Can Coherent Electron Cooling (CeC) cool muon beams in collider?

Vladimir N Litvinenko

Department of Physics and Astronomy, SBU

Collider-Accelerator Department, BNL

Center for Accelerator Science and Education

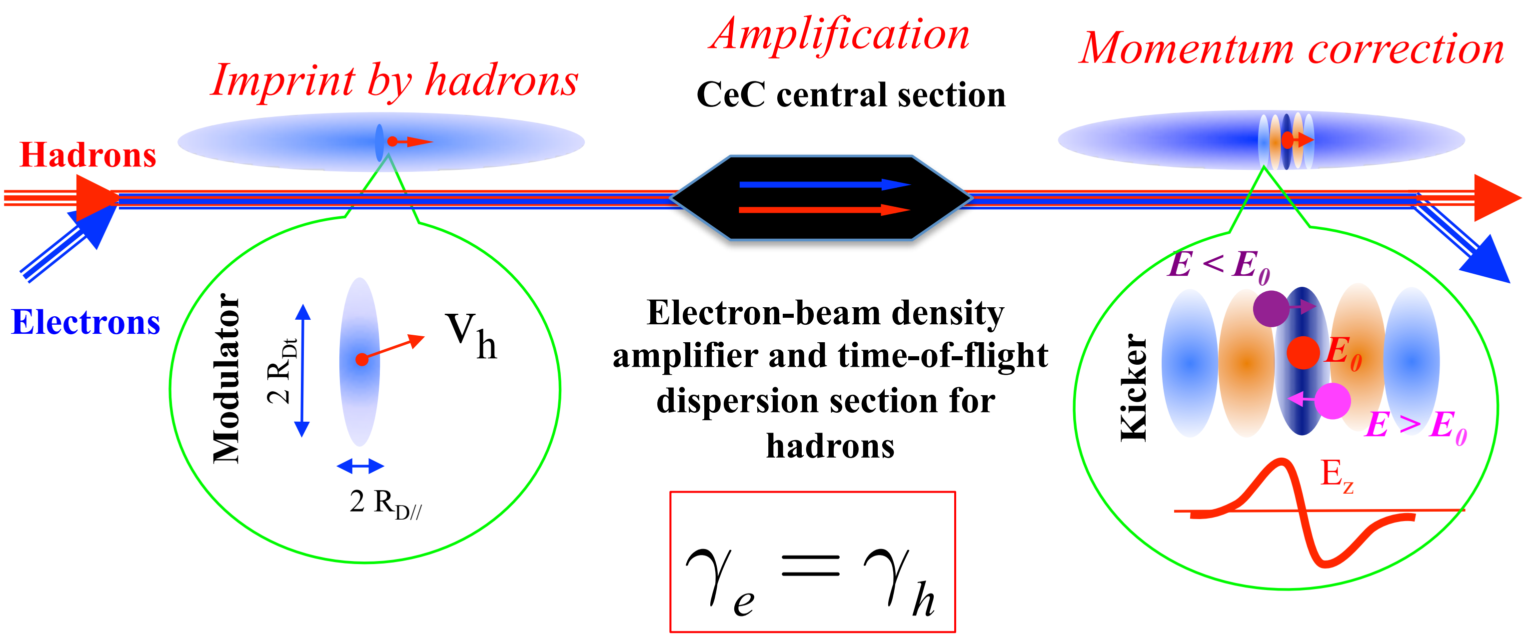
CASE Center for Accelerator Science and Education

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

What is Coherent electron Cooling

- Short answer – stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz
- Longer answer on next pages



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Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

