High Energy Hadron Cooling

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Transparencies of the following people were used:

M. Blaskiewicz & J. Brenann, Ilan Ben-Zvi, D. Kairan, S. Nagaitsev, M. Zolotarev

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- Introduction
- Stochastic cooling
- Electron cooling
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Workshop on Future Prospects in QCD at High Energy & a joint Electron-Ion-Collider and Hot-QCD workshop

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Methods to Cool Heavy Particles

- Stochastic cooling
  - Efficient for large emittances
  - But Cooling rate drops with particle number increase: $\lambda \propto 1/N$
- Electron cooling
  - Cooling strength does not depend on the ion beam intensity
  - But efficiency drops for large emittance beam
  - Expensive and challenging device for high energy ions
- Optical stochastic cooling
  - Addresses both problems but
  - Never was tested experimentally
  - Expensive if machine lattice was not built to accommodate cooling
  - Single energy operation if no hardware changes (undulators or laser amplifier, or both)
- All methods work better for multi-charged ions

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

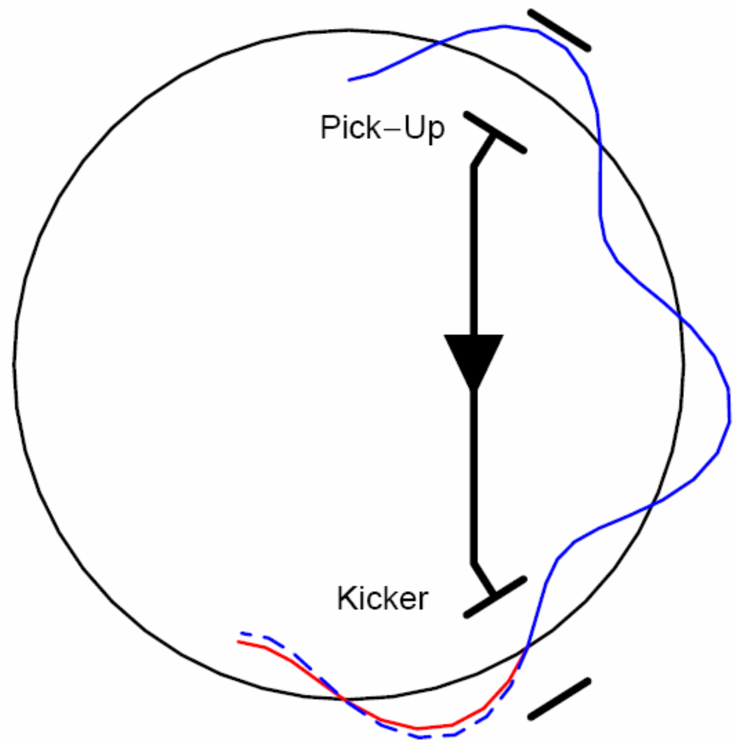
$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

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

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



- 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 (particle number in Debye sphere >>1)

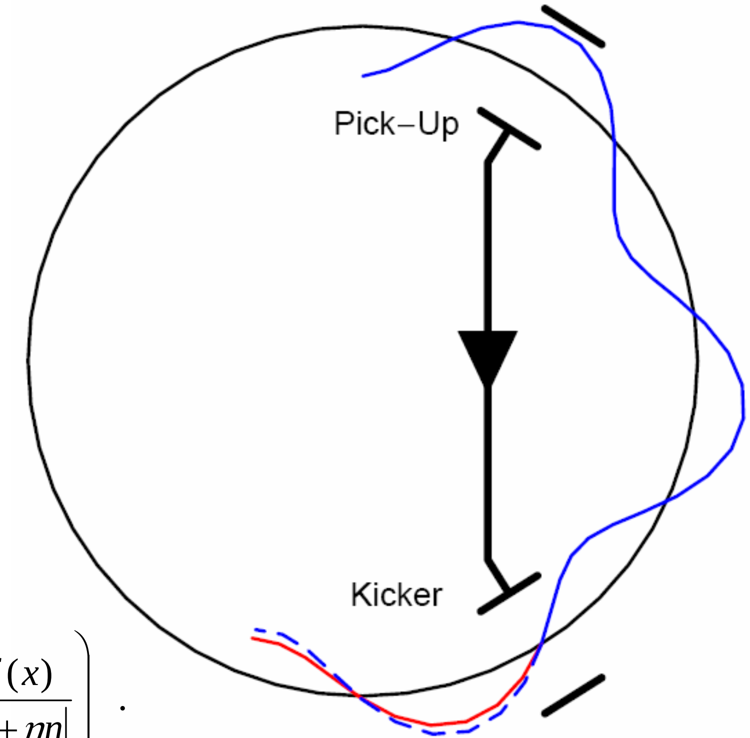
Transverse Stochastic Cooling

- **For transverse plane**

$$\frac{\partial f_\perp}{\partial t} + \lambda_\perp(x)\frac{\partial}{\partial I}\left(I f_\perp\right) = D_\perp(x)\frac{\partial}{\partial I}\left(I\frac{\partial f_\perp}{\partial I}\right)$$

$I \propto a^2$ is the particle action

$$x = \Delta p / p$$



$$\lambda_\perp(x) = \frac{1}{T_0}\sum_{n=-\infty}^{\infty}\mathrm{Re}\left(i\frac{G_{\perp 1}(\omega_n)}{\varepsilon_\perp(\omega_n)}e^{i\omega_n T_2\eta_2 x - 2\pi i\nu_2}\right),$$

$$\omega_n = \omega_0\left(n(1-\eta x) - (\nu + \xi x)\right)$$

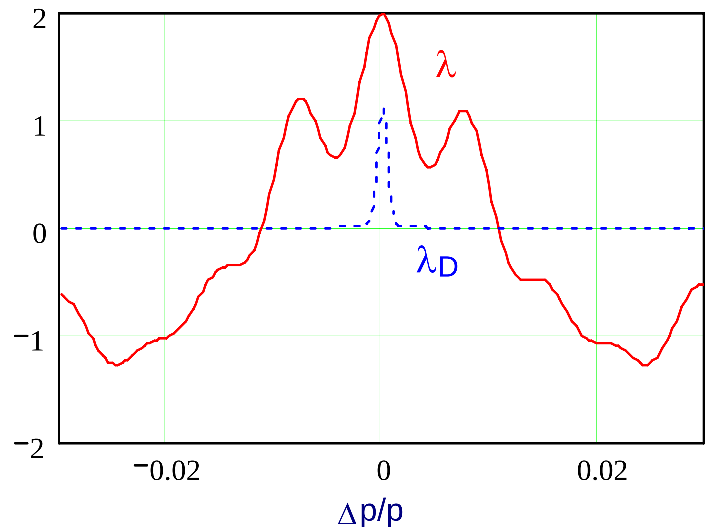
$$D_\perp(x) = \sum_{n=-\infty}^{\infty}\frac{1}{\left|\varepsilon_\perp(\omega_n)\right|^2}\left(\frac{\pi\beta_k}{2T_0^{\,2}}\left(\frac{e\left|Z_{k\perp}(\omega_n)\right|}{mc^2\beta^2\gamma Z_{ampl}}\right)^2 P_{\perp U}(\omega_n) + \left|G_{\perp 1}(\omega_n)\right|^2\frac{\langle I(x)\rangle N}{2T_0}\frac{f(x)}{\left|\xi+\eta n\right|}\right).$$

$$\varepsilon_\perp(\omega) = 1 - \frac{G_\perp(\omega)}{2}\int_{\delta\to 0_+}\frac{\left[e^{-i\omega T_0(1+\eta x)}\sin\left(2\pi(\nu_2+\xi_2 x)\right)+\sin\left(2\pi(\nu_1+\xi_1 x)\right)\right]e^{i\omega T_2\eta_2 x}}{\cos\left(\omega T_0(1+\eta x)\right)-\cos\left(2\pi(\nu+\xi x)\right)+i\delta\sin\left(\omega T_0(1+\eta x)\right)}f_0(x)dx$$

- $\varepsilon_\perp(\omega)$ – describes effect of screening of particle noise by other particles (effect of Schottky noise suppression)

Transverse Stochastic Cooling (continue)

- Cooling force term is not influenced by other particles and is proportional to the electronic gain and z^2
  - ♦ Cooling strength starts to drop with $\Delta p/p$ growth and then reverses to heating when particle signal changes sign
    - Change of relative particle position on the way from pickup to kicker is called bad mixing; zero if $\eta_2 = 0$
- Diffusion term is proportional to the square of gain
- Beam dielectric permeability, $\varepsilon(\omega)$, describes screening of particle signal by other particles
  - ♦ Screening gets stronger with the momentum spread decrease
  - ♦ Relative particle positions need to be changed at each turn – good mixing



Dependence of cooling and heating terms on momentum for transverse cooling in FNAL Debuncher

Longitudinal stochastic cooling

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

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

  - Examples: Cooling in FNAL Debuncher and Recycler

Longitudinal stochastic cooling (continue)

Equations describing longitudinal cooling

$$\frac{\partial \psi}{\partial t}+\frac{\partial}{\partial x}\left(F(x)\psi\right)=\frac{1}{2}\frac{\partial}{\partial x}\left(D(x)\frac{\partial \psi}{\partial x}\right)$$

