Coherent electron cooling

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Cooling intense high-energy hadron beams remains a major challenge for accelerator physics. Synchrotron radiation is too feeble, while efficiency of two other cooling methods falls rapidly either at high bunch intensities (i.e. stochastic cooling of protons) or at high energies (i.e. e-cooling). Possibility of coherent electron cooling using instabilities in electron beam was discussed by Derbenev since early 1980's . this talk is a first specific scheme with complete theoretical evaluation of its performance. The scheme is based present-day accelerator technology - a high-gain free-electron laser driven by an energy recovery linac. I will present some numerical examples and results on eRHIC luminosity increases. I also will discuss a proof-of-principle experiment using R&D ERL at RHIC.

*First paper: Vladimir N. Litvinenko, Yaroslav S. Derbenev, Free-Electron Lasers and High-Energy Electron Cooling, Proc. of 29th International FEL Conference, Novosibirsk, Russia, August 2008, http://accelconf.web.cern.ch/AccelConf/f07/HTML/AUTHOR.HTM *p. 268*

Content

Why it is needed for EIC?

A bit of history

Principles of Coherent Electron Cooling (CeC)

Analytical estimations, Simulations

Proof of Principle test using R&D ERL

Contributions from George Bell, Ilan Ben-Zvi, Michael Blaskiewicz, David Bruhwiler, Alexei Fedotov, Dmitry Kayran, Eduard Pozdeyev, Gang Wang

Collaboration on Coherent Electron Cooling includes scientists from BNL, Jlab, BINP (Novosibirsk), FNAL, Dubna, UCLA, TechX, LBNL… open for others: http://www.bnl.gov/cad/ecooling/cec.asp

In eRHIC luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4\pi\beta_h^* \varepsilon_h} \cdot h\left(\frac{\sigma_s}{\beta_h^*}\right)$$

Round beams $\beta_e^* \varepsilon_e = \beta_h^* \varepsilon_h$

$$L = \gamma_h \cdot (f_c \cdot N_h) \cdot \frac{\xi_h \cdot Z_h}{\beta_h^* \cdot r_h} \cdot h\left(\frac{\sigma_s}{\beta_h^*}\right)$$

$$\boxed{\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h}}$$

$$\xi_h \to 0.02 \quad \Leftrightarrow \quad L_{p\ e} \to 0.3 \cdot 10^{34}$$

Thus, reducing (cooling) emittance of hadron beam, ε_h, allows to proportionally reduce electron beam current (Ne~ε_h). This in return reduces strain on photocathode, loss on synchrotron radiation -> means higher energy!, X-ray back-ground in detectors…. In combination with reduction of the bunch length, this also allows reduction of β* and an increase of the luminosity.

Thus, strong cooling makes eRHIC a perfect EIC!

Decrements for hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, hrs	Trad. Electron cooling hrs	Coherent Electron Cooling, hrs 1D/3D
RHIC PoP	*Au*	*40*	-	-	-	*0.02/0.06*
eRHIC	Au	130	~1	20,961 ∞	~ 1	0.015/0.05
eRHIC	**p**	**325**	**~100**	**40,246 ∞**	**> 30**	**0.1/0.3**
LHC	p	7,000	~ 1,000	13/26	∞ ∞	0.3/<1

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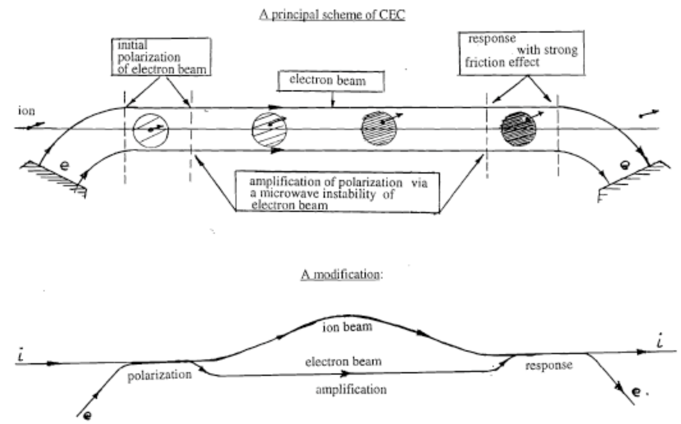
History

possibility and various options of coherent electron cooling were suggested by Yaroslav Derbenev about 27 years ago

- Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980)
- Coherent electron cooling, Ya. S. Derbenev, Randall Laboratory of Physics, University of Michigan, MI, USA, UM HE 91-28, August 7, 1991
- Ya.S.Derbenev, Electron-stochastic cooling, DESY , Hamburg, Germany, 1995 ……….



UM HE 91-28

August 7, 1991

COHERENT ELECTRON COOLING

1. Physics of the method in general

Ya. S. Derbenev

Randall Laboratory of Physics, University of Michigan

Ann Arbor, Michigan 48109-1120 USA

Conclusion

The method considered above combines principles of electron and stochastic cooling and microwave amplification. Such an unification promises to frequently increase the cooling rate and stacking of high-temperature, intensive heavy particle beams. Certainly, for the whole understanding of new possibilities thorough theoretical study is required of all principle properties and other factors of the method.

Q: What's new?

