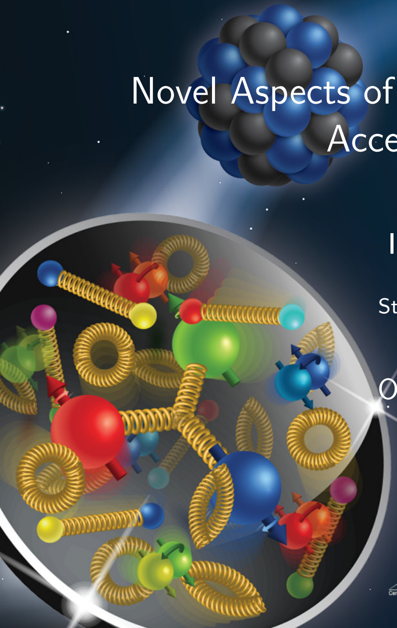


Novel Aspects of Beam Dynamics in the CeC Accelerating System

Irina Petrushina

Stony Brook University

October 17, 2017

Electron Ion Collider – eRHIC

CASE Center for Accelerator Science and Education
Stony Brook University
BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY Office of Science

Contents

What is cooling and why do we need it?

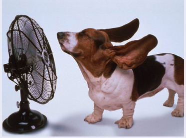
Luminosity characterizes the ability of a particle accelerator to produce the required number of interactions:

$$\frac{dN}{dt} = \sigma \cdot L \tag{1}$$

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

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.

Cooling Methods

Existing cooling methods are not sufficient:

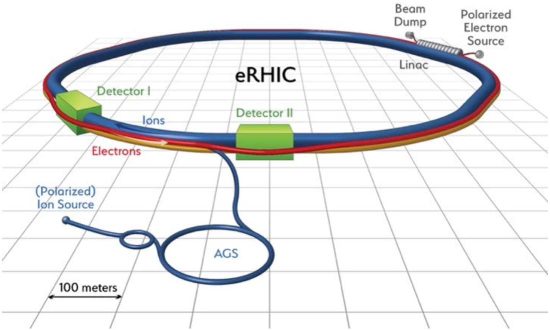
- Electrons and positrons have natural strong cooling mechanism: Synchrotron Radiation ($\sim$ milliseconds)
- Synchrotron Radiation will not help to cool hadrons at the currently available energies
- Main limitation of electron cooling is its rapidly falling efficiency with the increase of the beam energy $\tau \sim \gamma^{7/2}$
- Stochastic cooling (for a fixed bandwidth) is limited by the fact that its cooling time directly proportional to linear density of the particles and modern proton beams are simply too dense.

Cooling rate in hours for various cooling methods.

Machine	Energy, GeV/u	Stochastic Cooling	Synchrotron radiation	Electron cooling	Coherent electron Cooling
RHIC - CeC PoP (Au)	26	-	-	~ 1	10 sec - local, 30 min - bunch
eRHIC (p)	325	~ 100	∞	~ 30	~ 0.1
LHC (p)	7000	~ 1000	13(energy)/26(transverse)	∞	~ 1

Coherent electron Cooling (CeC) and eRHIC

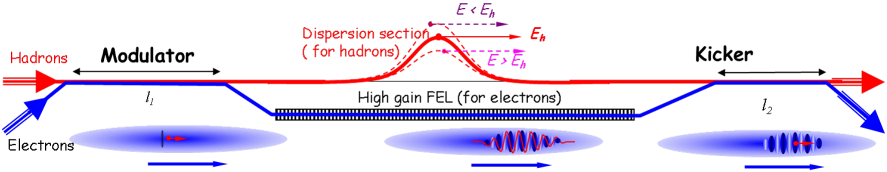
High energy luminosity Electron-Ion Collider requires strong hadron cooling: $<$ 1 min cooling time 250 GeV protons



If CeC is successful and fully operational, eRHIC Linac/Ring configuration could reach $2 \cdot 10^{33}$ luminosity with 5 mA polarized electron current.

Coherent electron Cooling (CeC)

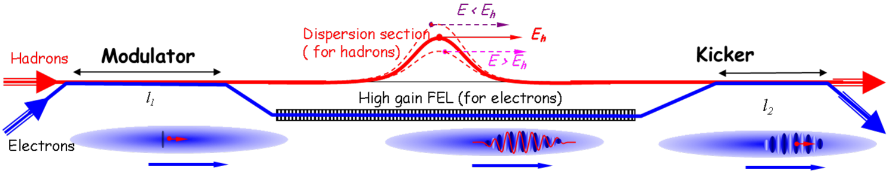
CeC scheme is based on electrostatic interactions between electrons and hadrons that are amplified either in a high-gain FEL or by other means.



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): Modulator

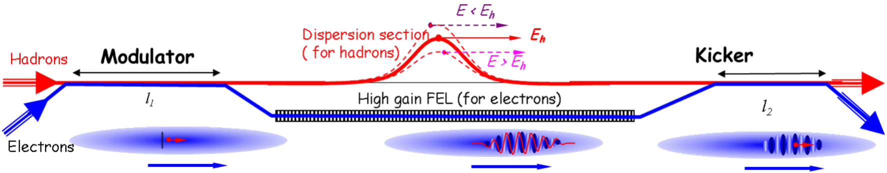


- Each individual hadron attracts surrounding electrons and generates density modulation
- In about a quarter of the plasme period, each hadron is surrounded by a cloud of electrons

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{\gamma m_e}} \tag{4}$$

- In the co-moving frame, the longitudinal velocity spread is much smaller than that in the transverse direction
- Electron cloud is shaped as a very flat pancake-like shape.