[1]*Brookhaven National Laboratory, Upton, Long Island, New York, USA*

[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA*

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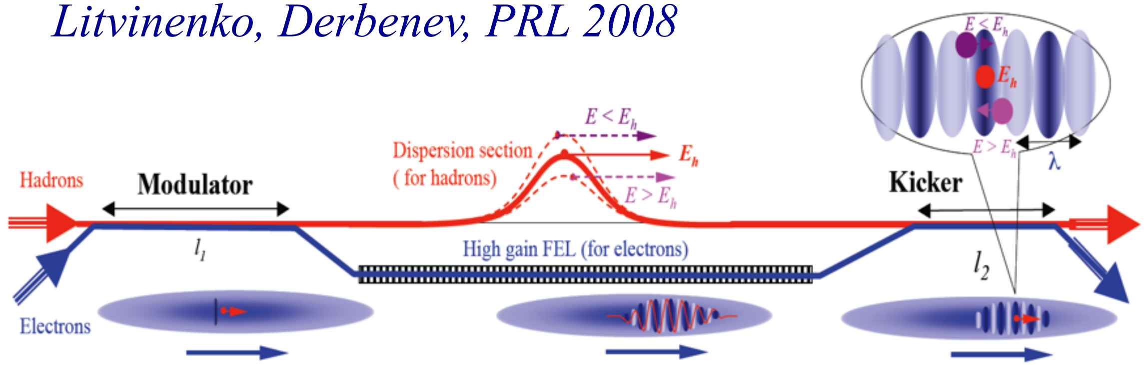
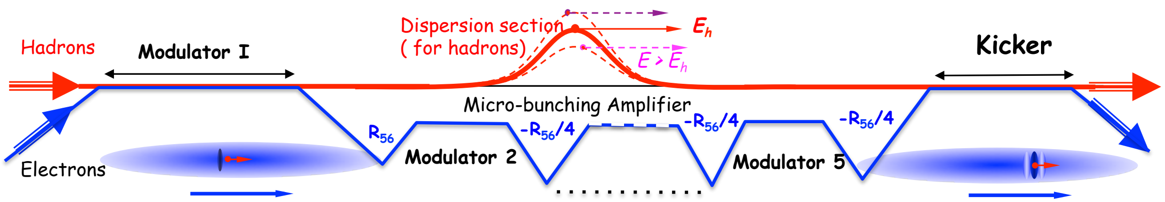
CeC schemes