A1. Accelerator technology progressed in last 20+ years and

- energy recovery linacs with high quality e-beam
- high gain amplification in FELs at μm and nm wavelengths

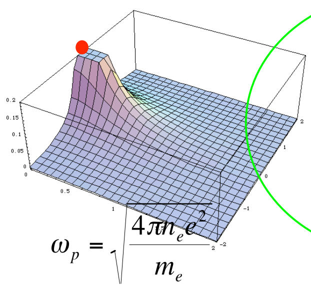
became reality in last decade

A2. A practical scheme with a complete theoretical evaluation had been developed (vl/yd) in 2007/2008

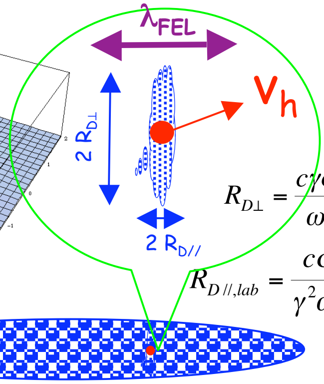
A3. Checks of most important tolerances on e-beam, hadron beam and lattice had been performed

A4. The scheme had been presented at major international forums (FEL'07 and COOL'07), at major accelerator labs (BNL, CERN, BINP, Jlab…) and passed fist tests of scrutiny

Coherent electron cooling, ultra-relativistic case ($\gamma >> 1$)

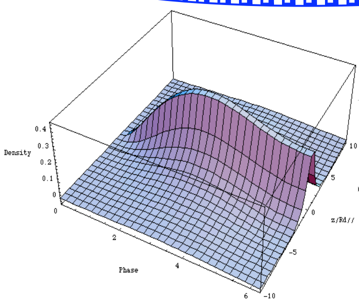


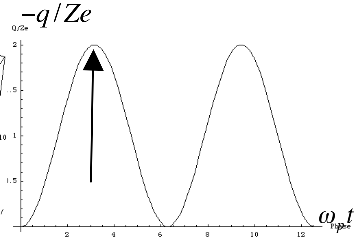
$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$



$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} > R_{D//}$$

$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_{pe}} << \lambda_{FEL}$$

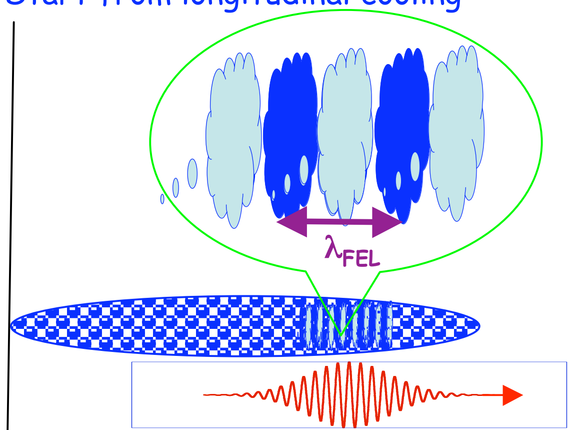




$$q = -Ze\cdot(1-\cos\omega_p t)$$

$$\varphi_1 = \omega_p L_1 / c\gamma$$

Start from longitudinal cooling



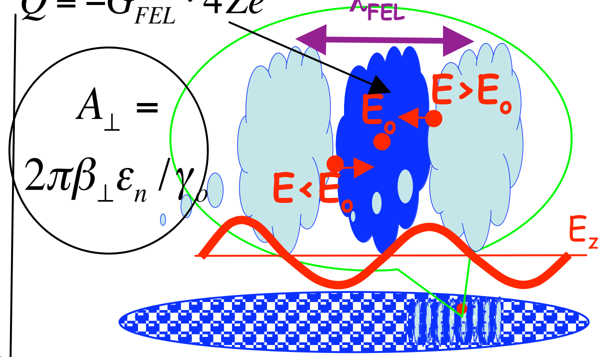
$$\lambda_{FEL} = \frac{\lambda_w}{2\gamma^2}(1+a_w^2) \quad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$

$$L_G = L_{Go}(1+\Lambda) \quad \Delta\varphi = \frac{L_{FEL}}{\sqrt{3}L_G}$$

$$G_{FEL} = e^{L_{FEL}/L_G}$$

$$Q = -G_{FEL}\cdot 4Ze$$

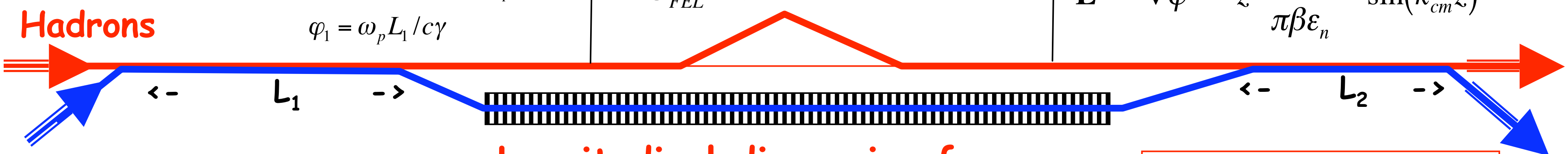
$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$



$$k_{cm} = \frac{\pi}{\gamma_o\lambda_{FEL}} \quad \boxed{\rho_{amp} = \frac{G\cdot Ze}{2\pi\beta\varepsilon_n}\cdot\frac{4k_{cm}}{\pi}\cos(k_{cm}z)}$$

$$\Delta\varphi = 4\pi\rho \Rightarrow \varphi = -\frac{8G\cdot Ze}{\pi\beta\varepsilon_n k_{cm}}\cdot\cos(k_{cm}z)$$

$$\vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\frac{8G\cdot Ze}{\pi\beta\varepsilon_n}\cdot\sin(k_{cm}z)$$