Coherent electron Cooling (CeC): Amplifier

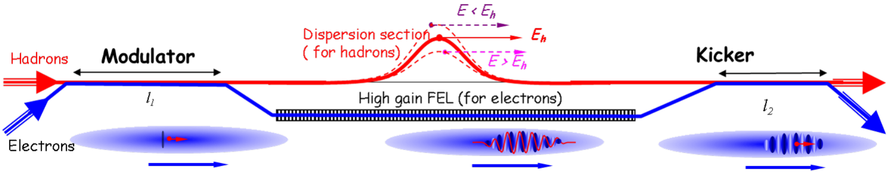


- An FEL is a resonant instability at the wavelength of:

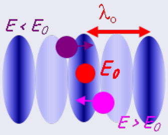
$$\lambda_o = \lambda_w \frac{1 + \langle \vec{a}_w^2 \rangle}{2\gamma^2}, \ \vec{a}_w = \frac{e\vec{A}_w}{mc^2} \tag{5}$$

- If the longitudinal extent of an induced perturbation is considerably shorter than FEL wavelength, it will be amplified.
- A periodic density modulation generates a periodic longitudinal field.

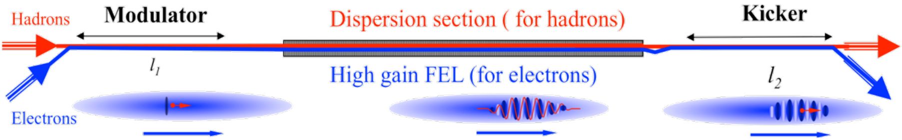
Coherent electron Cooling (CeC): Kicker



- 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.



Coherent electron Cooling (CeC): Proof of Principle



- Straight section between the modulator and kicker acts as a dispersion section for hadrons
- The optics and magnets have a very little effect on the hadrons' dynamics
- Group velocity of the wave-packet in the FEL:

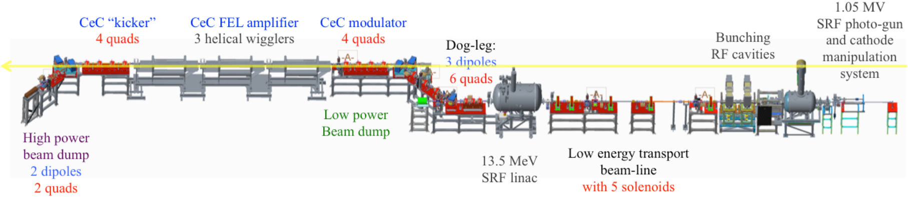
$$v_g = v_z^e(1-\alpha) + c\alpha,\ 0 < \alpha < 1 \tag{6}$$

$$v_z^e = c\left(1 - \frac{1+a_w^2}{2\gamma^2}\right) \tag{7}$$

$$v_g = c\left(1 - \frac{1+a_w^2}{2\gamma^2} + \alpha\right) = c\left(1 - \frac{1}{2\gamma^2}\right) + \frac{c}{2\gamma^2}\left(a_w^2 - \alpha(1+a_w^2)\right) \tag{8}$$

- Requirement: $v_g \geq v_h \Rightarrow \left(\alpha(1+a_w^2 - a_w^2)\right) > 0 \Rightarrow a_w \leq \sqrt{\frac{\alpha}{1-\alpha}}$

Coherent electron Cooling: Proof of Principle

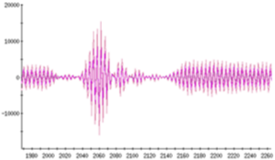


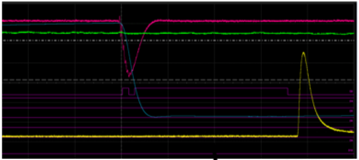
- e^- beam is generated by 113 MHz SRF gun with $\mathrm{CsK_2Sb}$ photocathode driven by a 532 nm laser
- Two 500 MHz copper cavities provide energy chirp and beam is compressed to desired peak current.
- After the compression beam is accelerated by a 704 MHz SRF cavity and merged into CeC PoP structure with three helical undulators.

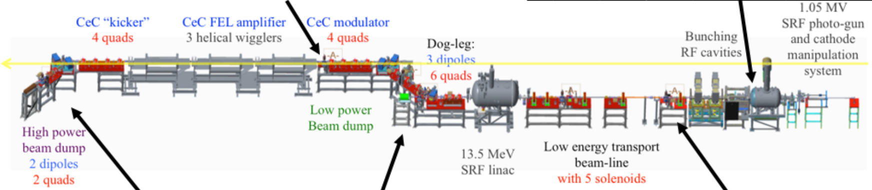
e^- beam parameters.

