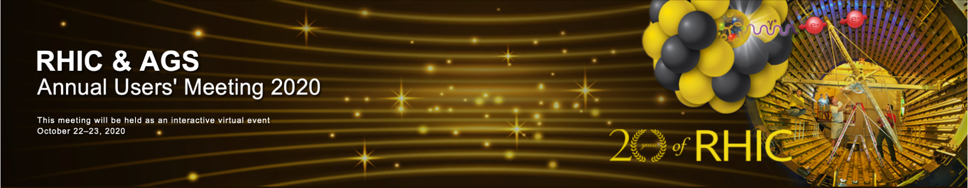

The Chilling Recount of an Unexpected Discovery: First Observations of the Plasma-Cascade Instability in the Coherent Electron Cooling Experiment

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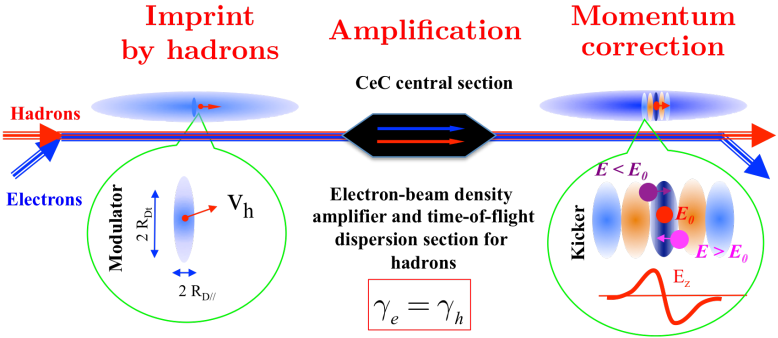
What is Coherent electron Cooling?

Short answer: stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1-1000 THz.

Long answer:



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Coherent Electron Cooling

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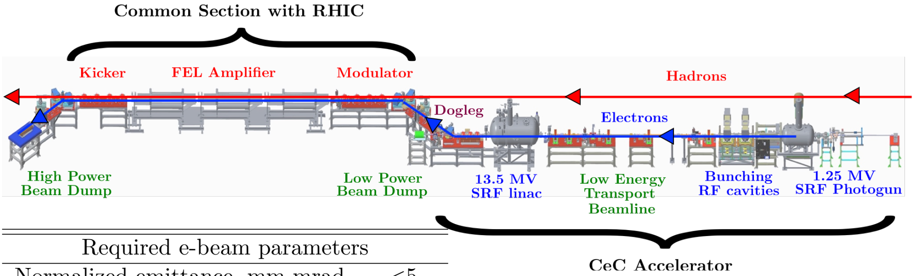
CeC Proof of Principle Experiment

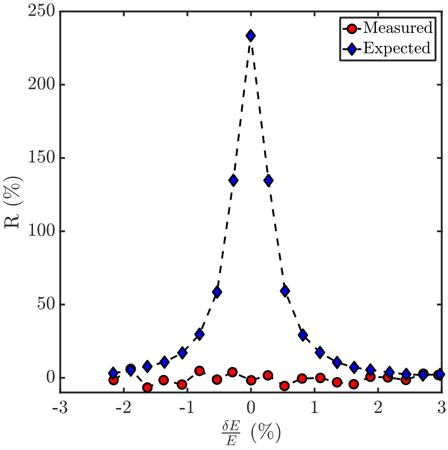
Goal: demonstrate longitudinal cooling of a single Au^{+79} bunch in the Relativistic Heavy Ion Collider.



Required e-beam parameters	
Normalized emittance, mm-mrad	<5
Relative energy spread σ_E/E	10^{-3}
Bunch charge, nC	0.5-1.5
Pulse repetition rate, kHz	78
RMS bunch length, ps	10-50
Peak current, A	>75
Kinetic energy, MeV	14.5
FEL wavelength, μm	30

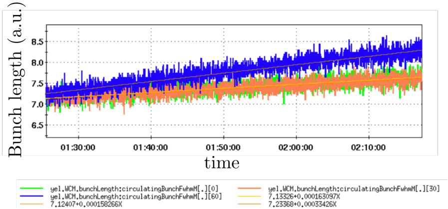
Hadron beam parameters	
Energy, GeV/u	27
Intensity, hadron/bunch	10^9
RMS bunch length, ns	5
Revolution frequency, kHz	78

Puzzle of the CeC Run 18



$$R = \frac{I_{\text{overlap}} - I_{\text{separated}}}{I_{\text{separated}}}$$

Evolution of the bunch lengths for interacting (blue trace) and witness bunches (orange and green traces).