$$Q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}}\rho(z)\cos(k_{FEL}z)dz$$

$$Q_{\lambda_{FEL}}(\max) \approx -2Ze;\ \rho_k = -Ze\frac{4k}{\pi A_\perp}$$

Modulator: region 1
a quarter to a half of plasma oscillation

Longitudinal dispersion for hadrons

$$\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D = D_{free} + D_{chicane};$$

$$D_{free} = \frac{L}{\gamma^2};\ D_{chicane} = l_{chicane}\cdot\theta^2$$

Amplifier of the e-beam modulation via FEL with gain G_{FEL}~10^2-10^3

Most versatile option

$$\boxed{\Delta E_i = -\frac{8G\cdot Z^2e^2}{\pi\beta\varepsilon_n}L_2\cdot\sin\left(k_{FEL}D\frac{E-E_o}{E_o}\right)\cdot\left(\frac{\sin\varphi_2}{\varphi_{p2}}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2}$$

Kicker: region 2, less then a quarter of plasma oscillation

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Completely Analytical Solution

© Michael Blaskiewicz, Gang Wang - to be published in Phys. Rev. B
In full agreement with the model used for coherent electron

$$f_0(\vec{v}) = \frac{1}{\pi^2 \sigma_x \sigma_y \sigma_z} \frac{1}{\left(1 + \frac{v_x^2}{\sigma_x^2} + \frac{v_y^2}{\sigma_y^2} + \frac{v_z^2}{\sigma_z^2}\right)^2}$$

The solution in x space can be obtained by Fourier transform.

$$\tilde{n}_1(\vec{x}, t) = \frac{Z_i \omega_p t \sin(\omega_p t)}{\pi^2 \sigma_x \sigma_y \sigma_z \left(t^2 + \frac{(x + v_{0x} t)^2}{\sigma_x^2} + \frac{(y + v_{0y} t)^2}{\sigma_y^2} + \frac{(z + v_{0z} t)^2}{\sigma_z^2}\right)^2}$$

If one uses the normalized variable

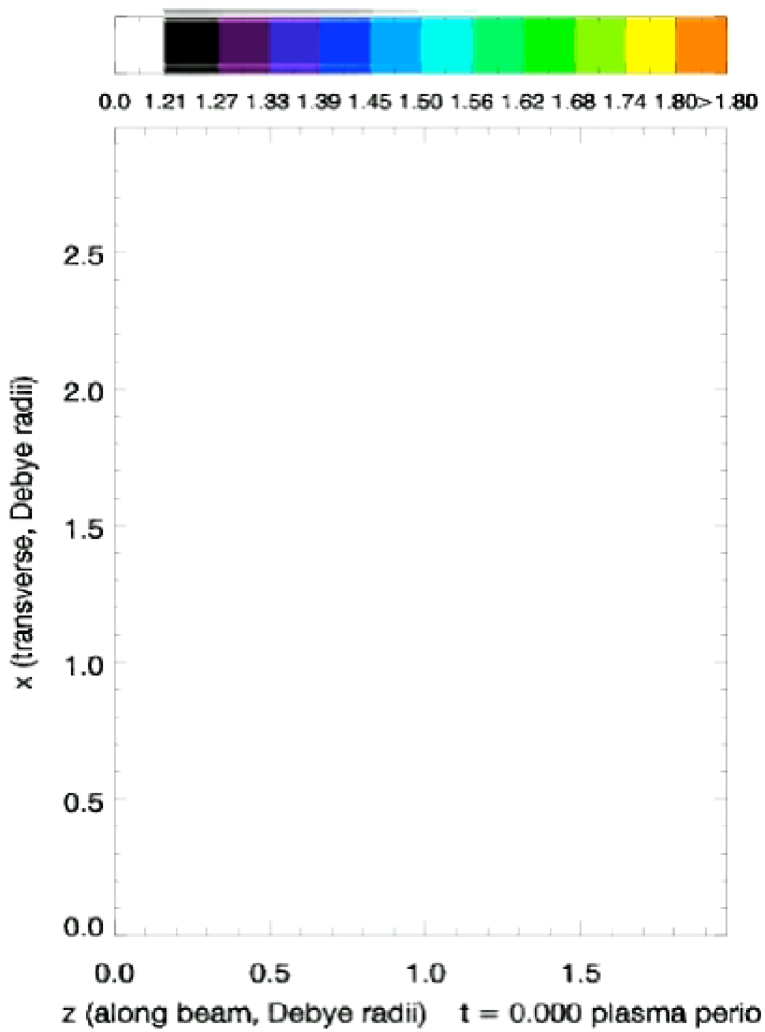
$$\psi \equiv \omega_p t \qquad \bar{v}_{0i} = \frac{\vec{v}_{0i}}{\sigma_i} \qquad \bar{x}_i = \frac{x_i}{r_{Di}}$$