Parameter	Value
Gun energy, MeV	1.05
Beam charge, nC	1-5
Final beam energy, MeV	22
Normalized emittance, mm-mrad	<5
Energy spread	10^{-3}
Pulse repetition rate, kHz	78 (26)

Results of commissioning






CeC "kicker"
4 quads

CeC FEL amplifier
3 helical wigglers

CeC modulator
4 quads

Dog-leg:
3 dipoles
6 quads

Bunching
RF cavities

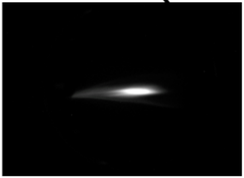
1.05 MV
SRF photo-gun
and cathode
manipulation
system

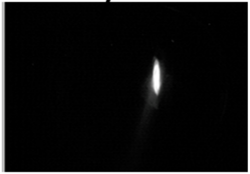
High power
beam dump
2 dipoles
2 quads

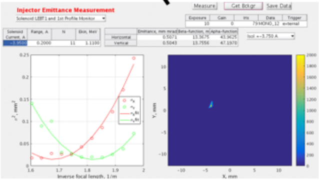
Low power
Beam dump

13.5 MeV
SRF linac

Low energy transport
beam-line
with 5 solenoids






Injector Emittance Measurement

Solenoid LEBT1 and 1st Profile Monitor

Exposure	Gain	Iris	Data	Trigger
10	0	79	MONO_12	external

Solenoid Current, A	Range, A	N	Ekin, MeV
-3.9500	0.2000	11	1.1100

	Emittance, mm mrad	Beta-function, m	Alpha-function
Horizontal	0.5071	13.3675	43.9625
Vertical	0.5043	13.7556	47.1970

Isol =-3.750 A

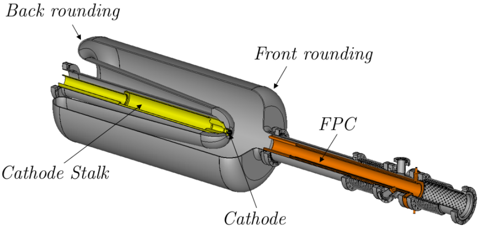
Parameters achieved

Achieved parameters of the e^- beam.

Parameter	Design	Status	Comment
Species in RHIC	Au^{+79} 40 GeV/u	Au^{+79} 26.5 GeV/u	To match e^- beam
Particles per bucket	$10^8 - 10^9$	$10^8 - 10^9$	✓
Electron energy, MeV	21.95	15	SRF linac quench
Charge per e^- bunch, nC	0.5-5	0.1-4	✓
Peak current, A	100	50	Sufficient for this energy
Pulse duration, ps	10-50	12	✓
Normalized emittance, mm-mrad	<5	3-4	✓
FEL wavelength, μm	13	30	New IR diagnostics needed
Repetition rate, kHz	78.17	26	Temporary*
e^- beam current, μA	up to 400	40	Temporary*
e^- beam power, kW	<10	0.6	Temporary*

- *Will be changed to 78 kHz after retuning the SRF gun frequency
- Beam parameters are sufficient for the CeC demonstration experiment

113 MHz SRF Photo-Injector: 1

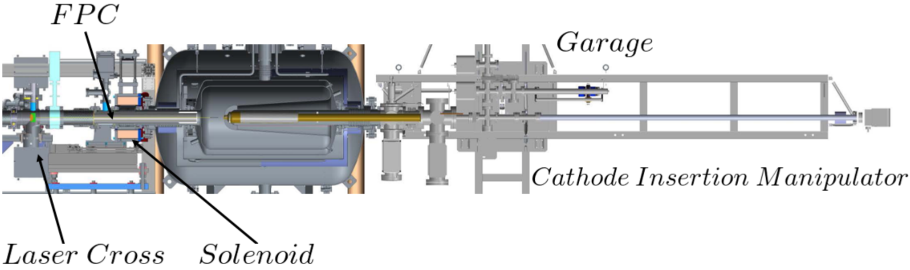


RF parameters of the gun.

Parameter	Value
Frequency, MHz	113
Quality Factor w/o cathode	3.5×10^9
R/Q, Ω	126
Geometry Factor, Ω	38.2
Operating temperature, K	4.5
Accelerating voltage, MV	1.05-1.2

- FPC provides RF power coupling and fine frequency tuning;
- With the travel of ± 2 cm, the tuning range will be ~ 4 kHz;
- A small cathode puck is inserted inside the stalk and can be replaced when necessary with a new one.

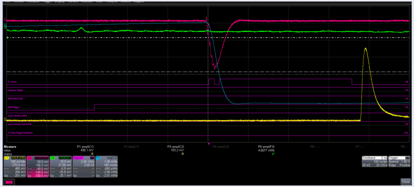
113 MHz SRF Photo-Injector: 2

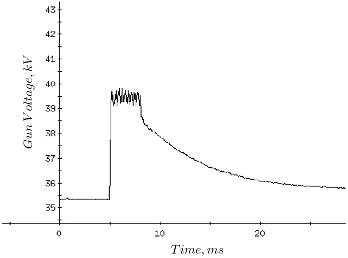


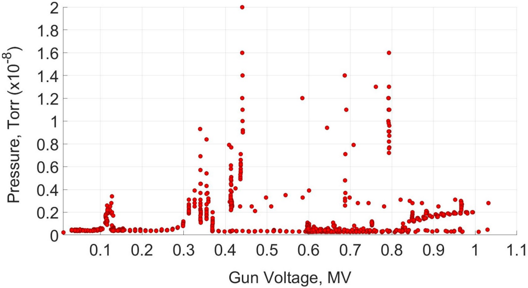
- Quarter-wave cavity;
- 4 K operating temperature;
- Manual coarse tuner;
- Fine tuning is performed with FPC;
- 2 kW CW solid state power amplifier;
- $\mathrm{CsK_2Sb}$ cathode is at room temperature;
- Cavity field pick-up is done with cathode stalk (1/2 wavelength with capacitive pick-up);
- Up to three cathodes can be stored in garage for quick change-out;
- Design gradient 22.5 MV/m

113 MHz SRF Photo-Injector: Commissioning

- 3.7 nC beam charge was observed during the commissioning;
- Achieved cavity voltage: 1.2 MV;
- Duration of the laser pulse: 1 ns.