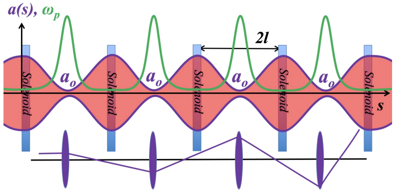
Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

Plasma-Cascade Instability (PCI)

Plasma-Cascade Instability—

longitudinal plasma oscillation with periodically varying plasma frequency:

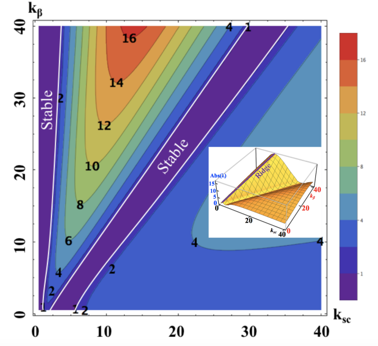
$$\tilde{n}'' + \omega_p^2(s)\tilde{n} = 0$$



$$\hat{a}'' - k_{\rm sc}^2 \hat{a}^{-1} - k_\beta^2 \hat{a}^{-3} = 0, \quad \hat{n}'' + 2k_{\rm sc}^2 \hat{a}^{-2}\hat{n} = 0.$$

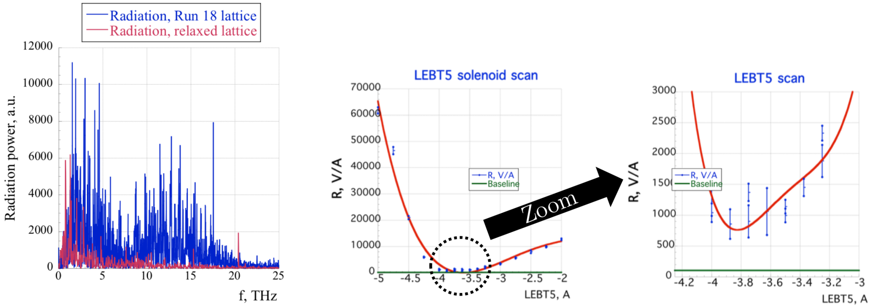
$$\hat{a} = \frac{a}{a_0}, \ \hat{s} = \frac{s}{l} \in \{-1, 1\}$$

$$k_{\rm sc} = \sqrt{\frac{2}{\beta^3\gamma^3}\frac{I_0}{I_a}\frac{l^2}{a_0^2}}, \ k_\beta = \frac{\varepsilon l}{a_0^2}$$



PCI is under control since 2019!

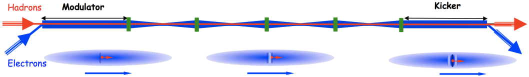
Demonstrated generation of electron beams with parameters satisfying/exceeding requirements for the CeC demonstration experiment.



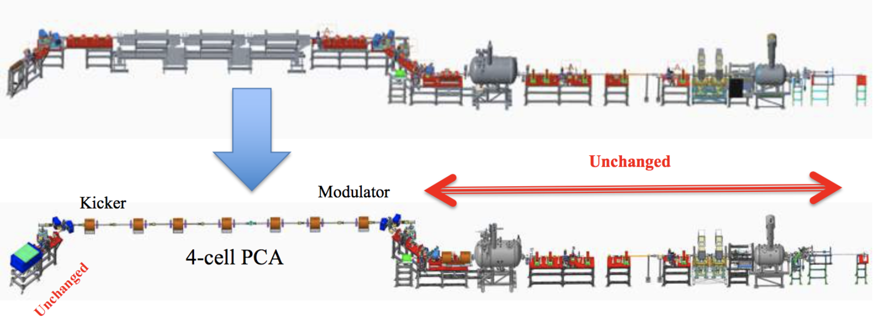
- As a result of optimization we were able to achieve the IR signal only factor two above shot noise level.
- The optimized set-up has rather flat response of the noise on the variation of the solenoid current leaving sufficient headroom for optimizing other beam parameters.

PCI applications → ACeC

The instability, while being an obstacle for the FEL-based CeC PoP, can come in handy if applied wisely!



Changing CeC amplifier: FEL → PCA



Thank you for your attention!

Special thanks:

- **CeC team:** V.N. Litvinenko, I. Pinayev, G. Wang, Y. Jing, J. Ma, K. Shih, Y.H. Wu
- **LLRF group:** G. Narayan, F. Severino, T. Hayes, K. Smith
- J. Tuozzolo[1], J.C. Brutus[1], S. Belomestnykh[3], C. Boulware[2], C. Folz[1], T. Grimm[2], P. Inacker[1], D. Kayran[1], G. Mahler[1], M. Mapes[1], T. Miller[1], T. Rao[1], J. Skaritka[1], Y. Than[1], E. Wang[1], B. Xiao[1], T. Xin[1], A. Zaltsman[1].