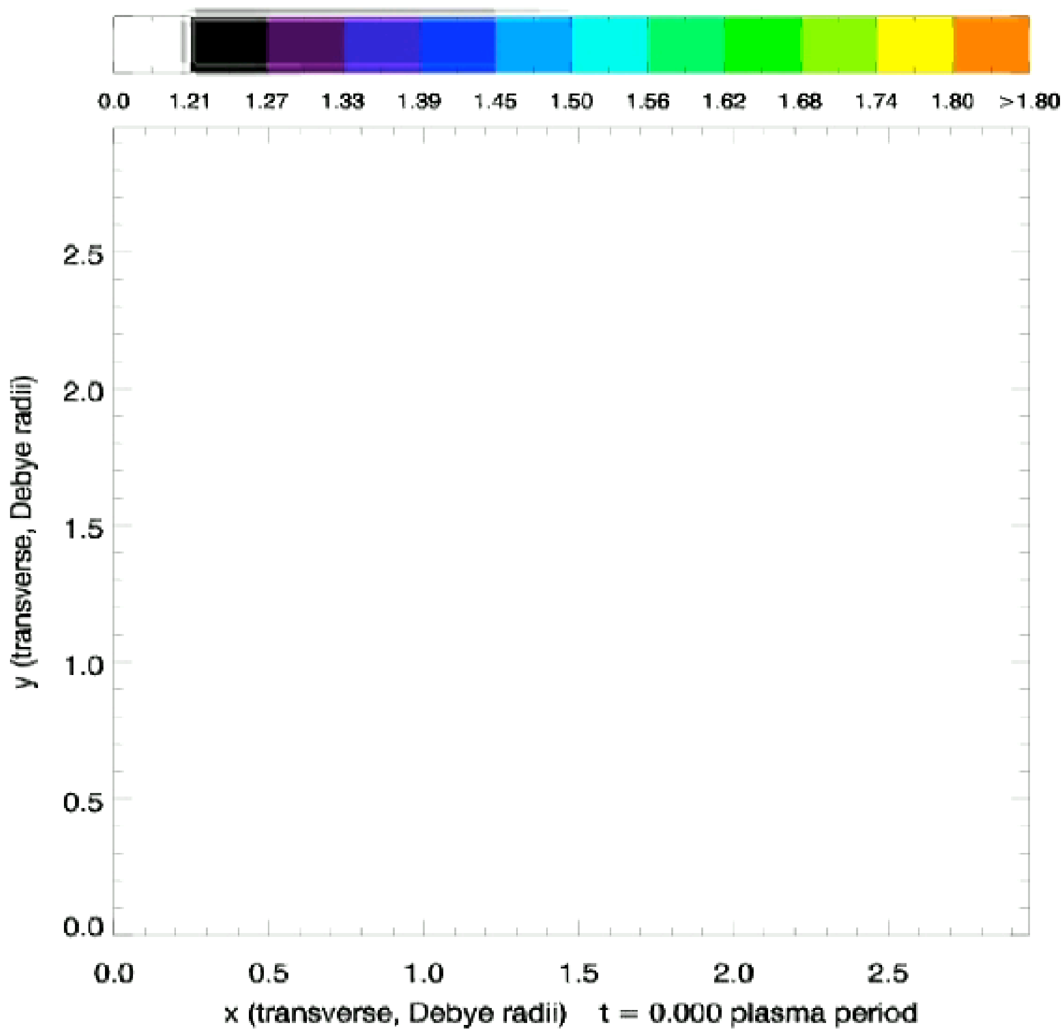
the electron density fluctuation is

$$\tilde{n}_1(\vec{x}, t) = \frac{Z_i}{\pi^2 r_{Dx} r_{Dy} r_{Dz}} \int_0^{\psi} \frac{\psi_1 \sin(\psi_1) d\psi_1}{\left(\psi_1^2 + (\bar{x} + \bar{v}_{0x}\psi_1)^2 + (\bar{y} + \bar{v}_{0y}\psi_1)^2 + (\bar{z} + \bar{v}_{0z}\psi_1)^2\right)^2}$$

which can be expressed into sum of sine integral.

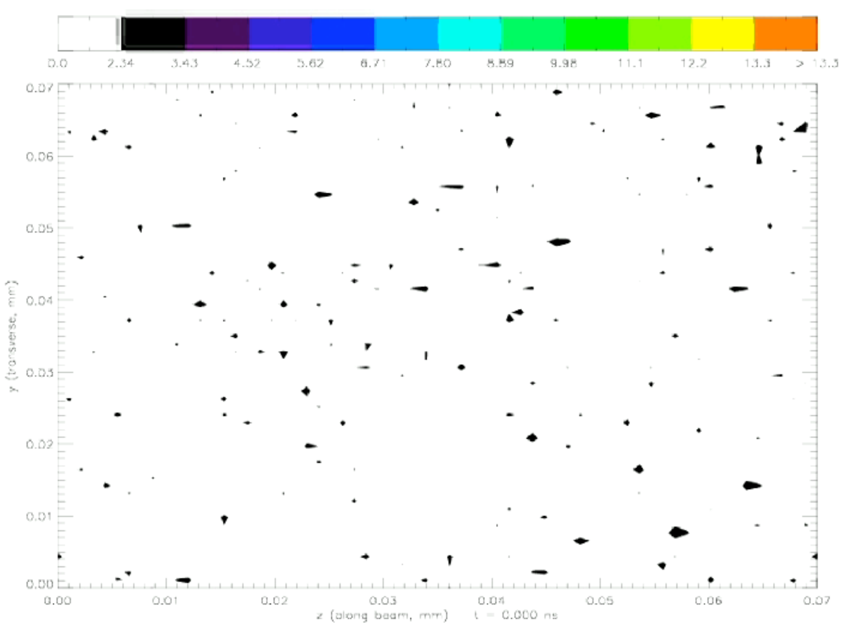
R=3; Z=0; T=0 – Asymmetry of electron velocity distribution → pancake-shaped wake