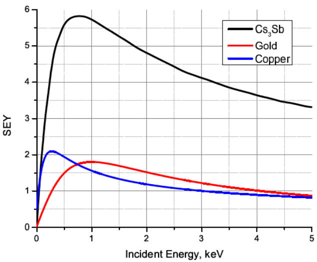


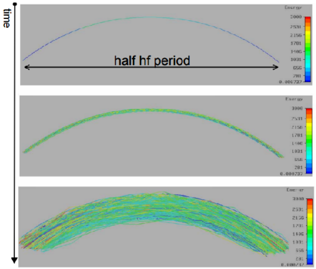
Definition of Multipacting

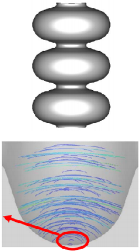
Multipacting discharge (multipacting) —

a resonant process in which an electron avalanche builds up within a small region of the cavity surface and is determined by the following factors:

- electric field levels;
- geometry of the cavity;
- material properties — Secondary Emission Yield (SEY).







An electron avalanche absorbs large amounts of RF power and deposits it as a heat ⇒ lower quality factor.

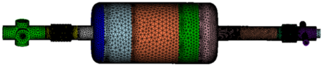
Multipacting Simulations

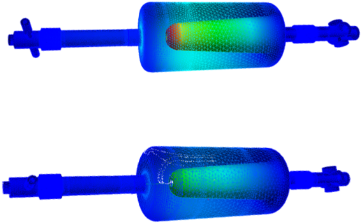
Calculate EM fields

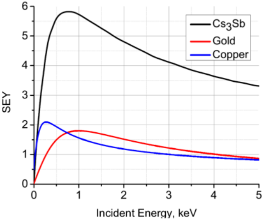
Define SEY

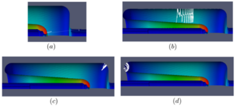
Define emitting surface

Analyze Enhancement Counter (EC) and trajectories

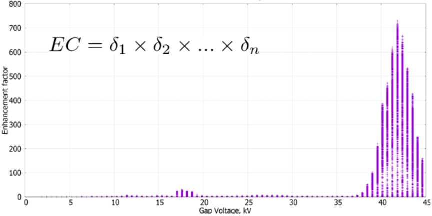






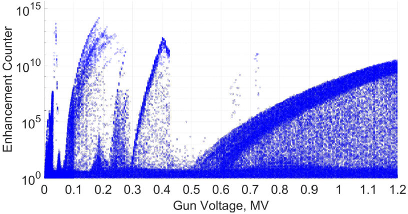

(a)
(b)
(c)
(d)

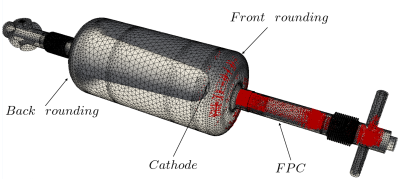
Gun without the cathode pack

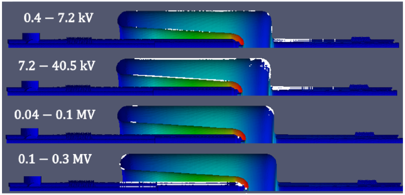


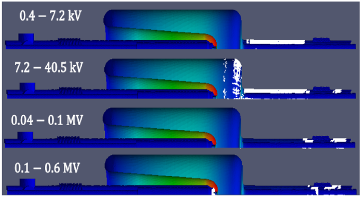
$$EC = \delta_1 \times \delta_2 \times \ldots \times \delta_n$$

Simulation Results









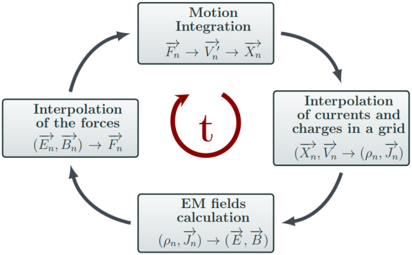
This work was presented at:

- IPAC'17 (MOPVA140: "Multipacting Behavior Study for the 112 MHz Superconducting Photo-Injector")
- FEL'17 (TUP034: "Novel Aspects of Beam Dynamics in CeC SRF Gun and SRF Accelerator")
- PRAB paper is in progress ("Mitigation of Multipacting in 113-MHz Superconducting RF Photo-Injector")

Self-Consistent Gun Simulation: Motivation

It is necessary to take into consideration:

- space-charge effects;
- retardation;
- boundary effects (wakefields).



Motion Integration
$\overrightarrow{F_n} \rightarrow \overrightarrow{V_n'} \rightarrow \overrightarrow{X_n'}$

Interpolation of currents and charges in a grid
$(\overrightarrow{X_n}, \overrightarrow{V_n} \rightarrow (\rho_n, \overrightarrow{J_n})$

EM fields calculation
$(\rho_n, \overrightarrow{J_n}) \rightarrow (\overrightarrow{E}, \overrightarrow{B})$

Interpolation of the forces
$(\overrightarrow{E_n}, \overrightarrow{B_n}) \rightarrow \overrightarrow{F_n}$