Litvinenko, Derbenev, PRL 2008



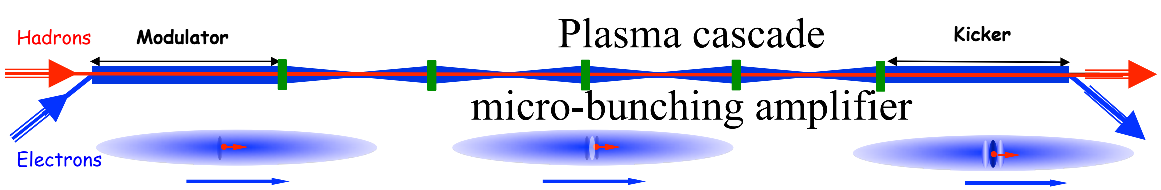
High gain FEL amplifier

Ratner, PRL 2013



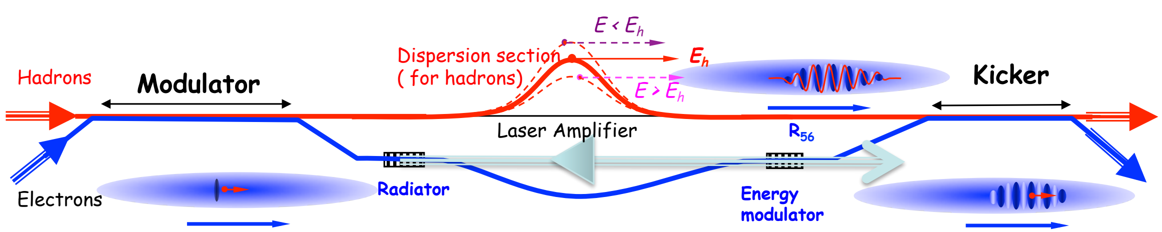
Multi- Chicane Microbunching amplifier

Litvinenko, Wang, Kayran, Jing, Ma, 2017



Plasma-Cascade Microbunching amplifier

Litvinenko, Cool 13

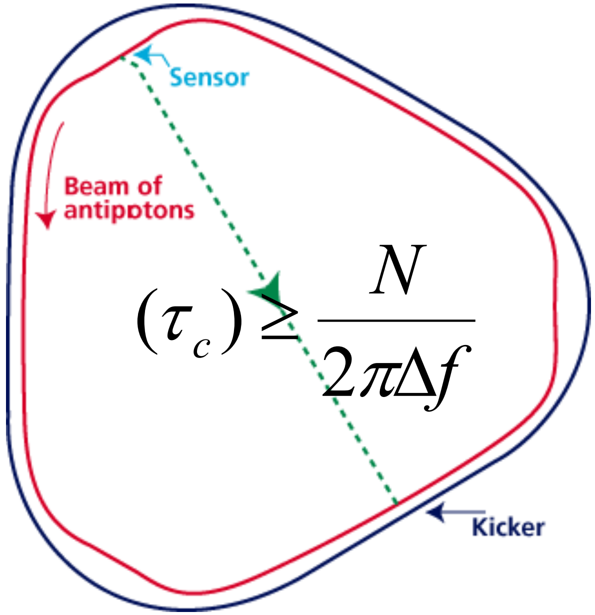


Hybrid laser-beam amplifier

Critical conditions for the stochastic cooler

S. van der Meer 1984 Nobel physics prize

RF stochastic cooling is reaching its limits at ~ 10 GHz bandwidth



$$(\tau_c) \geq \frac{N}{2\pi\Delta f}$$

$$\langle x \rangle = \frac{1}{N_s}\sum_i x_i = \frac{1}{N_s} x_k + \frac{1}{N_s}\sum_{i \neq k} x_i$$

$$\tau_c = -\left(f_{rev} \frac{1}{\varepsilon}\frac{d\varepsilon}{dn} \right)^{-1} = \frac{N_s}{f_{rev}} \propto \frac{I_{peak}}{Ze} \cdot \frac{1}{\Delta f}$$

$$N_s = \frac{\dot{N}}{\Delta f} = \frac{I_{peak}}{Ze} \cdot \frac{1}{\Delta f}$$

- ✓ **Linearity:** Amplifier must be linear (no saturation) and low noise
- ✓ **Overlapping:** Amplified signal induced by individual particle in the modulator (pick-up, sensor) must overlap with the particle in the kicker
- ✓ **Bandwidth:** Does not matter how high is the gain of the amplifier, cooling decrement per turn can not exceed $1/N_s$, where N_s is number of the particles fitting inside the response time of the system: $\tau \sim 1/\Delta f$
- ✓ **Noise:** noise in the stochastic cooling system should not significantly exceed system signal introduced by shot noise in the hadron beam

S. van der Meer, Rev. Mod.Phys. 57, (1985) p.689
S. van der Meer, 1972, Stochastic cooling of betatron oscillations is ISR, CERN/ISR-PO/72-31

Main questions

- What the cooling rate (speed) has to be in a muon collider?
- Is CeC bandwidth sufficient to cool muons?
- What should be CeC gain and peak electron beam current to cool muons?

$$\frac{1}{\tau_{o\mu}} \cdot \frac{C_{ring}}{\gamma c} < \xi_{CeC} \le \min\left\{ \left(G \frac{r_\mu}{\varepsilon_\perp \sigma_\gamma} \right) \cdot ff, \frac{1}{N_s} = 2\Delta f \frac{\sqrt{2\pi}\sigma_{t\mu}}{N_\mu} \right\}; ff = \min\left(1, \frac{\sigma_{te}}{\sigma_{t\mu}}\right);$$

$$T = \frac{C_{ring}}{\gamma c} \sim const; \ \Delta f < f$$

$$\Delta f > \frac{1}{\sqrt{2\pi}} \frac{N_\mu}{\tau_{o\mu} \cdot \sigma_{t\mu}} \cdot T; \qquad G > \frac{1}{\tau_{o\mu}} \cdot \frac{T}{f} \cdot \frac{\varepsilon_\perp \sigma_\gamma}{r_\mu}; \ G_{\max} < \sqrt{\frac{\Delta f}{f} \frac{N_e}{f\sqrt{2\pi}\sigma_{te}}} < \sqrt{\frac{N_e}{f\sqrt{2\pi}\sigma_{te}}}$$

What the cooling rate (speed) is needed?