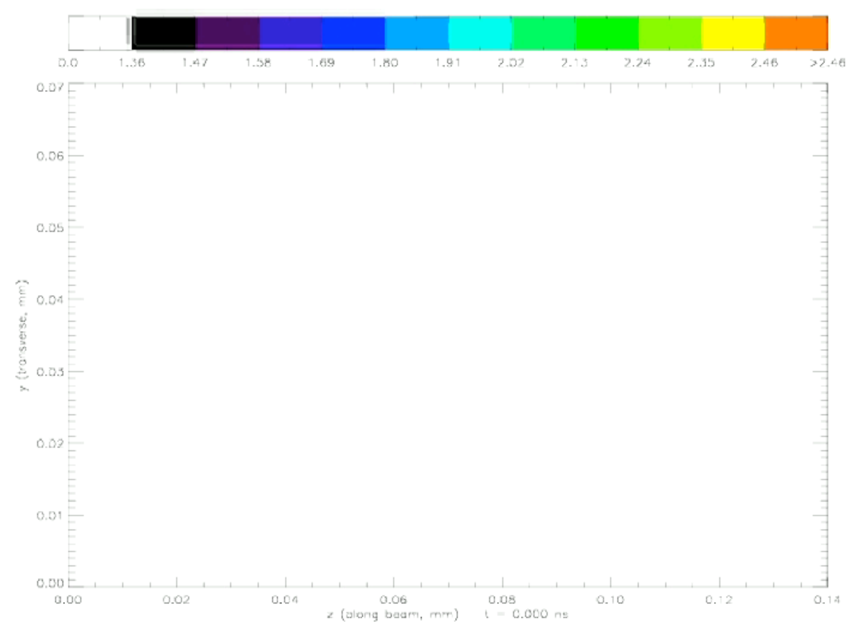




Parameter #	Value	Comments
Relative ion velocity	3.0E5 m/sec	The ion is moving in the z direction (parallel to the beam)
Interaction Distance	10 m	In the lab frame.
Interaction Time (tau)	3.1E-10 sec	In the beam frame.
Box Size (z)	1.4E-4 m	This is the length of the simulation along the horiontal (z) axis. This is about 50% larger than vrel*tau = 9.3E-5 m.
Box Size (x)	7.0E-5 m	This is the length of the simulation along the vertical (x) axis.
Density Plot Slice (y)	2.1E-6 m	A thin slice around y=0 was taken to create the density plot. In the actual simulation the y Box Size is the same as the x Box Size.
Electron Density	8.10E+15 e-/m^3	

Vx (rms) = Vy (rms) = 2.8E4 m/s, Vz (rms) 9.0E3 m/s

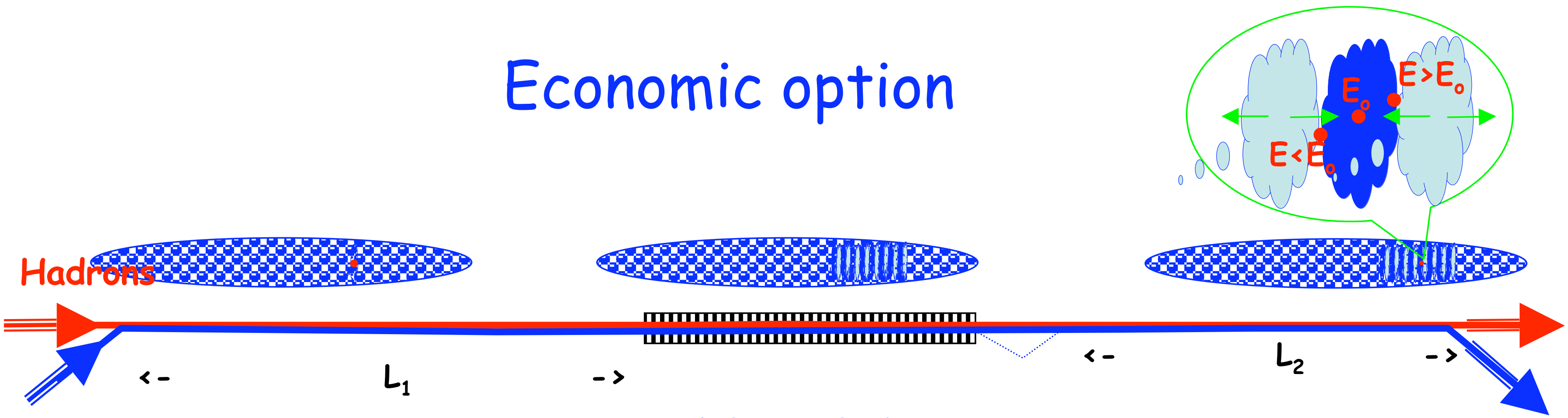




Note: Given the density and box size above, the number of actual electrons in the slice shown is only_8.10E15 e-/m^3)(5.3E-5 m)(2.1E-6 m)(1.0E-4 m) = 90_n order to get reasonable statistics, each electron was split into N microparticles having the same charge/mass ratio. In the simulations, N=3500. An individual wake behind a gold ion will be much noisier

Coherent electron cooling, ultra-relativistic case ($\gamma >> 1$)

Economic option



Electrons

Modulator:region 1
a quarter to a half of plasma oscillation

Amplifier of the e-beam modulation via High Gain FEL and

Longitudinal dispersion for hadrons

Kicker: region 2

Electron density modulation is amplified in the FEL and made into a train with duration of $N_c \sim L_{gain}/\lambda_w$ alternating hills (high density) and valleys (low density) with period of FEL wavelength λ. Maximum gain for the electron density of HG FEL is ~ 10^3.

$$v_{group} = (c + 2v_{//})/3 = c\left(1 - \frac{1 + a_w^2}{3\gamma^2}\right) = c\left(1 - \frac{1}{2\gamma^2}\right) + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right) = v_{hadrons} + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right)$$

Economic option requires: $2a_w^2 < 1$!!!