$\psi(x)$ is the distribution function

$$F(x)\equiv\frac{dx}{dt}=\frac{1}{T_0}\sum_{n=-\infty}^{\infty}\frac{G(x,\omega_n)}{\varepsilon(\omega_n)}\left(1-A(\omega_n)e^{-i\omega_n T_0}\right)e^{i\omega_n T_2\eta_2 x}$$

$$\omega_n=n\omega_0(1-\eta x)$$

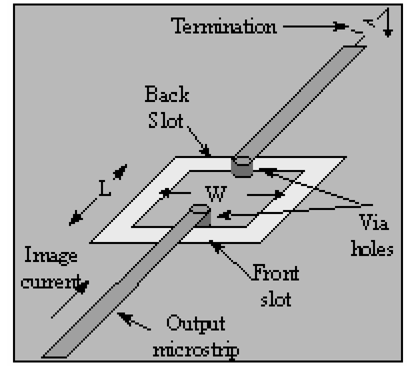
$$D(x)=\sum_{n=-\infty}^{\infty}\frac{1}{\left|\varepsilon(\omega_n)^2\right|}\left[\frac{2\pi e^2 P_{Unoise}(\omega_n)}{T_0{}^2\left(\gamma\beta^2 mc^2\right)^2}\left|\frac{Z_k(\omega_n)}{Z_{ampl}}\right|^2+\right.$$

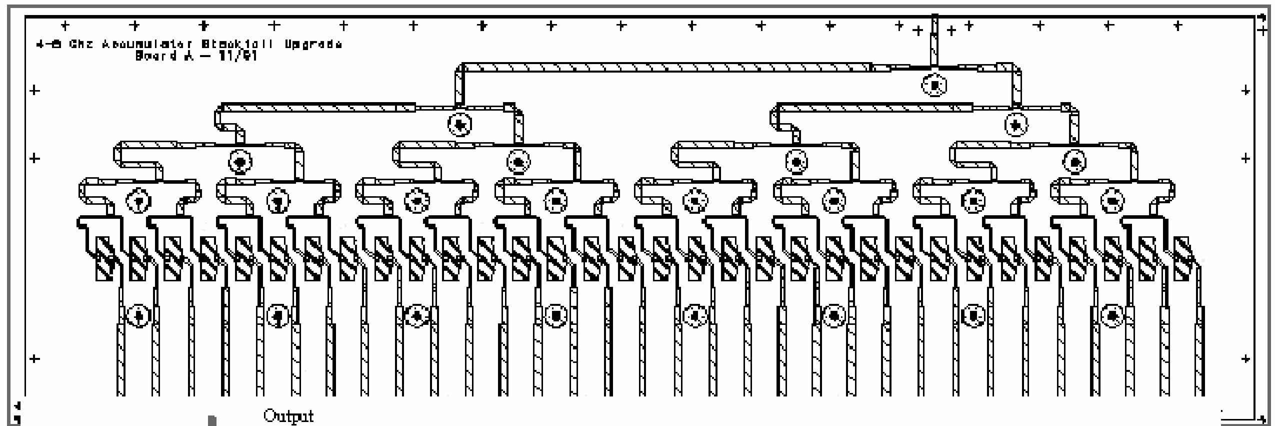
$$\left.\frac{N}{T_0}\left|G(x,\omega_n)\left(1-A(\omega_n)e^{-i\omega_n T_0}\right)\right|^2\sum_{k=-\infty}^{\infty}\frac{1}{|k\eta|}\psi\left(\frac{k-(1-\eta x)n}{\eta k}\right)\right]$$

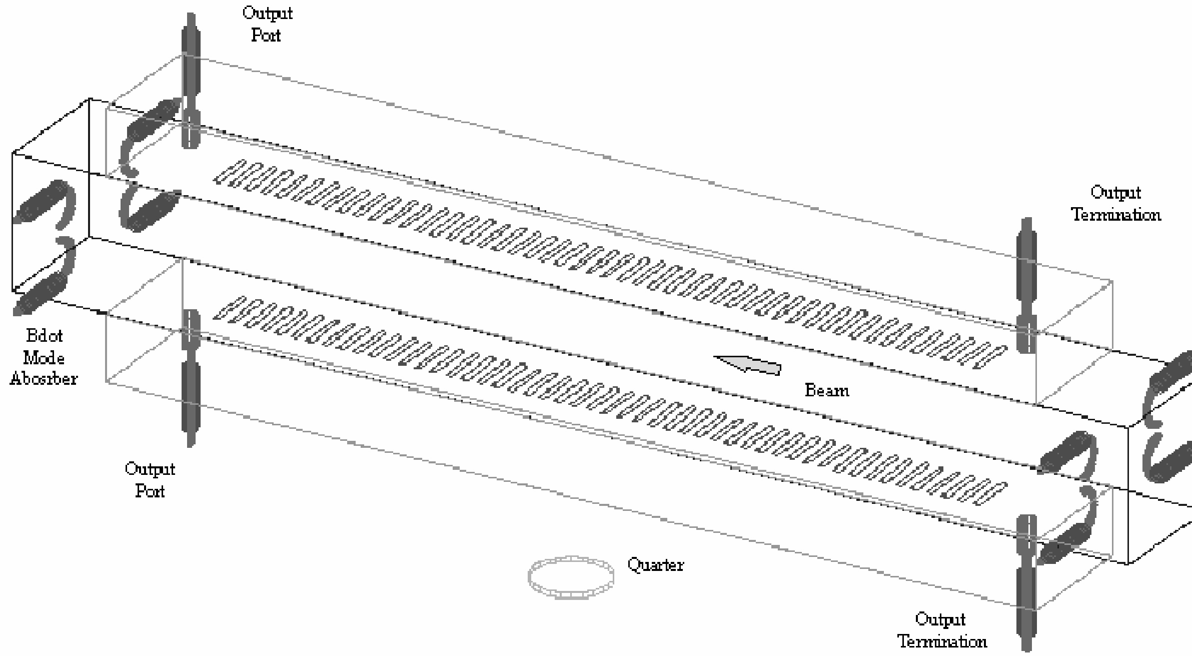
$$\varepsilon(\omega)=1+\left(1-A(\omega)e^{-i\omega T_0}\right)N\int_{\delta\to 0_+}\frac{d\psi(x)}{dx}\frac{G(x,\omega)e^{i\omega T_2\eta_2 x}}{e^{i\omega T_0(1+\eta x)}-(1-\delta)}dx$$

Stochastic Cooling Hardware

- Pickups and kickers are built on the same technology
- Planar loops
  - Printed circuit board technology
  - Works good at small frequencies ($f \le 4$ GHz)
- Slotted waveguides
  - Higher frequency
  - Higher impedance
  - Narrower band ($\Delta f/f \sim 0.1 - 0.2$)
- Pickups and preamplifiers can be cooled to low temperature to reduce thermal noise







Simple cooling estimates

- For optimized cooling when accelerator parameters are matched to parameters of electronics simple estimate can be used
- Continuous beam cooling

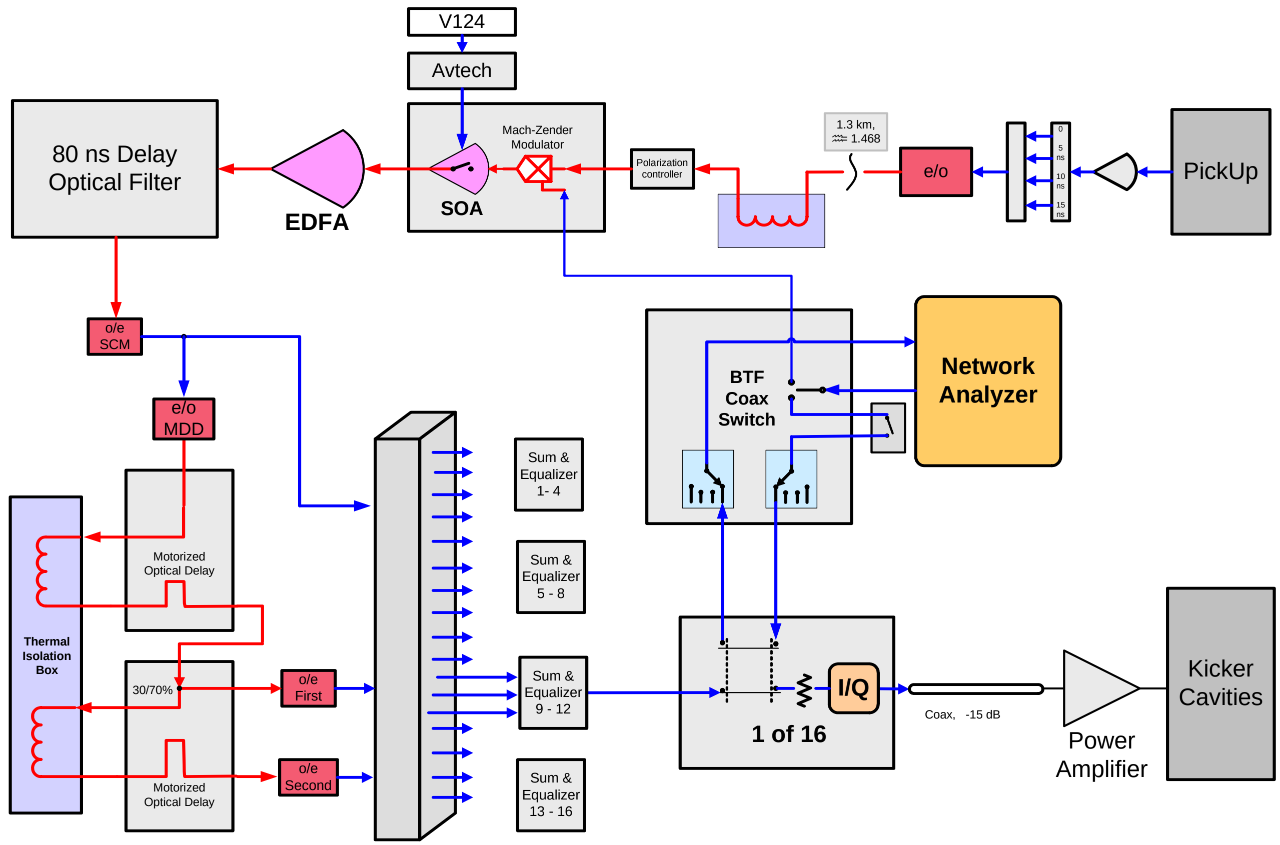
$$\tau \approx \frac{2N}{W}$$

  - FNAL Accumulator: $N = 150 \cdot 10^{10}$, $W \sim 3$ GHz $\Rightarrow$ $\tau \sim 1000$ s
    - close to experimentally achieved value of ~20 min
  - FNAL Debuncher: $N = 1.5 \cdot 10^{8}$, $W \sim 3$ GHz $\Rightarrow$ $\tau \sim 0.1$ s
    - Experimentally achieved: $\tau \sim 0.5$ s – limited by power of TWT