Self-Consistent Simulation

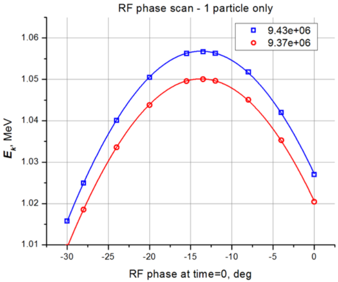
Calculate EM fields

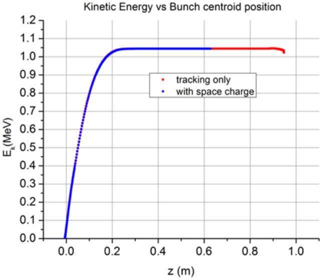
Study mesh convergence

Study convergence in #of particles and time step

Perform phase and amplitude scan

Analyze evolution of emittance

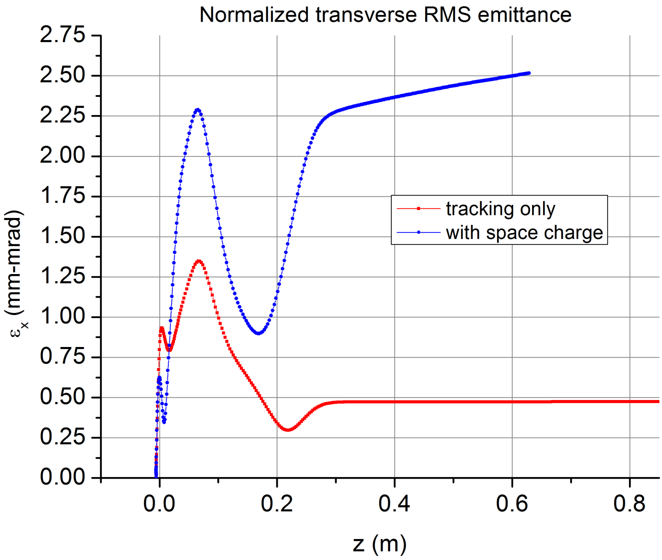




Parameters of the beam.

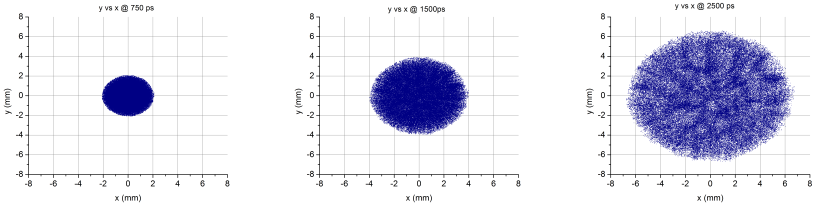
Parameter	Value
Total Charge, nC	0.5
Initial Velocity, β_z	0.003
Type of radial Distribution	Uniform
Radius, mm	1.5
Type of Longitudinal Distribution	Flat Top
Duration of the flat top, ns	0.5
Rise/Drop time, ns	0.005

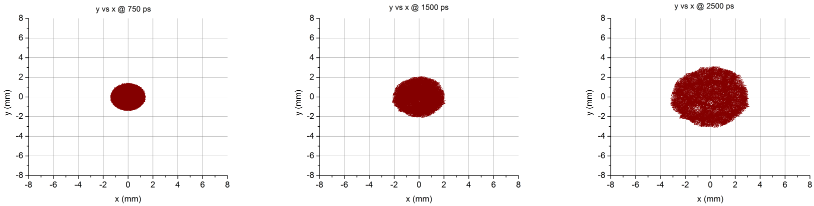
Simulation Results: Evolution of Emittance—preliminary



With and Without Space Charge : xy plot—preliminary

With Space Charge

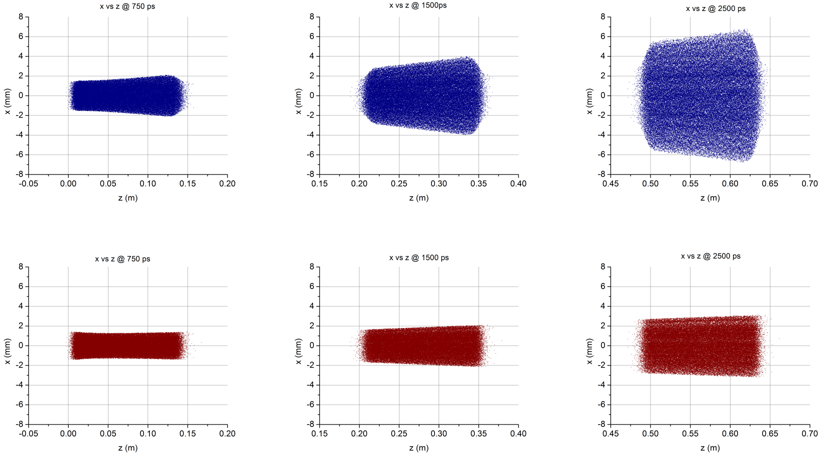




Without Space Charge

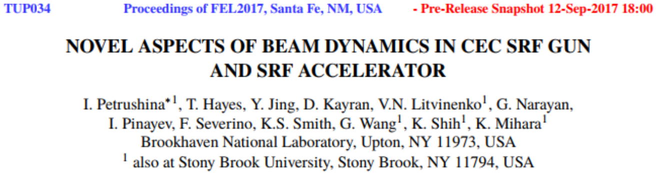
With and Without Space Charge : xz plot—preliminary

With Space Charge



Without Space Charge

Self-Consistent Gun Simulation: Scattered Fields

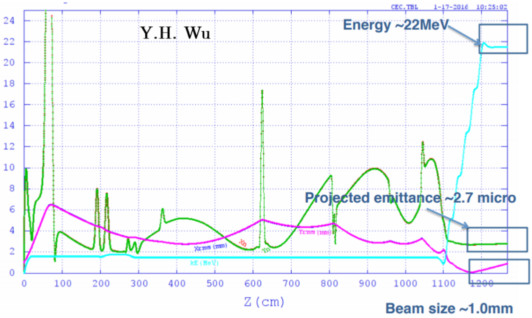


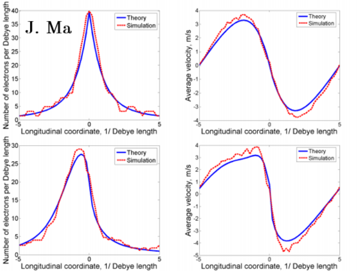
TUP034 Proceedings of FEL2017, Santa Fe, NM, USA - Pre-Release Snapshot 12-Sep-2017 18:00