Analytical formula for damping decrement

- 1/2 of plasma oscillation in the modulator creates a pancake of electrons with the charge -2Ze
- electron clamp is well within $\Delta z \sim \lambda_{FEL} / 2\pi$
- gain in SASE FEL is $G \sim 10^2\text{-}10^3$
- electron beam is wider than $2\gamma_o \lambda_{FEL}$ - it is 1D field
- Length of the region 2 is ~ beta-function

$$\zeta = -\frac{\Delta E_i}{E - E_o} = A \cdot \frac{L_2}{\beta} \cdot \chi \cdot \mathrm{sinc}(\varphi_3) \cdot \mathrm{sinc}\varphi_2 \cdot \left(\sin\frac{\varphi_1}{2}\right)^2$$

$$A = \frac{8G}{\pi} \cdot \frac{Z^2}{A} \cdot \frac{r_p}{\varepsilon_{n,h}\sigma_\varepsilon}; \quad \chi = k_{FEL} D \cdot \sigma_\varepsilon;$$

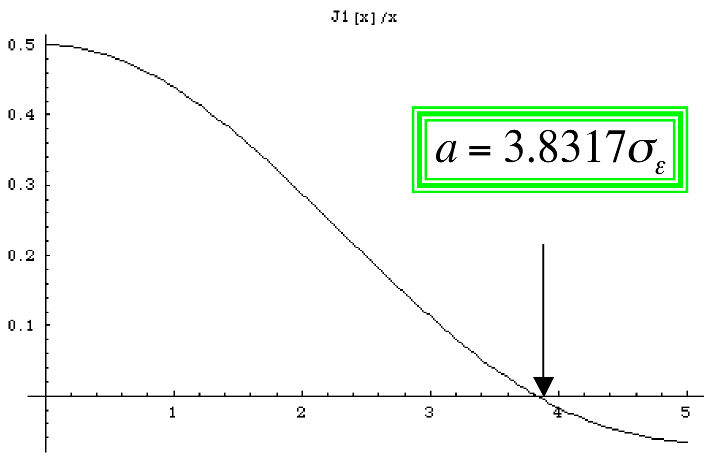
$$\mathrm{sinc}(\varphi) = \sin(\varphi)/x; \ \varphi_3 = k_{FEL} D \varepsilon; \quad \varepsilon = \frac{E - E_o}{E_o}$$

$$\delta = a \cdot \sin\Omega_s t$$

$$\langle \delta^2 \rangle' = -\left\langle 2A \cdot a^2 \cdot \cos^2 \Omega_s t \cdot \sin\left(\frac{a}{\sigma_\varepsilon} \cdot \chi \cdot \sin\Omega_s t\right)\right\rangle$$

$$= -2A \cdot \langle \delta^2 \rangle \cdot J_1\left(\chi \cdot \frac{a}{\sigma_\varepsilon}\right)$$

$$\boxed{\frac{L_2}{\beta} \cdot \chi \cdot \mathrm{sinc}(\varphi_3) \cdot \mathrm{sinc}\varphi_2 \cdot \left(\sin\frac{\varphi_1}{2}\right)^2 \sim 1}$$



$$\boxed{a = 3.8317\sigma_\varepsilon}$$

$$\boxed{\chi = 1}$$

Beam-Average decrement

$$\int \frac{2J_1(x)}{x} e^{-x^2/2} dx = 0.889$$

ε_L

$$\langle \zeta_{CeC} \rangle = \zeta \frac{\sigma_{\tau,e}}{\sigma_{\tau,h}} = \kappa \cdot \frac{8G}{\pi} \cdot \frac{Z^2}{A} \cdot \frac{r_p \cdot \sigma_{\tau,e}}{\varepsilon_{n,h}(\sigma_\varepsilon \cdot \sigma_{\tau,h})}; \ \kappa \sim 1$$

- Electron bunches are usually much shorter and cooling time for the entire bunch is proportional to the bunch-lengths ratios

Analytical formula for damping decrement

$$\left\langle \zeta_{CeC} \right\rangle = \zeta \frac{\sigma_{\tau,e}}{\sigma_{\tau,h}} = \kappa \cdot \frac{8G}{\pi} \cdot \frac{Z^2}{A} \cdot \frac{r_p \cdot \sigma_{\tau,e}}{\varepsilon_{n,h}\left(\sigma_\varepsilon \cdot \sigma_{\tau,h}\right)}; \ \kappa \sim 1$$

Note that damping decrement:

a) **does not depend on the energy of particles !**

b) **Improves as cooling goes on**

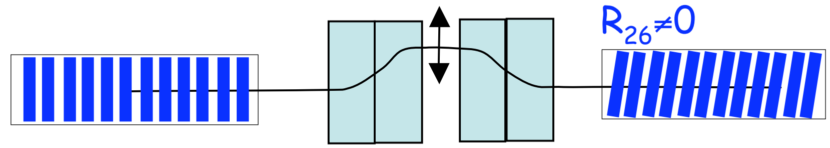
$$\left\langle \zeta_{CeC} \right\rangle \sim \frac{1}{\varepsilon_{long,h}\varepsilon_{trans,h}}$$