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What is cooling and why do we need it?

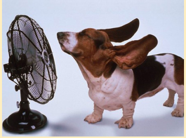
Luminosity characterizes the ability of a particle accelerator to produce the required number of interactions:

$$\frac{dN}{dt} = \sigma \cdot L \quad (1)$$

$$L = \frac{N_1 \times N_2 \times frequency}{Overlap\ Area} = \frac{N_1 \times N_2 \times f_{coll}}{4\pi\beta^*\varepsilon} \times h\left(\frac{\sigma_s}{\beta^*}\right) \quad (2)$$

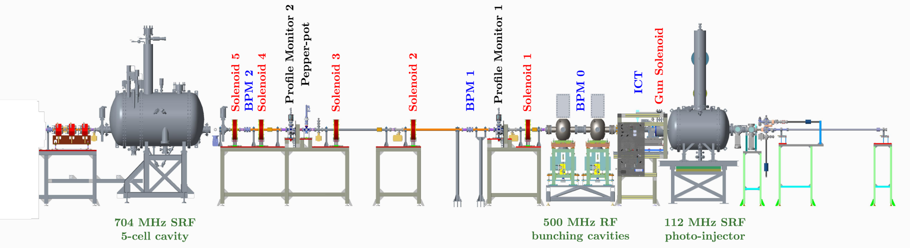
We want to have a large charge per bunch, high collision frequency and small spot size!

Cooling:



reduces beam phase space volume, emittance and momentum spread in order to improve beam quality.

CeC Accelerator

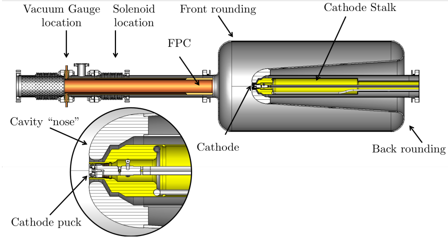


- 113 MHz SRF gun with CsK_2Sb photocathode. Cathode operation—weeks.
- 532 nm drive laser.
- Two 500 MHz copper cavities for ballistic compression to the required peak current.
- 704 MHz SRF accelerator cavity.

Demonstrated e-beam parameters	
Normalized emittance, mm-mrad	3-4
Relative energy spread σ_E/E	3×10^{-4}
Bunch charge, nC	0.03-10.7
Pulse repetition rate, kHz	78
RMS bunch length, ps	10-500
Kinetic energy, MeV	14.5

113 MHz SRF gun with warm CsK_2Sb photocathode

Transverse emittance from our SRF gun satisfies the requirements for a CW X-Ray FEL (0.4 mm-mrad for 100 pC bunches)!



Parameter	Value
Gun voltage, MV	1.25
Charge per bunch, nC	0.1-10
Average beam current @ 100 pC, mA	0.15
Transverse RMS slice emittance @ 100 pC, mm-mrad	0.15
Transverse RMS projected emittance @ 100 pC, mm-mrad	0.3
Longitudinal RMS slice emittance @ 100 pC, keV·ps	0.7
Quantum Efficiency, %	1-4

CeC 113 MHz SRF gun Operation Highlights

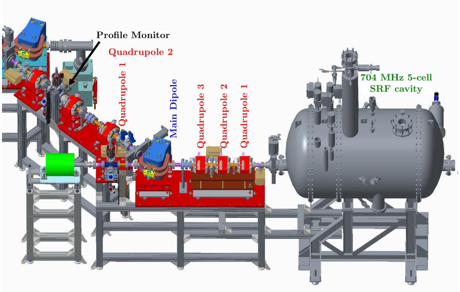
- Routine operation for the Coherent electron Cooling (CeC) experiment since 2016
- 1-2 months lifetime of high-QE CsK_2Sb cathodes
- Dedicated procedure for the cavity start-up—no issues with multipacting
- 0.15 mm-mrad normalized RMS slice emittance measured for 100 pC bunches

CeC PoP Accelerator Performance

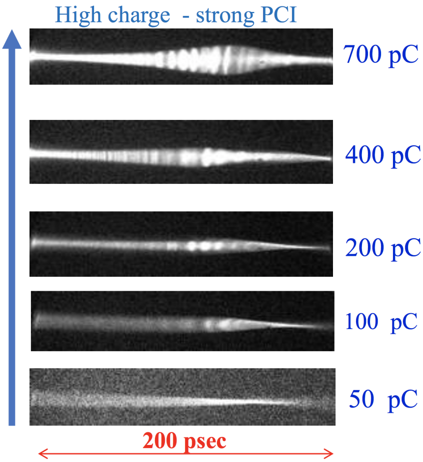
Achieved parameters of the e^- beam.