NOVEL ASPECTS OF BEAM DYNAMICS IN CEC SRF GUN AND SRF ACCELERATOR

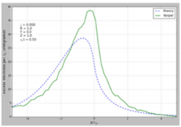
I. Petrushina*[1], T. Hayes, Y. Jing, D. Kayran, V.N. Litvinenko[1], G. Narayan,
I. Pinayev, F. Severino, K.S. Smith, G. Wang[1], K. Shih[1], K. Mihara[1]
Brookhaven National Laboratory, Upton, NY 11973, USA
[1] also at Stony Brook University, Stony Brook, NY 11794, USA

What has been done before:

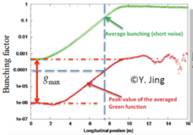




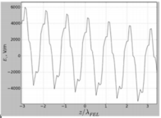
Comparison of theory and numerical simulations of density (left) and velocity (right) modulation by stationary (top) and moving (bottom) ion with respect to uniform electron cloud.



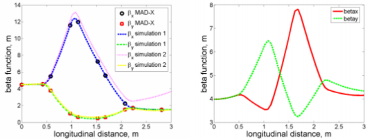
VORPAL 3D δf PIC computation of e-density perturbation near Au^{+79} ion (green) vs. idealized theory (blue). On Cray XE6 cluster at NERSC.



GENESIS parallel computation of electron beam bunching in free electron laser (FEL) shows amplification of modulator signal.



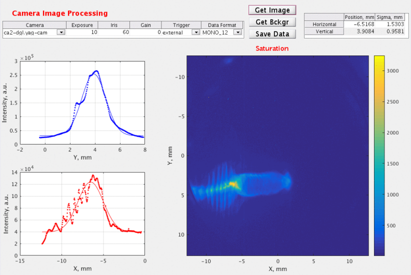
VORPAL prediction of the coherent kicker electric field E_k due to e-density perturbation from modulator, amplified in the FEL.



Transverse β function changes in quadrupoles magnetic field.

Future Work

The longitudinal bunch structure was studied during the commissioning. 1.2 nC bunch in the dogleg has a periodic micro-bunching with a period of about 1.5 psec which can originate from:



Camera Image Processing

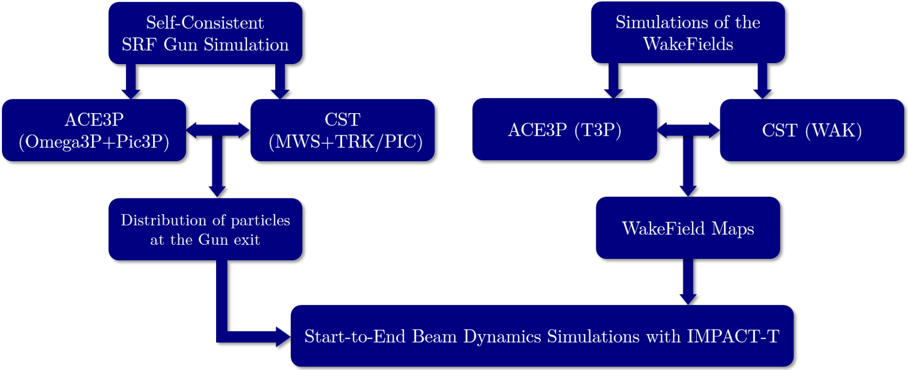
Camera	Exposure	Iris	Gain	Trigger	Data Format
ca2-dgl.yag-cam	10	60	0	external	MONO_12

	Position, mm	Sigma, mm
Horizontal	-6.5168	1.5303
Vertical	3.9084	0.9581

- The time structure of the initial laser pulse
- The space-charge driven micro-bunching instability
- The wakefileds induced by the beam in the transport channel.

Perform a comprehensive wakefield study in the entire CeC system using software for 3D simulations, and include the resulting fields into the IMPACT-T calculations of the beam dynamics in order to see the influence of the wakefields on the beam structure.

Future Work: Diagram



Self-Consistent SRF Gun Simulation

ACE3P (Omega3P+Pic3P)

CST (MWS+TRK/PIC)

Distribution of particles at the Gun exit

Simulations of the WakeFields

ACE3P (T3P)

CST (WAK)

WakeField Maps

Start-to-End Beam Dynamics Simulations with IMPACT-T

Thank you for your attention!