!!!! Protons in RHIC & LHC

Transverse cooling

- Transverse cooling can be obtained by using coupling with longitudinal motion via transverse dispersion
- Sharing of cooling decrements is similar to sum of decrements theorem for synchrotron radiation damping, i.e. decrement of longitudinal cooling can be split into appropriate portions to cool both transversely and longitudinally: $J_s+J_h+J_v=1$
- Vertical (better to say the second eigen mode) cooling is coming from transverse coupling

Non-achromatic chicane installed at the exit of the FEL before the kicker section turns the wave-fronts of the charged planes in electron beam



$$\delta(ct) = -R_{26}\cdot x$$

$$\Delta \mathbf{E} = -eZ^2\cdot E_o\cdot L_2\cdot \sin\left\{k\left(D\frac{\mathbf{E}-\mathbf{E}_o}{\mathbf{E}_o} + R_{16}x' - R_{26}x + R_{36}y' + R_{46}y\right)\right\};$$

$$\Delta x = -D_x\cdot eZ^2\cdot E_o\cdot L_2\cdot kR_{26}x + ...$$

$$\zeta_\perp = J_\perp \zeta_{CeC};\quad \zeta_{//} = (1-2J_\perp)\zeta_{CeC};$$

$$\frac{d\varepsilon_x}{dt} = -\frac{\varepsilon_x}{\tau_{CeC\perp}};\frac{d\sigma_\varepsilon{}^2}{dt} = -\frac{\sigma_\varepsilon{}^2}{\tau_{CeC\,//}}$$

$$\tau_{CeC\perp} = \frac{1}{2J_\perp\zeta_{CeC}};\ \tau_{CeC\perp} = \frac{1}{2(1-2J_\perp)\zeta_{CeC}};$$

Coherent e-Cooling for eRHIC

(protons are the main challenge)

Main Parameters	CeC	
Modulator Length	15	m
Kicker length	5	m
Peak current, e	100.0	A
Amplification	200.00	
Wavelength	500	nm
λ_w	5	cm
FEL bandwidth	0.1	

Cooling time		
Emittance, Full bunch	0.086	hrs
Ampl, Full bunch	0.171	hrs
Local	50.23	sec
Length of the system	32.49	m
FEL length	12.49	m
FEL gain length	0.99	m

Hadrons		
Z	1	
A	1	
Energy per nucleon	**325**	GeV
Energy per nucleon	3.250000E+11	eV
γ	346.38	=
N, part/bunch	**2.00E+11**	
Charge	32.04	nC
Bunch length	0.433	nsec
Bunch lengt, RMS	0.130	m
Peak current	29.50	A
Emmitance, norm	**2**	mm mrad
Emmitance, m rad	5.77398E-09	
σE/E	4.00E-04	

Electrons		
	1	
Energy	0.177	GeV
Energy	1.770E+08	eV
γ	346.38	
N, part/bunch	3.12E+10	
Charge	**5.0**	nC
Bunch length	0.050	nsec
Bunch lengt, full	0.015	m
Peak current	100.0	A
Emittance, norm, RMS	**5**	mm mrad
Emittance, RMS	1.443E-08	m rad
σE/E	2.26E-04	
σ_E	4.00E+04	eV
Long emittance	2.000E-06	eV sec

Main advantages of ERL + cooling

$$L = \gamma_p \frac{f_{col} N_p}{\beta_p^* r_p} \xi_p \qquad \xi_p = \frac{r_p}{4\pi} \cdot \frac{N_e}{\varepsilon_{p\ norm}};$$

$$\frac{N_e}{\varepsilon_{p\ norm}} = const \Rightarrow \xi_p = const; \quad L = const$$

$$N_e \propto \varepsilon_{p\ norm} \Rightarrow I_e \propto \varepsilon_{p\ norm} \Rightarrow P_{SR} \propto \varepsilon_{p\ norm}!$$

- Main point is very simple: if one cools the emittance of a hadron beam in electron-hadron collider, the intensity of the electron beam can be reduced proportionally without any loss in luminosity or increase in the beam-beam parameter for hadrons
- Hadron beam size is reduced in the IR triplets - hence it opens possibility of further β* squeeze and increase in luminosity
- Electron beam current goes down -> relaxed gun!, losses for synchrotron radiation going down, X-ray background in the detectors goes down....

Stationary state: IBS vs. CeC

$$\frac{\sigma_\varepsilon^2}{\tau_{IBS//}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s} \left\langle \frac{f(\chi_m)}{\beta_y v} \right\rangle; \quad \frac{\varepsilon_x}{\tau_{IBS\perp}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s} \left\langle \frac{H}{\beta_y^{1/2}} f(\chi_m) \right\rangle; \kappa = 1$$

$$f(\chi_m) = \int_{\chi_m}^{\infty} \frac{d\chi}{\chi} \ln\left(\frac{\chi}{\chi_m}\right) e^{-\chi}; \ \chi_m = \frac{r_c m^2 c^4}{b_{\max} \sigma_E^2}; b_{\max} \cong n^{-1/3}; \ r_c = \frac{e^2}{mc^2}; \quad (e->Ze; m->Am)$$