Bunched Beam Stochastic Cooling in RHIC*

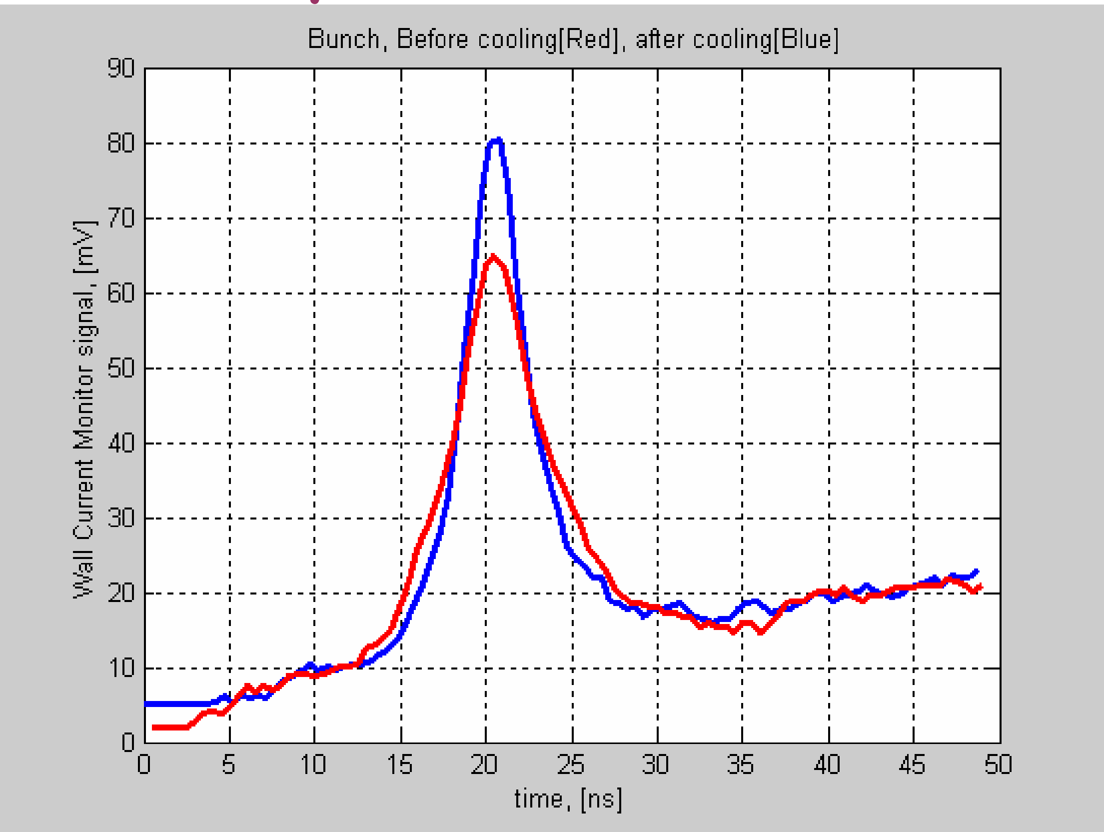
- Planar loop pickups, 5-8 GHz (built for Tevatron)
- 16 narrow band kickers
- Fiber optic based notch filter
- Transversal filter to filter out undesired lobes of pickup signal

Stochastic Cooling Low Level Block Diagram



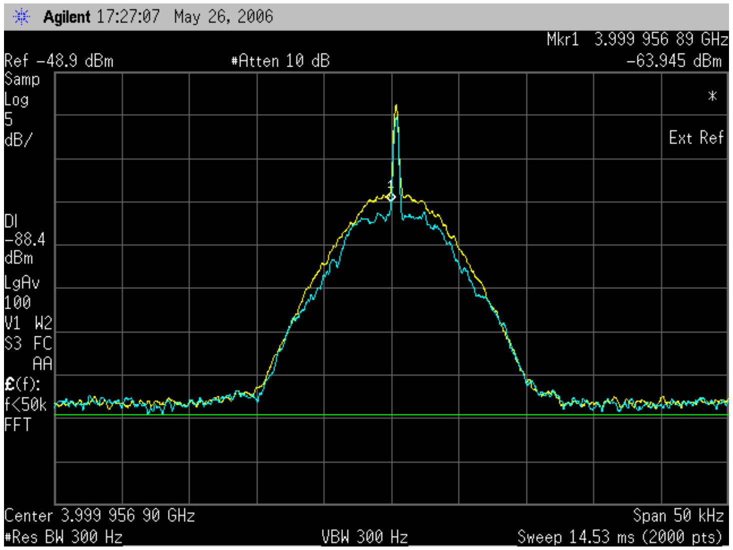
* Courtesy of M. Blaskiewich & J. Brennan

Preliminary Results of Stochastic Cooling in RHIC

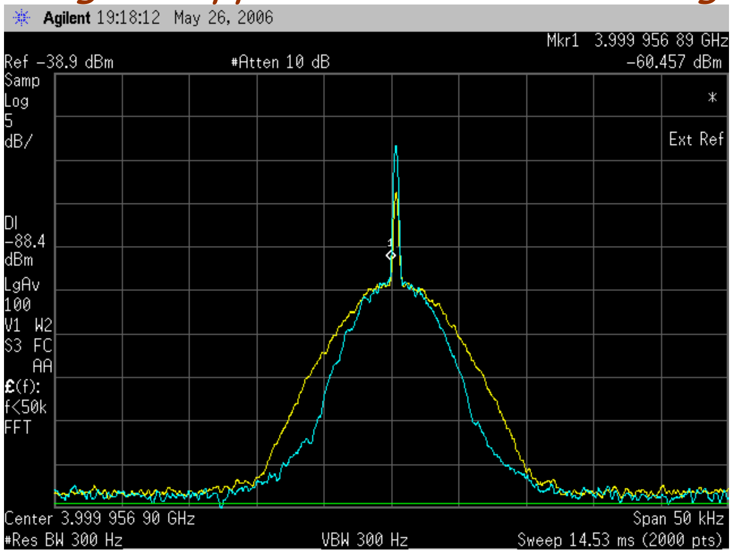


Wall Current Monitor signal of cooled bunch. The higher bunch (Blue) has been cooled for about 90 minutes. The lower trace (Red) is the bunch before cooling started.

- Cooling time ~7 hour
- Achieved cooling rate is barely sufficient to counteract IBS