References

- Vladimir N. Litvinenko and Yaroslav S. Derbenev, *Coherent Electron Cooling*, Physicsl Review Letters, March 2009;
- V.N. Litvinenko et.al., *Coherent Electron Cooling Demonstration Experiment*, IPAC'11, San Sebastian, Spain, 2011;
- S. Belomestnykh et.al., *SRF and RF systems for CeC PoP experiment*, NA-PAC'13 Pasadena, CA, 2013;
- I. Pinayev et.al., *First results of the SRF gun test for CeC PoP*, IPAC'16, Busan, Korea, 2016;
- I. Pinayev et.al., *Commissioning of the CeC PoP accelerator*, NAPAC'16, Chicago, IL, 2016;
- S. Belomestnykh et.al., *Commissioning of the 112 MHz SRF gun*, SRF2015, Canada, 2015;
- I. Pinayev et.al., *Performance of CeC PoP Gun During Commissioning*, NAPAC'16, Chicago, IL, 2016;
- H. Padamsee, *RF Superconductivity*, 2009;
- T.P. Wangler, *RF Linear Accelerators*, 2008;
- E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov *The Physics of Free Electron Lasers*, 2000

Back-Up: Luminosity and Hourglass effect

For two beams with N_1 and N_2 particles per bunch colliding with a certain frequency f_{coll}:

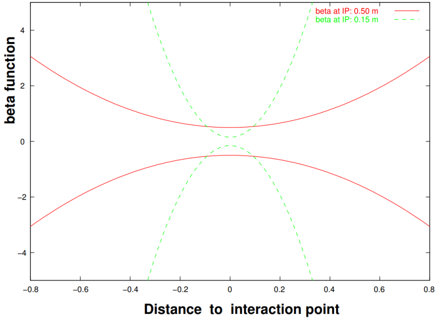
$$L = \frac{N_1 \times N_2 \times f_{coll}}{4\pi\beta^*\varepsilon} \times h\left(\frac{\sigma_s}{\beta^*}\right) \tag{9}$$

$$h(x) = \frac{\sqrt{\pi}}{x} e^{1/x^2} erfc\left(\frac{1}{x}\right) \tag{10}$$

where β^* is the transverse β-function at the collision point, ε is the transverse emittance of the beam, σ_s is the bunch length.

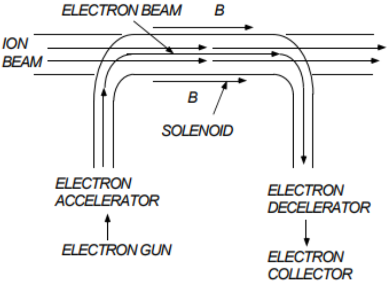
- The hourglass effect is caused by variations in the beam's size $\sigma_r^2 = \beta^*\varepsilon\left(1 + \frac{s^2}{(\beta^*)^2}\right)$ along the length of the collision region and is defined by the bunch length σ_s.
- For $h > 0.75$ it's required that $\beta^* \geq \sigma_s$
- Longitudinal cooling allows reduction of β^* and increase of the luminosity

Back-Up: Hourglass effect



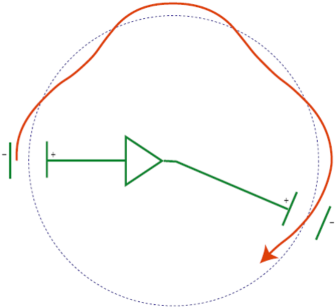
- β-function has its minimum at the collision point and grows away from it $\beta(s) = \beta^* \left(1 + \frac{s^2}{(\beta^*)^2}\right)$
- therefore the beam size increases: $\sigma = \sqrt{\beta(s)\varepsilon}$
- becomes important when σ_s approaches $\beta(s)$

Back-Up: Electron Cooling



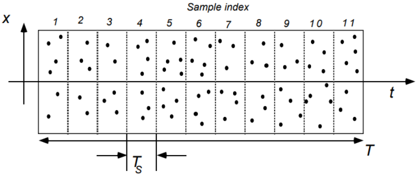
- A beam of dense quasi-monoenergetic electrons is produced and merged with the ion beam to be cooled.
- The velocity of the electrons is made equal to the average velocity of the ions.
- The ions undergo Coulomb scattering in the electron gas and exchange momentum with the electrons.
- Thermodynamic equilibrium is reached when the particles have the same momentum, which requires that the much lighter electrons have much higher velocities. Thus, thermal energy is transferred from the ions to the electrons.
- The electron beam is finally bent away from the ion beam.

Back-Up: Stochastic Cooling



- "Single-particle cooling"—let there be only one particle in the ring, with a deviation from the center x_T after T turns and x_{T+1} after $T+1$ turns
- The stochastic cooling system measures x_T at the pickup, and delivers a kick so that $x_{T+1} = x_T - g \cdot x_T$
- $g = 1$ removes the oscillation completely. The transverse momentum is reduced to zero: The particle is "cooled" in one turn

Each particle in the sample receives a kick proportional to the mean displacement $<x>$; for the k^{th} particle, the new displacement will be $x_k - g <x>$



Back-Up: Alternative CeC Schemes

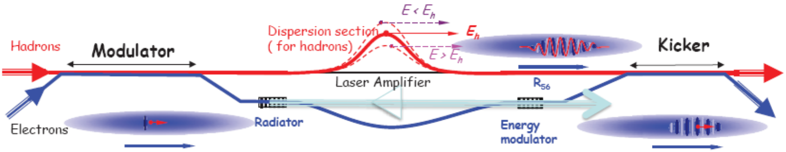


Figure 2: A hybrid CeC schematic uses a broad-band laser amplifying electron-beam's radiation from a short wiggler. The amplified laser power then, in a second wiggler, modulates the electrons energy. The latter is transferred into a density modulation using the R_{56} of an achromatic dog-leg.