Parameter		Higgs	Top	Top Lumi	TeV1	TeV2	TeV3
c.m. Energy	TeV	0.126	0.35	0.35	1.5	3	6
Beam energy	MeV	63000	175000	175000	750000	1500000	3000000
γ		596	1,656	1,656	7,098	14,197	28,393
Curcumference	m	300.0	700.0	700.0	2500.0	4500.0	6000.0
T	sec	1.00E-06	2.33E-06	2.33E-06	8.34E-06	1.50E-05	2.00E-05
Lifetime	sec	1.31E-03	3.64E-03	3.64E-03	1.56E-02	3.12E-02	6.24E-02
Turns		1309	1558	1558	1870	2078	3117
Lumi decay	turns	655	779	779	935	1039	1558
Minimum rate		1.53E-03	1.28E-03	1.28E-03	1.07E-03	9.63E-04	6.42E-04

Is CeC bandwidth sufficient to cool muons?

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Minimum rate		1.53E-03	1.28E-03	1.28E-03	1.07E-03	9.63E-04	6.42E-04
Nμ per bunch		4.00E+12	4.00E+12	3.00E+12	2.00E+12	2.00E+12	2.00E+12
Norm emittance	mm mrad	200	200	50	25	25	25
Emittance	m rad	3.35E-07	1.21E-07	3.02E-08	3.52E-09	1.76E-09	8.80E-10
Bunch length	RMS, cm	6.3	0.9	0.5	1	0.5	0.5
	sec	2.101E-10	3.002E-11	1.668E-11	3.336E-11	1.668E-11	1.668E-11
Energy spread	RMS,	4.00E-05	1.00E-04	1.00E-03	1.00E-03	1.00E-03	1.00E-03
Nμ /sec	1/sec	7.59E+21	5.32E+22	7.18E+22	2.39E+22	4.78E+22	4.78E+22
Δf, min	**Hz**	**1.16E+19**	**6.82E+19**	**9.21E+19**	**2.56E+19**	**4.60E+19**	**3.07E+19**
Scale	m	2.58E-11	4.39E-12	3.26E-12	1.17E-11	6.51E-12	9.77E-12
	Å	0.26	0.04	0.03	0.12	0.07	0.10
Optimistic							
CeC bandwidth	Hz	5.7E+15	4.4E+16	4.4E+16	8.1E+17	3.2E+18	1.3E+19
Shortage		**2040**	**1554**	**2098**	**32**	**14**	**2**

No, too many muons per second…..

What should be CeC gain and peak electron beam current to cool muons?

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Nμ per bunch		4.00E+12	4.00E+12	3.00E+12	2.00E+12	2.00E+12	2.00E+12
Norm emittance	mm mrad	200	200	50	25	25	25
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Δf, min	**Hz**	**1.16E+19**	**6.82E+19**	**9.21E+19**	**2.56E+19**	**4.60E+19**	**3.07E+19**
Scale	m	2.58E-11	4.39E-12	3.26E-12	1.17E-11	6.51E-12	9.77E-12
	Å	0.26	0.04	0.03	0.12	0.07	0.10
$\sigma\gamma$		2.39E-02	1.66E-01	1.66E+00	7.10E+00	1.42E+01	2.84E+01
Gain, min		4.48E+05	9.42E+05	2.35E+06	9.81E+05	8.83E+05	5.89E+05
Ne/sec	est	2.33E+30	6.05E+31	5.10E+32	2.46E+31	3.59E+31	1.06E+31
Ipeak	A	3.74E+11	9.69E+12	8.18E+13	3.94E+12	5.75E+12	1.70E+12

Not even close – too many muons, emittance is too large and required cooling rate is too high!

Conclusions

- Cooling few 10^{12} muons in about a thousand turns required stochastic cooler with bandwidth of soft γ-rays, e.g. 10^{19} Hz – it is unrealistic
- Similarly, required CeC amplitude gain ~ 10^6 (~10^{12} in power) and corresponding peak current of electron beam (to avoid saturation) are astronomic 10^{12} to 10^{13} A scale!– no chance to reach a world to get there

$$rate = \frac{\Delta \mathbf{E}}{\sigma_{\mathbf{E}}} \propto \frac{2 r_\mu G}{\sigma_\gamma \varepsilon}$$