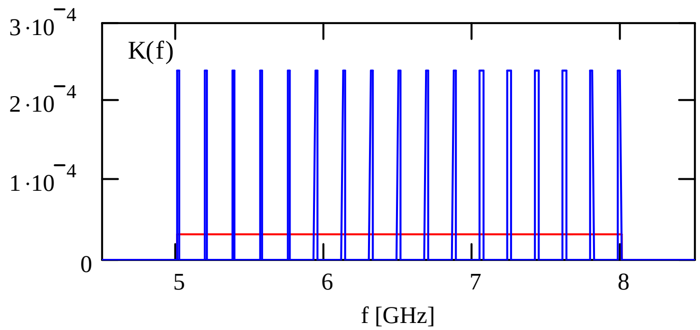


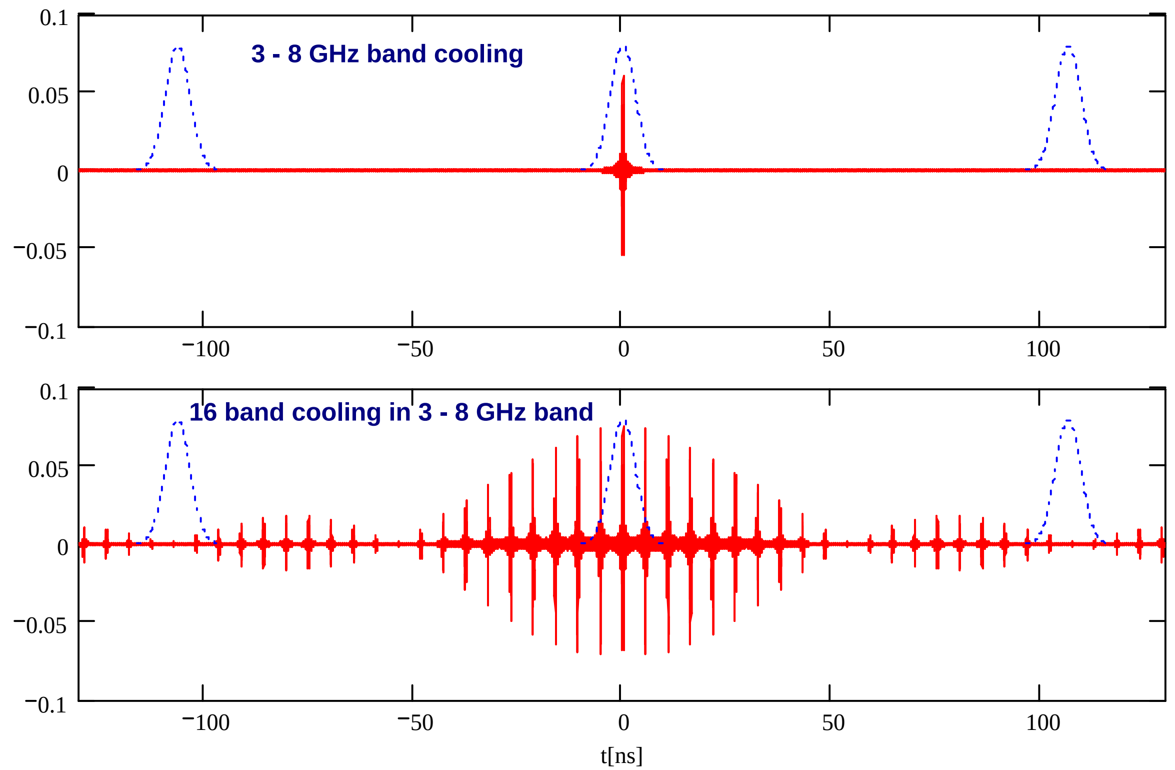
Signal suppression at 0 min cooling



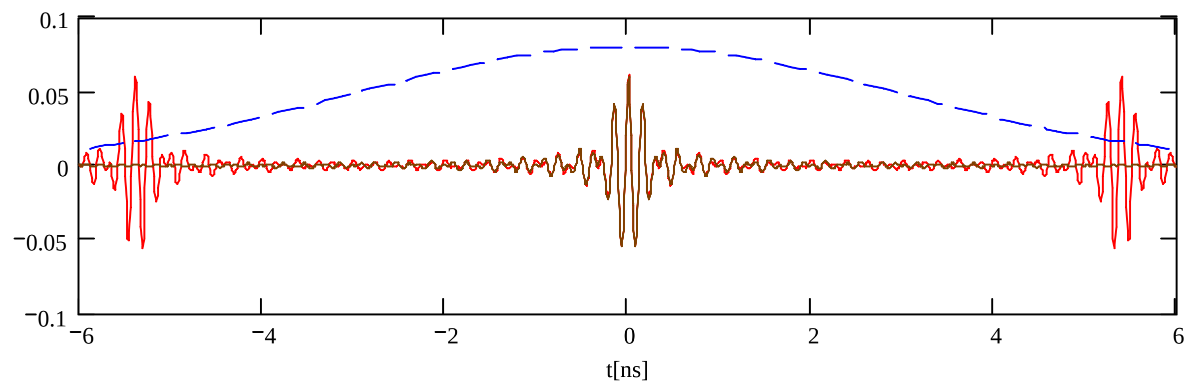
After 110 min cooling; measurements are done with cooling off
Yellow line reference signal (0 min)

Difference between cooling of bunched and continuous beams





- Effective cooling implies that signal of a particle should minimally excite motion of other particles, i.e. be localized at small distance
- But for the bunched beam there is no particles outside the bunch and response outside the bunch is not counted



- Estimate of effective bandwidth of RHIC bunched cooling

$$\tau \approx \frac{2N_b}{W}\frac{C}{L_b}$$

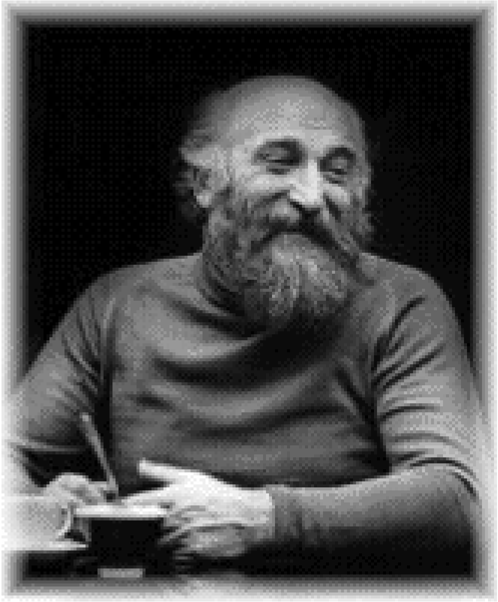
  - RHIC cooling: $N = 1.5\cdot10^9$, $\tau \sim 5$ hour, $C/L_b \sim 2000 \Rightarrow W \sim 0.4$ GHz
- Why effective band is an order of magnitude smaller than actual band?
  - Small number of sub-bands
    - 16 => 32 would decrease diffusion by factor of 2 with corresponding factor of 2 gain in cooling time
  - Insufficient "good mixing" due to small momentum compaction
    - Mixing can be improved by increase of revolution freq. spread. That requires an increase of RF voltage or momentum compaction with corresponding growth of $\Delta p/p$
    - Wider frequency band would be another way to improve performance???
- These deficiencies are expected to be gone for cooling of real ion beam (Mike Blaskiewicz)
  - Accurate comparison to theory would be helpful

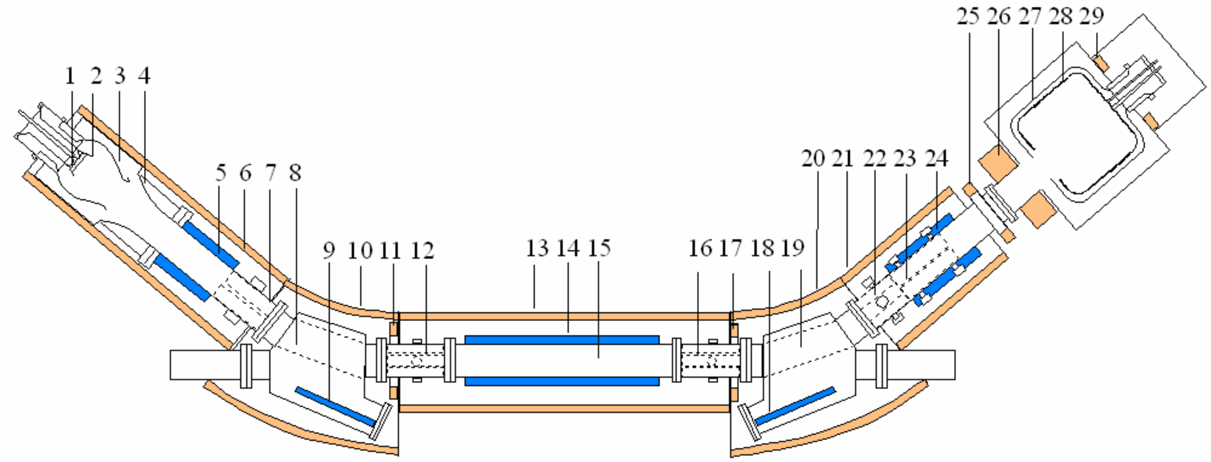
Transverse Stochastic Cooling in RHIC – Is it possible?

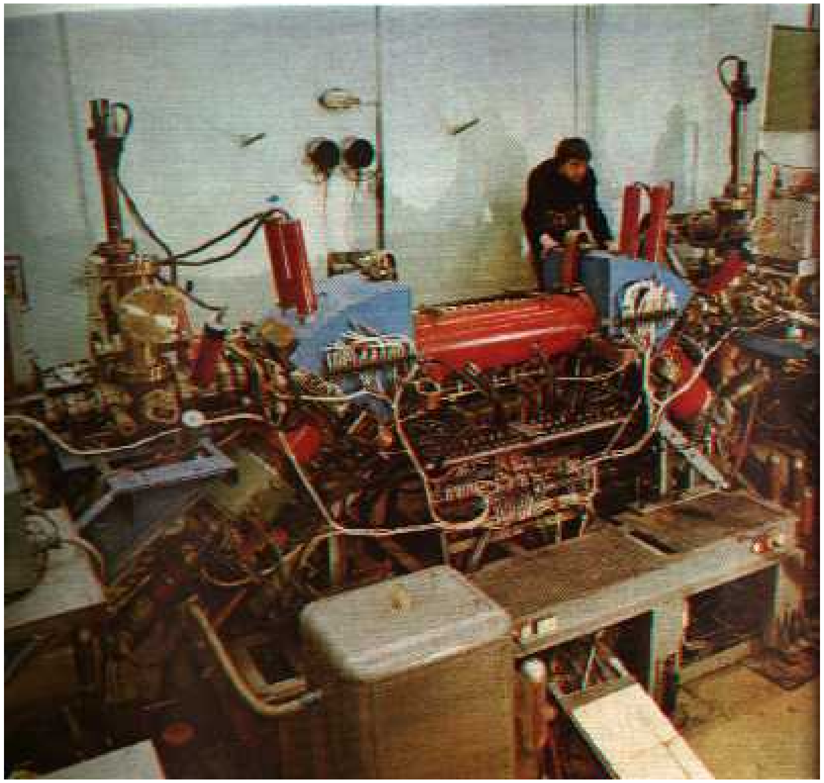
- Cooling rates for transverse cooling should be close to the longitudinal one
  - We lose factor of $\frac{A}{\sigma}$ ~100 in pickup sensitivity due to small beam size
  - We gain it back due to high ion charge (present measurements are done with protons)
- Beam offsets relative to the pickup electrical center excite large signal at the revolution frequency harmonics (so called common mode signal)
  - Additional "slow" feedback system is required to stabilize the beam position in the pickup
    - BPM accuracy ~1 μm is required (already achieved at FNAL)
    - notch filter will suppress the rest (~60 Db)
- Cooling time of 1-3 hour is feasible for all 3 planes for Z~100 !!!