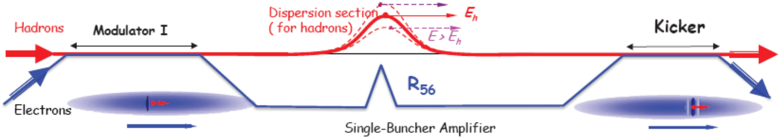
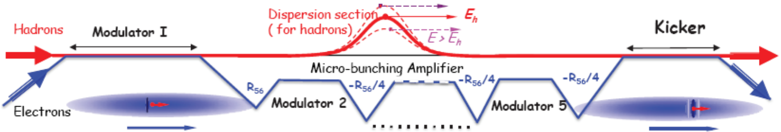


Figure 3: A CeC with an enhanced bunching by a single strong-field buncher. The scheme requires that the electron beam has special qualities [15-19].



Back-Up: Modulator—pancake formation

- The motion of the particles in co-moving frame is non-relativistic
- Velocity distribution is highly anisotropic with RMS velocity spread in longitudinal direction:

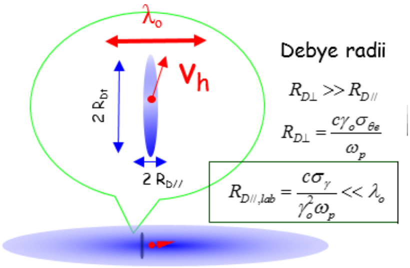
$$\sigma_{v||}^{cm} \cong c \cdot \sigma_\delta = c\frac{\delta E}{E} \tag{11}$$

- RMS velocity spread in transverse direction is much larger:

$$\sigma_{v\perp}^{cm} \cong c\gamma\sigma_\theta \tag{12}$$

- The velocity spreads will determine the size of Debye ellipsoid:

$$r_{D||}^{cm} \sim T_{1/4} \cdot \sigma_{v||}^{cm} \;\Rightarrow\; r_{D||}^{lab} \sim \frac{\pi c}{2\omega_p}\frac{\sigma_\delta}{\gamma} \tag{13}$$



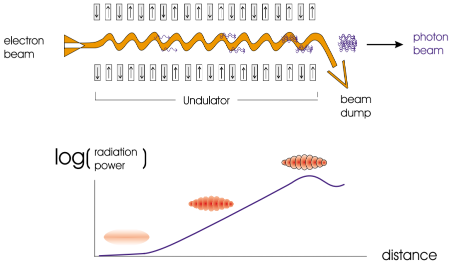
Debye radii

$$R_{D\perp} >> R_{D//}$$

$$R_{D\perp} = \frac{c\gamma_o\sigma_{\theta e}}{\omega_p}$$

$$\boxed{R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma_o^2\omega_p} << \lambda_o}$$

Back-Up: FEL as an amplifier



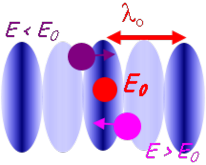
- While traveling with relativistic velocity through the undulator, the electrons are accelerated in the direction transverse to their propagation due to the Lorentz force
- They emit SR in a narrow cone in the forward direction. The typical opening angle of the wavelength integrated radiation is $\frac{1}{\gamma}$
- In the undulator, the deflection of the electrons from the forward direction is comparable to the opening angle of the SR cone.

- This interference effect is reflected in the formula:

$$\lambda_o = \lambda_w \frac{1 + \langle \vec{a}_w^2 \rangle}{2\gamma^2}, \;\; \vec{a}_w = \frac{e\vec{A}_w}{mc^2} \tag{14}$$

- Oscillating through the undulator, the electron bunch then interacts with its own electromagnetic field created via spontaneous emission.
- Through this interaction a longitudinal fine structure, the so called micro-bunching, is established which amplifies the electromagnetic field.

Back-Up: Kicker



- In the kicker section, we have sinusoidal modulation of the electron beams density, which, in the CMS frame is

$$\rho = \frac{k}{2\gamma}\frac{G_{FEL}Ze}{A} sin\left(\frac{kz}{2\gamma}\right), \; A = \frac{2\pi\beta^*\varepsilon}{\gamma} \qquad (15)$$

- In the CMS frame the field is electrostatic, so solve:

$$\nabla \cdot \mathbf{E} = 4\pi\rho \qquad (16)$$

- Because Lorentz transformation doesn't change the amplitude of a longitudinal field component, we have in the lab frame:

$$E_z \cong \frac{2G_{FEL}Ze}{\beta^*\varepsilon}\gamma sin\left(\frac{k(z-vt)}{\beta}\right) \qquad (17)$$

Back-Up: Emittance definition

- The solution of 1D Hill's equation for the single particle:

$$x(s) = A\sqrt{\beta(s)}cos(\psi(s)) \tag{18}$$

- Phase-space trajectory in $x - x'$ space—ellipse:

$$\gamma x^2 + 2\alpha x x' + \beta^2(x') = A^2,\ \alpha = -\frac{1}{2}\frac{d\beta(s)}{ds},\ \gamma = \frac{1+\alpha^2(s)}{\beta(s)} \tag{19}$$

- Area of the ellipse is constant $Area = \pi A^2$
- The emittance ε is defined to be the area of the phase space ellipse $\varepsilon = \pi A^2$
- For a beam, take the amplitude of motion as a standard deviation of particle position in the beam σ: $r = \sigma = A\sqrt{\beta}$ which gives $\varepsilon = \frac{\sigma^2}{\beta}$ (sometimes $\varepsilon = \frac{\pi\sigma^2}{\beta}$)
- When a beam accelerates, the transverse beam size shrinks. The idea of invariant emittance can still be used if the emittance is scaled according to the beam energy, $\varepsilon_N = \varepsilon\beta\gamma$
- Statistical definition of emittance:

$$\varepsilon = \sqrt{< x^2 >< (x')^2 > - < xx' >^2} \tag{20}$$

Back-Up: WakeFields