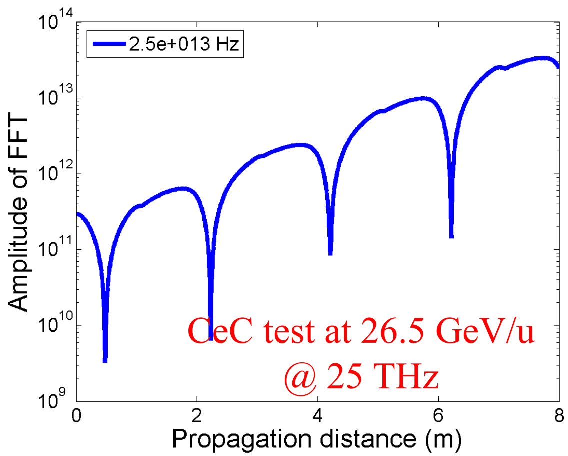
- CeC with microbunching amplifier can be capable of 10^{15} to 10^{17} Hz bandwidth and gains ~ 100 to 1,000. It means that to come close to required rate, muon beam has to be much brighter, e.g. $\sigma_\gamma \varepsilon$ should be lower by ~ 3 orders of magnitude or more.
- This, for given set of muon beam parameters neither CeC (or any other stochastic cooling system – RF or optical stochastic) would be incapable of cooling muon beams faster than luminosity decays…..

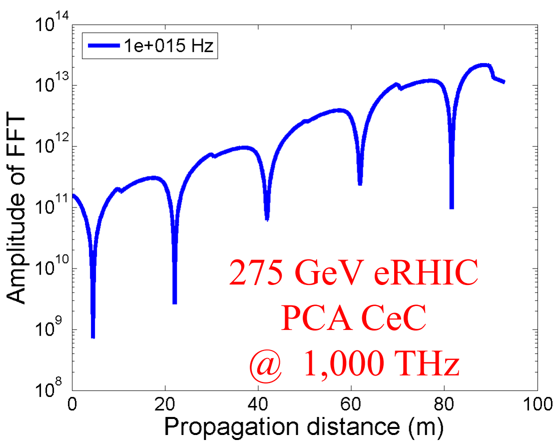
Back-ups

Simulation of Plasma-Cascade Instability

- SPACE code was modified to solve 3D beam dynamics of PCI self-consistently for a beam with a constant energy
- We had a good agreement between the theory and the SPACE 3D simulations for periodic systems and constant beam energy
- We can comfortably predict performance of microbunching Plasma Cascade Amplifier (PCA) for CeC: either for CeC test experiment or for eRHIC energy
- We are still exploring possibility of using a generic code Impact-T for simulating PCI in arbitrary accelerator (e.g. including acceleration and compression)
- While we have initial indication that this approach could work, this work is still in progress.