Electron cooling

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







- Many installations since then, up to 300 kV electron beam (GSI, Darmstadt)
  - The same scheme

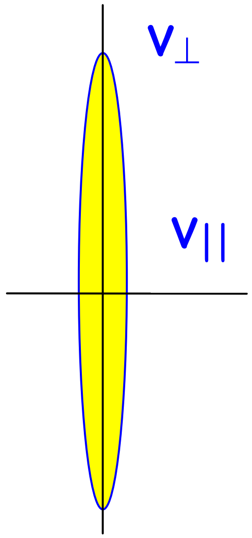
Physics of electron cooling

- Friction force

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

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

- Flattened distribution due to particle acceleration



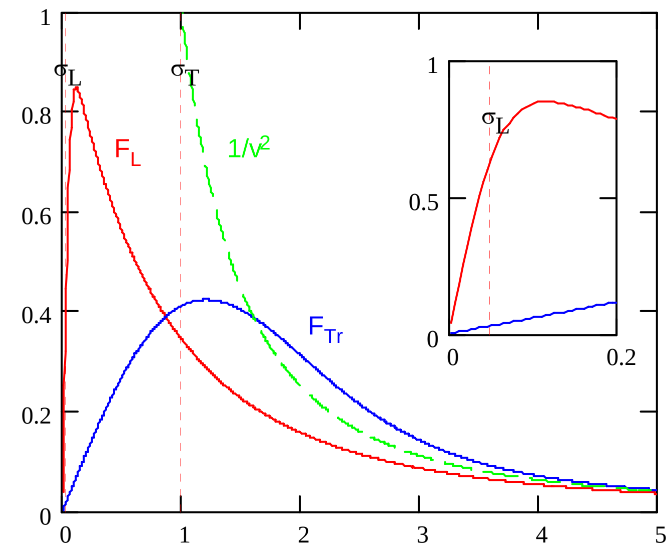
- Maximum cooling force (very small electron temperature, $T \le e^2 n_e^{1/3}$)

$$F \approx Z e^2 n_e^{2/3}$$

is achieved at ion velocities of

$$\mathrm{v}_i \approx 5 Z e^2 n_e^{1/3}$$

- Required $T_{||}$ (~10 μeV for n_e=10^9 cm^{-3}) is usually achieved after acceleration but this small $T_\perp$ was never achieved experimentally

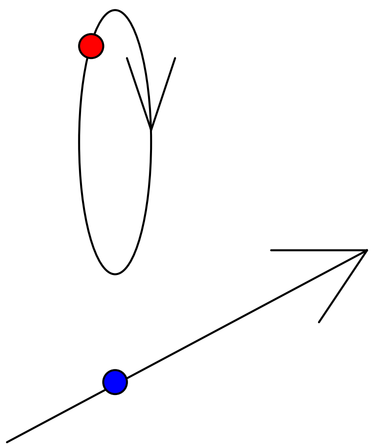


Dependence of longitudinal and transverse friction forces on velocity for non-magnetized electron cooling, σ_L/σ_{Tr} = 0.05

Magnetized electron cooling

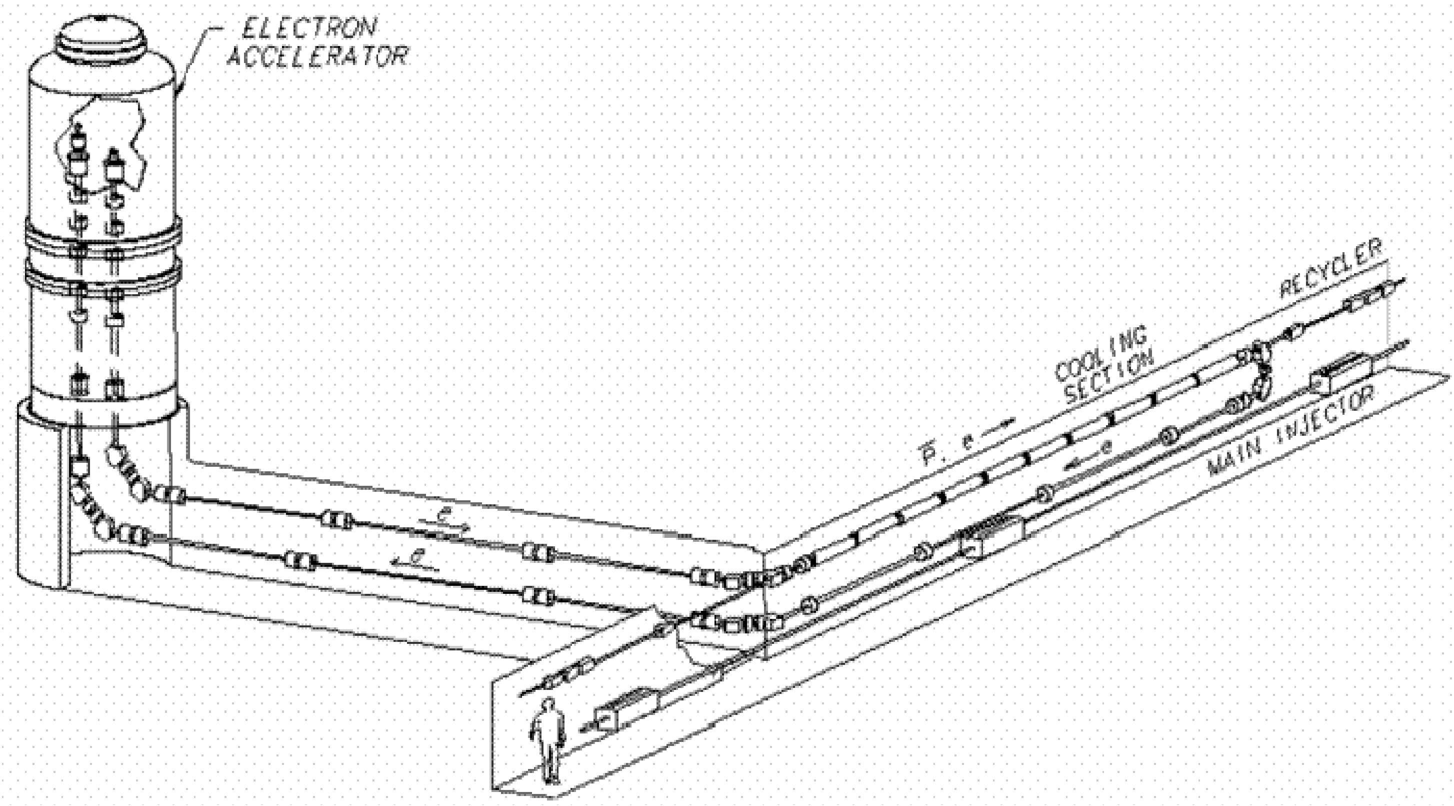
Effect of magnetic field

- For $r_L < (r_{max} = v/\omega_p)$ the transverse temperature is magnetized out
  - That results in an increase of force for small velocities, $v_i < v_{Tr}$
- Magnetization is very helpful for small energy coolers, but does not change much for high energy coolers because of much larger relative ion velocities
  - High energy magnetization also requires very high accuracy of magnetic field, $\Delta B_{\perp}/B < 10^{-5}$



Electron Cooling at FNAL

- Fermilab made next step in 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)



Electron Cooling at FNAL (2)

What makes Fermilab electron cooler unique?

