beam}=30 μA), B_0=1.3 kG. Solid line is calculated with

$$T_{\parallel} = \frac{T_c^{\,2}}{2W_e} + 1.9 e^2 n_e^{\,1/3}$$

$$\delta W_e = \sqrt{2 W_e T_{\parallel}}$$

Requirements & Limitations for e-p Collider Cooling

- There has not been hadron collider with cooling at collision energy
- However in addition to theory we can base our judgment on experience with Recycler @ Tevatron Run II: 8 GeV, 16 hours storage time
  - Overcooling of antiprotons in Recycler
    - Loss of transverse stability (too small tails)
    - Loss of beam lifetime (too dense core)
    - The loss was mitigated by:
      - reduction of electron cooling for small amplitudes by transverse separation of el. and pbar beams
      - and additional application of stochastic cooling for cooling of transverse tails which was absolutely essential

⇨ Minimum List of requirements

(1) $\perp$ cooling range of at least 6σ is required to mitigate beam-beam

(2) L. cooling range can be smaller: beam-beam does not create L. tails

(3) Cooling time is set by IBS to 0.5 – 2 hour

(4) Energy range: 50 – 300 GeV

Why do we need cooling?

- Accumulation and stacking of rare particles
  - Antiprotons
  - …
- Reduction of beam emittances
  - Colliders
  - Atomic physics
- Cooling at collision energy – luminosity increase