Parameter	Design	Status	Comment
Species in RHIC (GeV/u)	Au^{+79} 40	Au^{+79} 26.5	to match e-beam
Electron energy (MeV)	21.95	14.56	linac quench
Charge per e-bunch (nC)	0.5-5	0.1-10.7	✓
Peak current (A)	100	50-100	✓
Bunch duration (psec)	10-50	12	✓
Normalized emittance (μm)	<5	3-5	✓
Energy spread, RMS (%)	0.1	0.1	✓
FEL wavelength (μm)	13	31	new IR diagnostics
Repetition rate (kHz)	78.18	78.18	✓
CW beam (μA)	<400	150	✓

Puzzle of the CeC Run 18



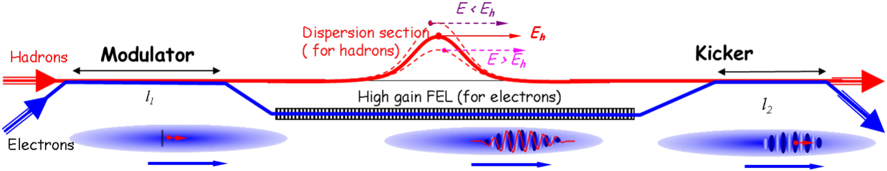
- Bunch spectra have demonstrated a broadband PCI gain peaking at ∼0.4 THz in an uncompressed beam.
- Bunched beam spectrum has a peak at 10 THz.
- The measurements were confirmed through simulations done by SPACE and Impact-T.



Beam profiles showing the dependence of the structures on charge per bunch.

Coherent electron Cooling (CeC)

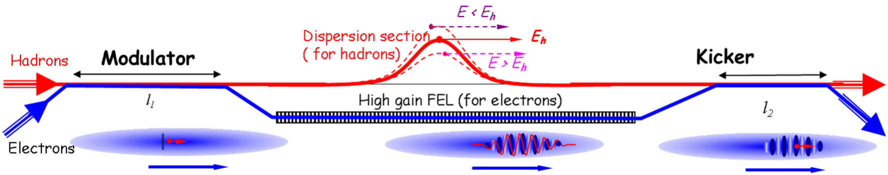
CeC scheme is based on electrostatic interactions between electrons and hadrons that are amplified either in a high-gain FEL or by other means.



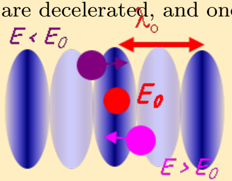
The electron and hadron beams co-propagate in a vacuum along a straight line in the modulator and kicker with the same velocity:

$$\gamma = \frac{E_e}{m_e c^2} = \frac{E_h}{m_h c^2} \tag{3}$$

Coherent electron Cooling (CeC): Kicker



- When the hadron and electron beams are recombined, hadrons are exposed to the longitudinal electric field
- With a proper delay section, a hadron with central energy E_0 arrives at the kicker on top of the electron density peak—zero electric field
- Hadrons with higher energy are decelerated, and ones with lower energy are pulled forward.



Overview of existing SRF photoinjectors

Parameter	CeC PoP	FZD	HZB	NPS	UW
Cavity type	QWR*	Elliptical	Elliptical	QWR	QWR
Number of cells	1	3.5	1.4	1	1
RF frequency, MHz	113	1300	1300	500	200
LiHe Temperature, K	4	2	2	4	4
Beam energy, MeV	1.25-1.5	3.3	1.8	0.47	1.1
Charge per bunch, nC	10.7	0.3	0.006	0.078	0.1
Beam current, μA	150	18	0.005	<0.0001	<0.1
Dark current, nA	<1	120	-	$<20,000$	<0.001
E_{cath}, MV/m	10-20	5	7	6.5	12
Photocathode	CsK_2Sb	Cs_2Te	Pb	Ni	Cu

*QWR—Quarter Wave Resonator

[1] A. Arnold et al. “A high-brightness SRF photoelectron injector for FEL light sources”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 593.1 (2008), pp. 57–62.

[2] M. Schmeißer et al. “Results from beam commissioning of an SRF plug-gun cavity photoinjector”. In: (2013).

[3] J.R. Harris et al. “Design and operation of a superconducting quarter-wave electron gun”. In: *Physical Review Special Topics-Accelerators and Beams* 14.5 (2011), p. 053501.

[4] J. Bisognano et al. “Wisconsin SRF Electron Gun Commissioning”. In: *Proc. NAPAC'13* (2013), pp. 622–624.