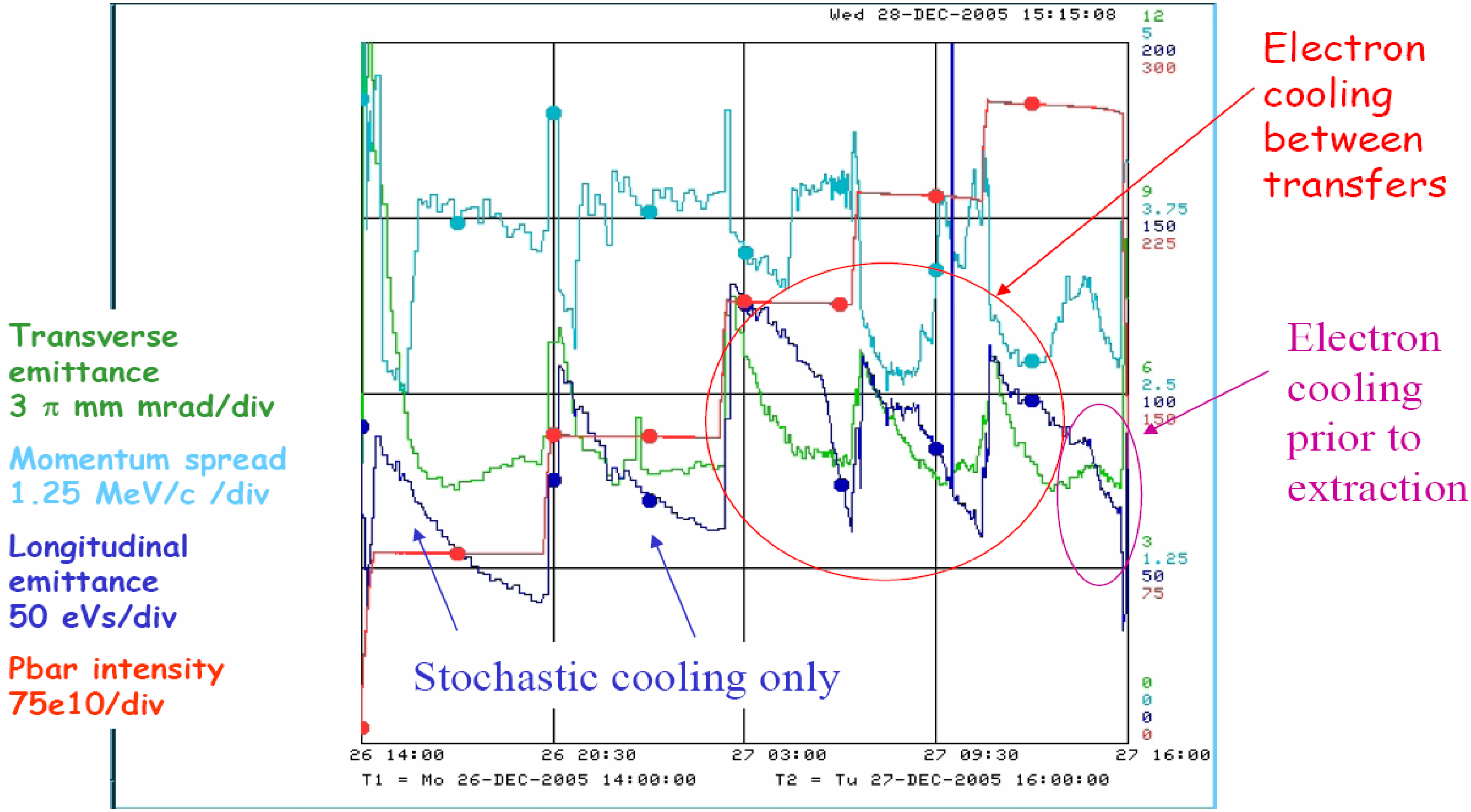
- No strong longitudinal magnetic field accompanying electron beam all the way from gun to collector
  - Angular-momentum-dominated beam transport line
  - Phase advance Q~6
  - Fully coupled motion
  - Length of beam transport~70 m
- Cooling with low-magnetic field – something that had never been tested, B=100 G
- 15 times higher energy than any cooler before (GSI ~0.3 MV)
- Accurate optics measurements
- Simultaneous operation of electron and stochastic cooling

Pelletron

Cooling section

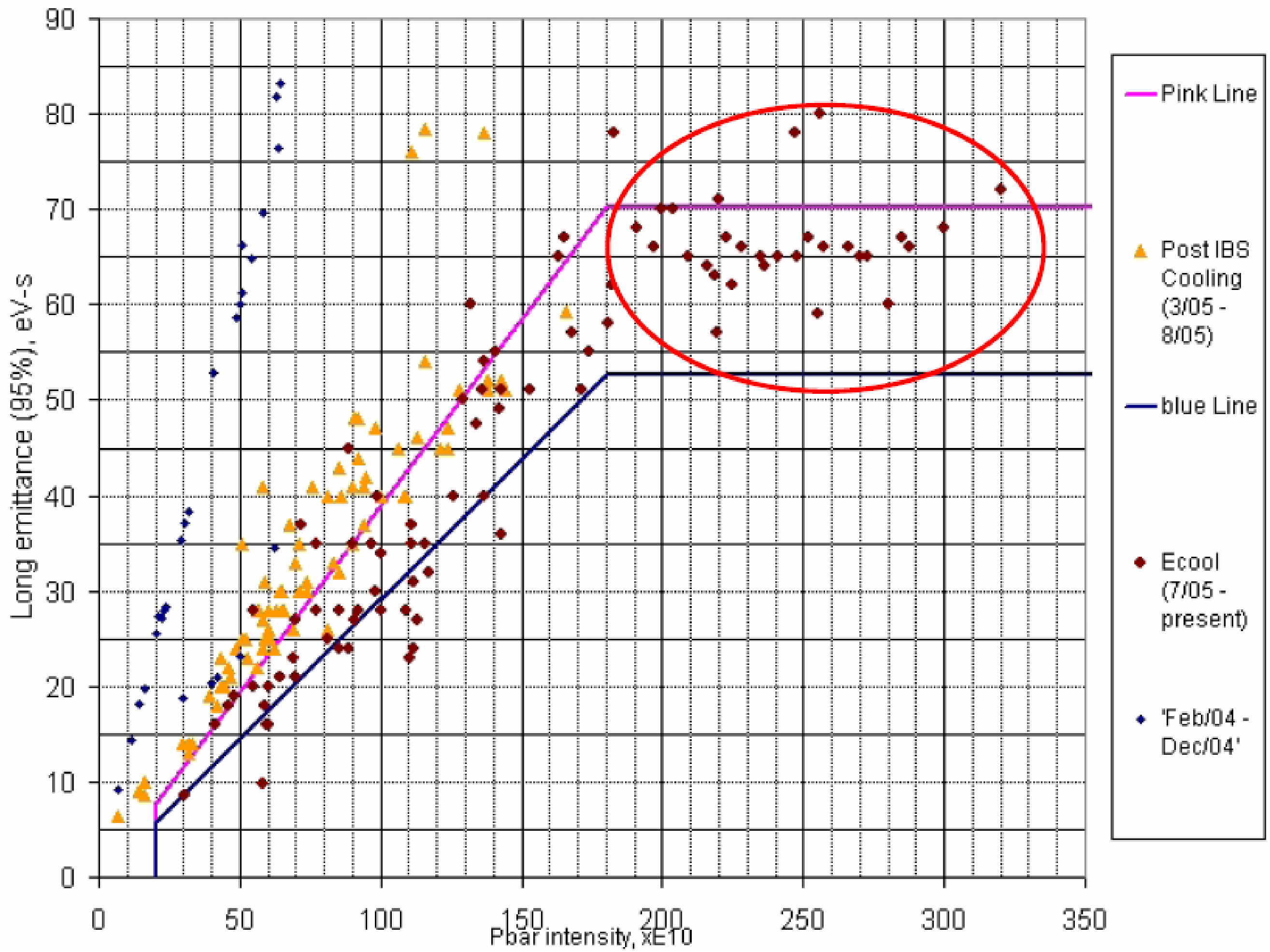
Storing Antiprotons in Recycler

- Stacking rate in Accumulator drops with stack size
  - Transfers to Recycler after ~$50 \cdot 10^{10}$ allows to stay close to maximum stacking rate



Storing Antiprotons in Recycler (2)

- Both stochastic and electron coolings operate
- Electron cooling is more effective for longitudinal degree of freedom
- One long bunch (~1 km of 3 km) to prevent storing of the ions
- Extraction: 9 transfers of 4 bunches each

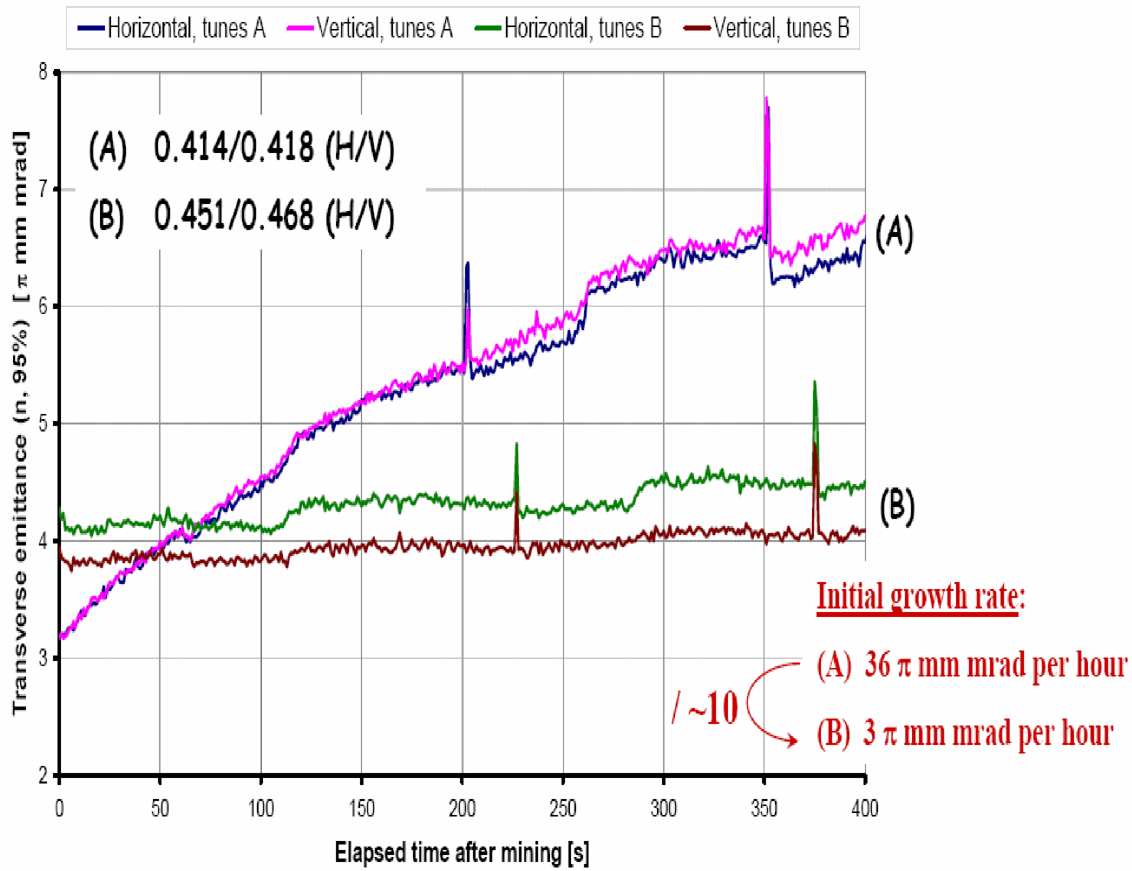


Recycler longitudinal emittance with electron cooling

Storing Antiprotons in Recycler (3)