SPACE code simulations of microbunching PCA for CeC

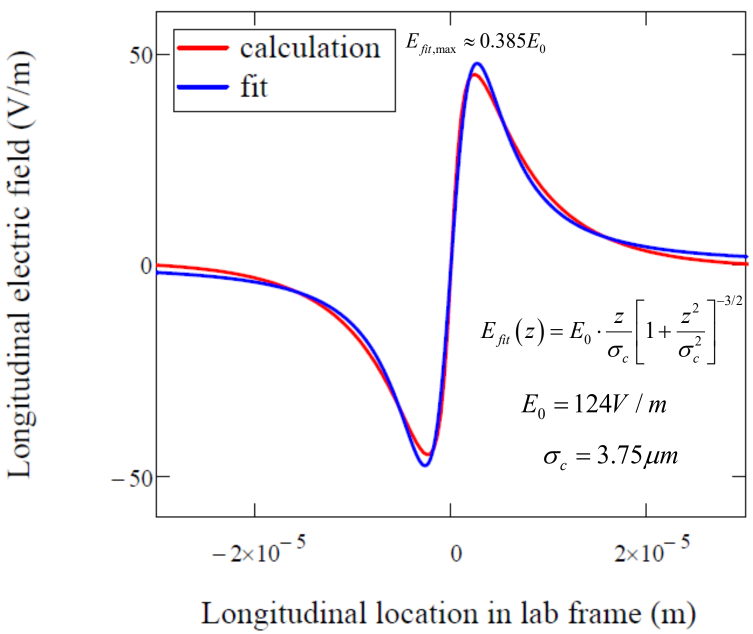




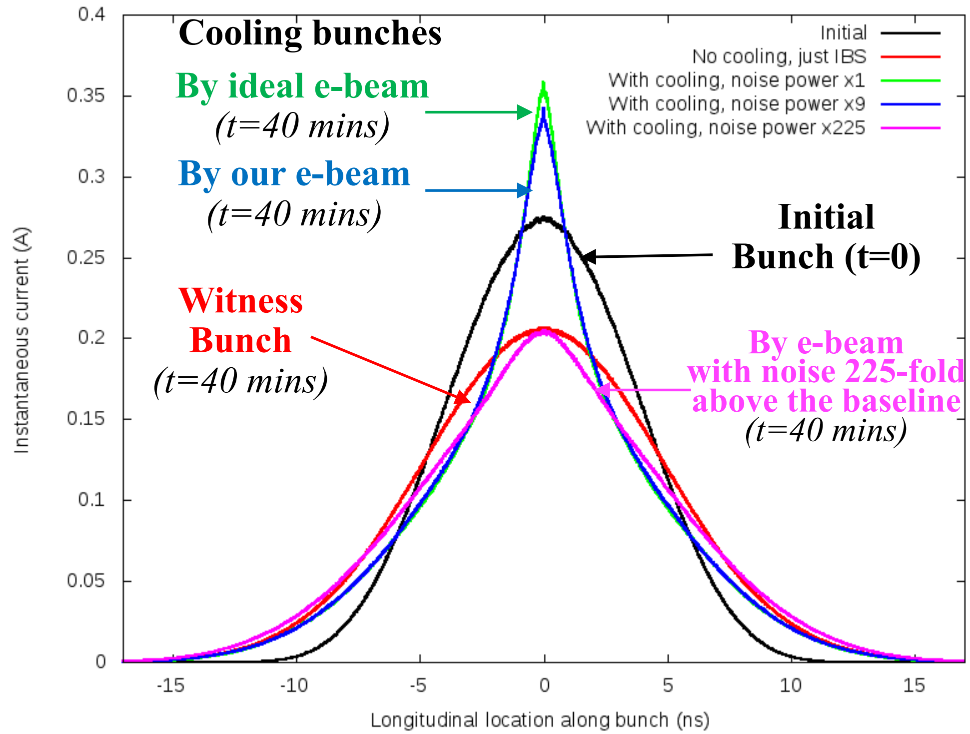
Simulated performance: full 3D treatment

CeC theory is important for scaling and for benchmarking of codes – full 3D simulations is the must for any reliable predictions, which have to be tested experimentally

Predicted evolution of the 26.5 GeV/u ion bunch profile in RHIC



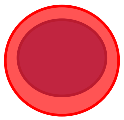
Simulated and fitted (used in simulations of the ion beam cooling) energy kick in the PCA-based CeC experiment system

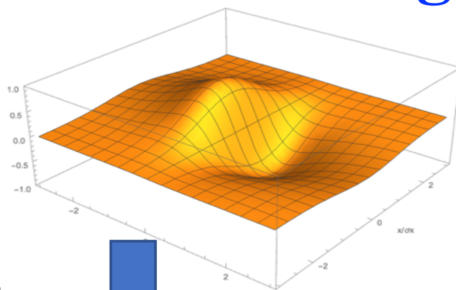


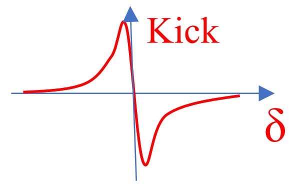
Black – initial profile, red – witness (non-interacting) bunch after 40 minutes. Profiles of interacting bunches after 40-minutes in PCA-based CeC for various levels of <u>white noise amplitude</u> in the electron beam: green– nominal statistical shot noise (baseline), dark blue – 9 fold above the baseline, and green – 225 fold above the baseline

Cooling will occur if electron beam noise is below 225-times the base-line (shot noise)
We demonstrated beams with noise as low as 6-times the baseline

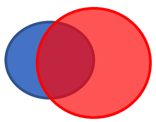
Distribution of cooling between longitudinal and transverse degrees of freedom – real kick