Recycler instabilities

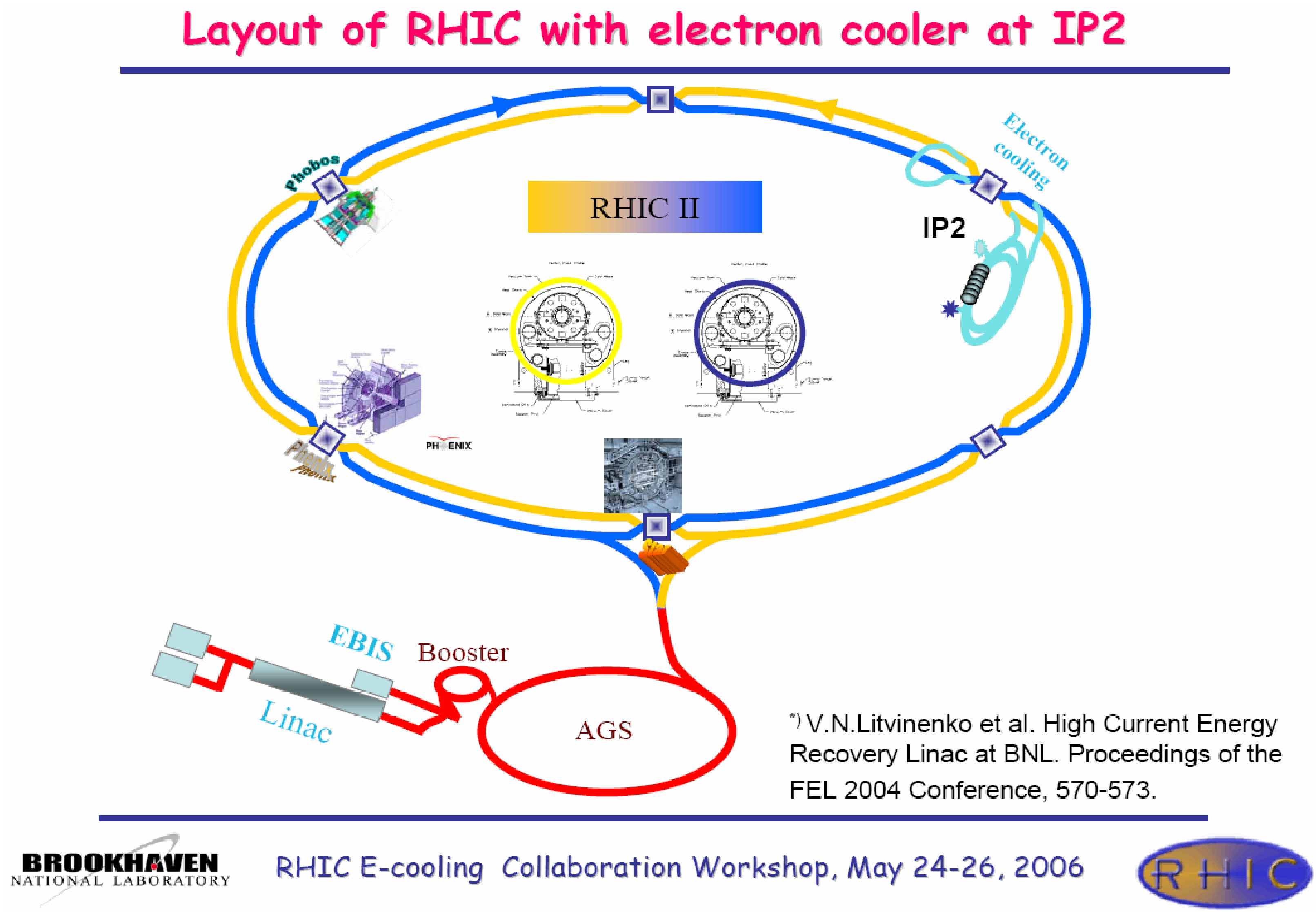
- Instabilities limit 6D phase density of the beam
- Resistive wall is stabilized by transverse dampers (~20 MHz)
    - Dampers Upgrade during shutdown (~90 MHz)
- Emittance growth due to mining
    - Likely due to quadrupole instability (see Alexei Burov at HB-2006)
    - Coupling decrease suppressed emittance growth and the lifetime degradation
- Phase density of cooled **Pbars** is approximately the same as for **Ps**



Effect of tune change on the emittance growth at mining

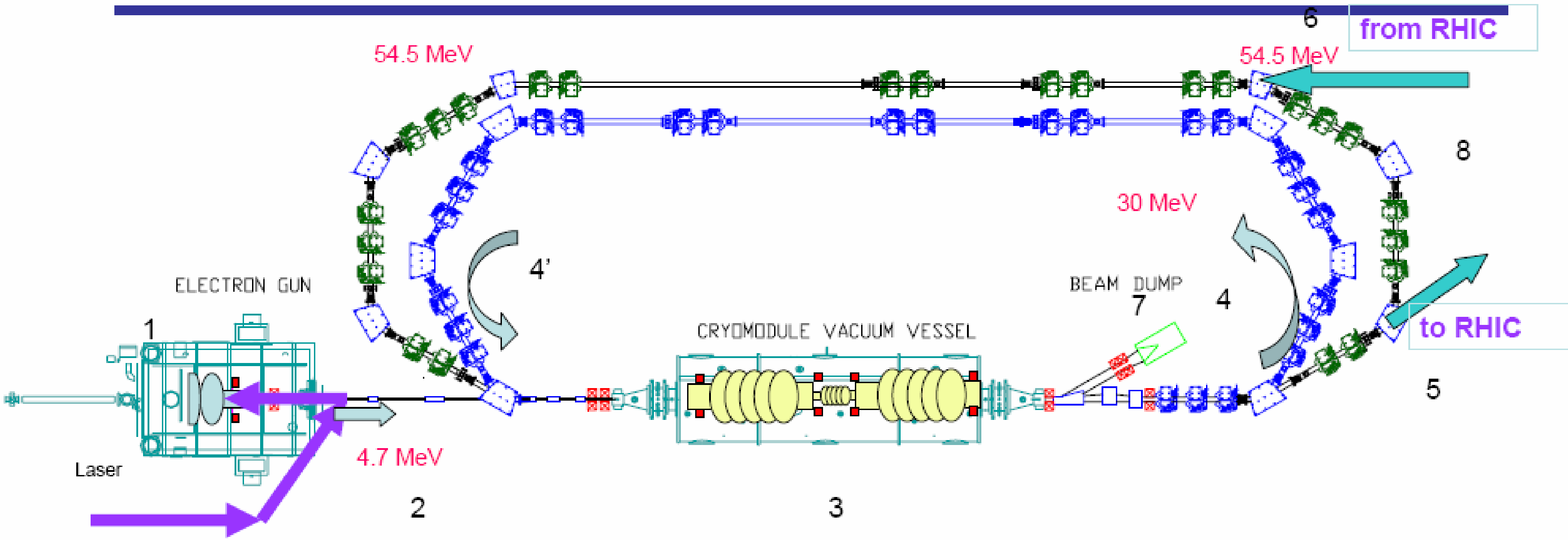
Proposal for RHIC Electron Cooler

- Another order of magnitude in the electron energy
  4 MeV => 50 MeV
- Strong bunching ($\Sigma L_b / C \ll 1$) helps to reduce average electron beam current



Proposal for RHIC Electron Cooler (2)

E-cooler: 2 passes ERL layout



1. SRF Gun,
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3rd harmonic cavity

4, 4'. 180° achromatic turns

5, 6. Transport lines to and from RHIC,

7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

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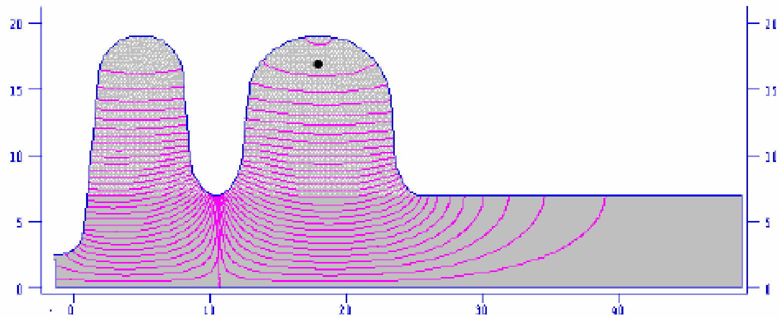
RHIC

Proposal for RHIC Electron Cooler (3)

SRF Gun

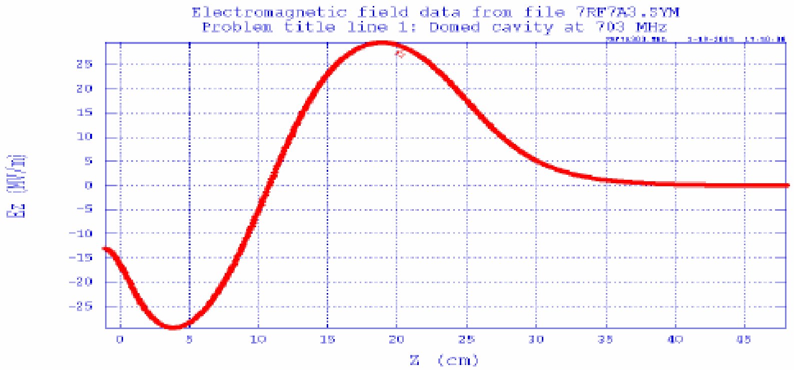
R (cm)



Frequancy: 703.75 MHz

Maximum field on axis: 29.5 MV/m

Maximum field on surface: 49.3(MV/m)



Electric field profile: results of SUPERISH simulation

Z (cm)

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Results of numerical simulation

The parameters of the electron beams for different initial distribution at the exit of the test-bed system at required kinetic energy 54.3 MeV

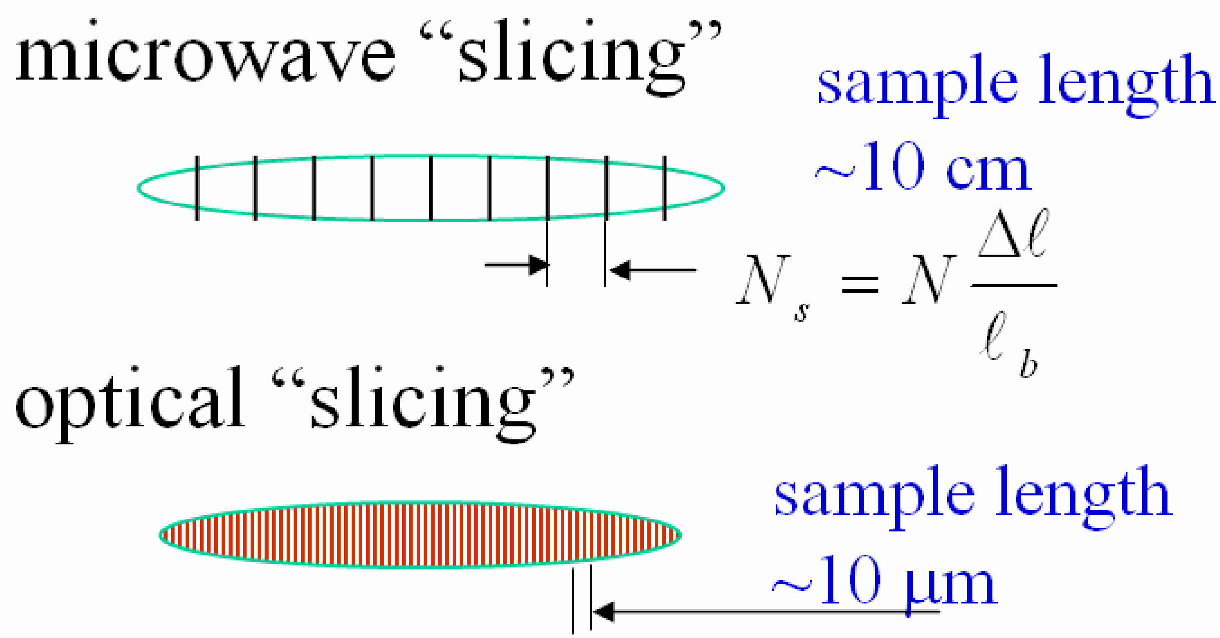
	Required for cooling	**Parmela simulation results** *)		
				Beer-can (T_{eff}=0.4eV)
Charge per bunch, nC	5			5
Energy, MeV	54.3			54.3
Threshold average current, mA	>50			1500
Transverse emittances, $\varepsilon_x/\varepsilon_y$ mm*mrad	<4			3.2/2.7
RMS Energy spread, $\delta E/E$	3×10^{-4}			3.8×10^{-4}
RMS Bunch length, cm	>1			0.78

✓The results of the beam dynamics studies according of start-to-end PARMELA simulation are very promising and provide the needed parameters for RHIC e-cooling project.

Optical stochastic cooling

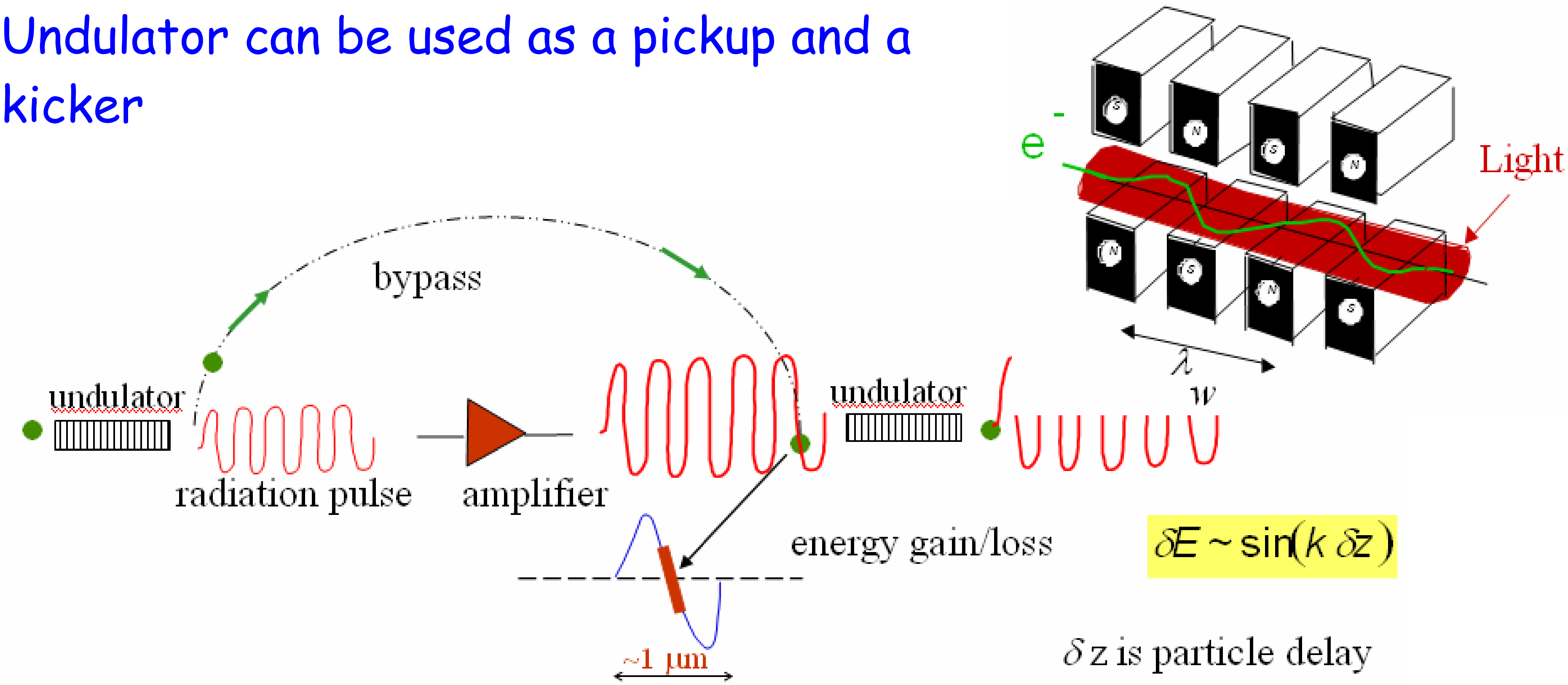
- OSC obeys the same principles as the microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~ 10^{14} Hz
- Pickup and kicker must work in the optical range and support the same bandwidth as the amplifier

Amplifier	λ [nm]	$\Delta f/f$
Ti-Sapphaire	800	0.2
Dye	300-900	0.2
Parametric	350-1500	0.2



Optical stochastic cooling (continue)

- Undulator can be used as a pickup and a kicker



- A pick-up and a kicker should be installed in a position with a nonzero dispersion function for a simultaneous cooling of energy and transverse coordinates (similar to the Palmer's method of the momentum cooling).

Optical stochastic cooling (continue)

- Pickup to kicker transfer matrix

$$\begin{bmatrix} x \\ \theta \\ s \\ \Delta p/p \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & 0 & D_{16} \\ M_{21} & M_{22} & 0 & D_{26} \\ D_{51} & D_{52} & 1 & M_{56} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ \theta \\ s \\ \Delta p/p \end{bmatrix}$$

  - Symplecticity binds up D_{1x} to D_{2x}
  - Non-zero dispersion => dependence of path length on angle and coordinate
- Coupling can be used to share dumping between horizontal and vertical coordinates

Optical stochastic cooling (continue)

- Optical parametric amplifiers with wide bandwidth operating in the infrared region (10-20 μm) open up possibility of cooling heavy ions at RHIC.

  λ = 10 μm, γ=100

  $$\Rightarrow \quad \lambda_{undulator} \approx 2\gamma^2\lambda \sim 20 \text{ cm}$$

- For one hour cooling time at RHIC this requires 16 W of amplifier power
- Reasonable requirements for stabilization of beam position (1<mm) and magnet currents (<10^{-4})
- Optical manipulation of beams is an emerging technology which will keep progressing along with the laser and accelerator technology

Conclusions

Stochastic cooling

- Inexpensive, may be implemented fast for all 3 planes (1-2 years)
- Can address near term RHIC problems

Electron cooling

- Very ambitious project
- Long way to implement
  - It took almost 10 years to develop much simpler FNAL cooling
- Very effective for heavy ions, much more difficult for protons

In comparable conditions: $$\frac{\lambda_{cool}}{\lambda_{IBS}} \propto Z$$

Optical stochastic cooling

- In theory it has the best achievable decrements
  - not tested experimentally
- Requires an expensive lattice modification and significant downtime
- Does not work in wide range of γ parameter (energy)

No "silver" bullet; Electron cooling looks OK but challenging