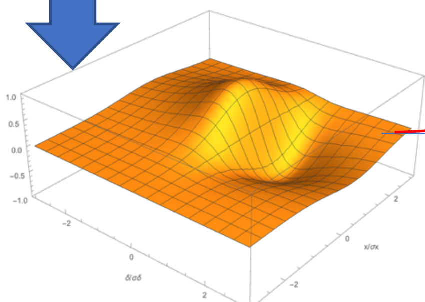


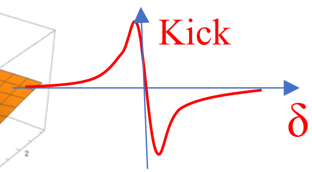




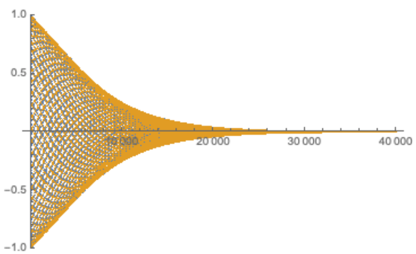
$\Delta x = 0.75\sigma_x$
zero energy kick at $0.4\sigma_\delta$



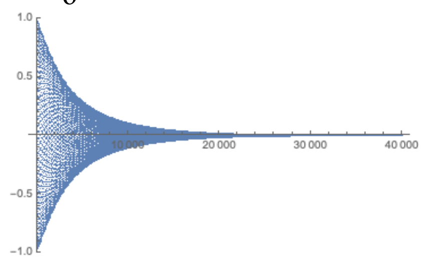




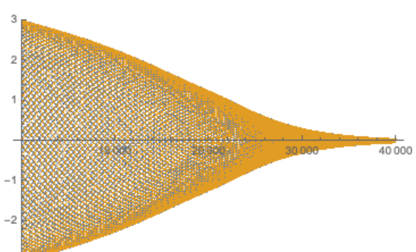
x/σ_x



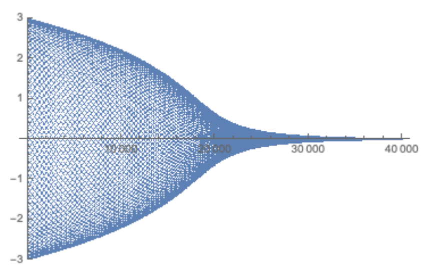
δ/σ_δ



x/σ_x

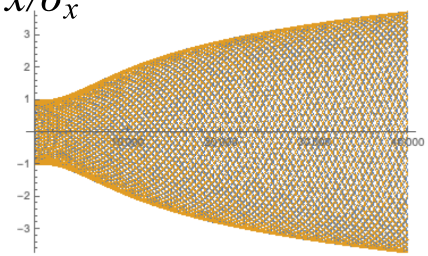


δ/σ_δ

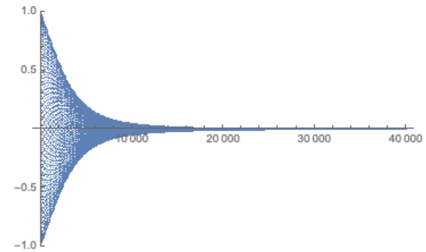


Wrong sign of displacement
$\Delta x = -0.75\sigma_x$

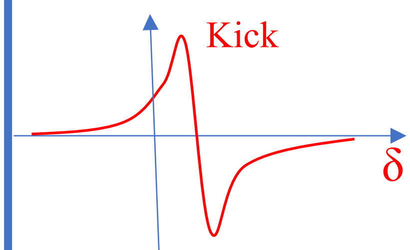
x/σ_x

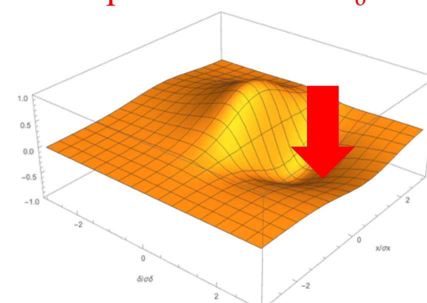


δ/σ_δ

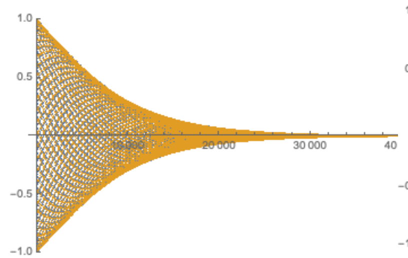


Excessive shifting of zero-kick point to $\delta = 0.6\sigma_\delta$





x/σ_x



δ/σ_δ