J.LeDuff, "Single and Multiple Touschek effects", Proceedings of CERN Accelerator School, Rhodes, Greece, 20 September - 1 October, 1993, Editor: S.Turner, CERN 95-06, 22 November 1995, Vol. II, p. 57

$$X = \frac{\varepsilon_x}{\varepsilon_{xo}}; \ S = \left(\frac{\sigma_s}{\sigma_{so}}\right)^2 = \left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

$$\frac{dX}{dt} = \frac{1}{\tau_{IBS\perp}} \frac{1}{X^{3/2} S^{1/2}} - \frac{\xi_\perp}{\tau_{CeC}} \frac{1}{S};$$

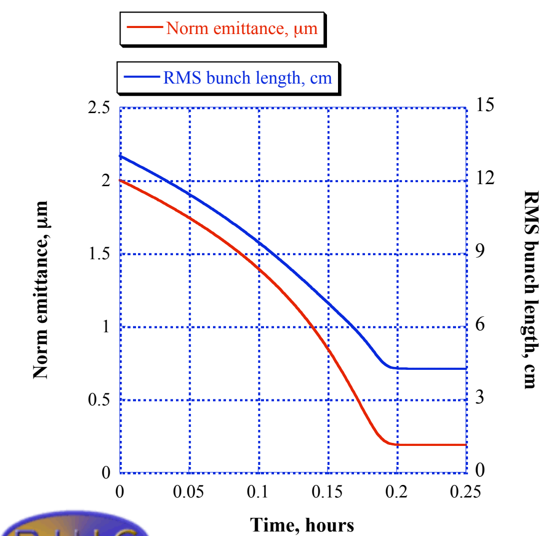
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}} \frac{1}{X^{3/2} Y} - \frac{1 - 2\xi_\perp}{\tau_{CeC}} \frac{1}{X};$$

$$\varepsilon_{xn0} = 2\,\mu m; \ \sigma_{s0} = 13\ cm; \ \sigma_{\delta 0} = 4 \cdot 10^{-4}$$
$$\tau_{IBS\perp} = 4.6\ \ hrs; \ \tau_{IBS//} = 1.6\ \ hrs;$$

IBS in RHIC for eRHIC, 250 GeV, N_p=2·10^{11} Beta-cool, ©A.Fedotov

Stationary solution:

$$X = \frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}} \frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}}; \quad S = \frac{\tau_{CeC}}{\tau_{IBS//}} \cdot \sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}} \cdot \sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$



$$\varepsilon_{xn} = 0.2\,\mu m; \ \sigma_s = 4.9\ \ \text{cm}$$

This allows

a) keep the luminosity as it is

b) reduce polarized beam current down to 25 mA (5 mA for e-I)

c) increase electron beam energy to 20 GeV (30 GeV for e-I)

d) increase luminosity by reducing β* from 25 cm down to 5 cm

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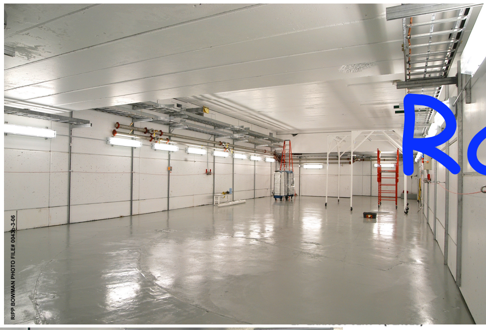
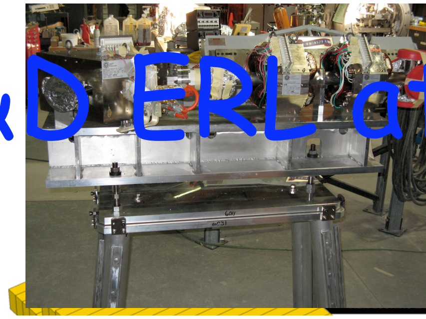
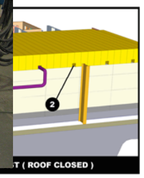
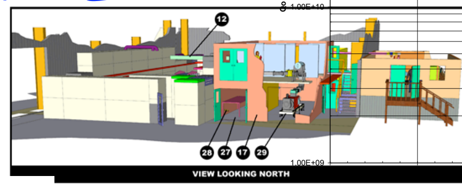
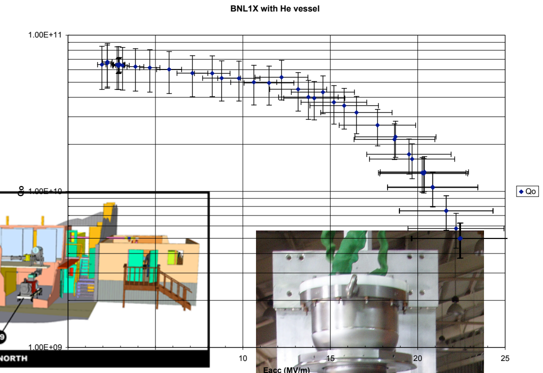
R&D ERL at BNL











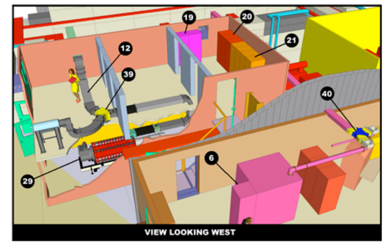
E_{inj} =2.5-.3.5 MeV

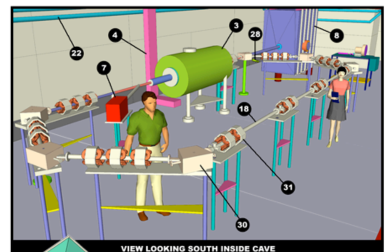
E_{total} = 25 MeV, I_{max} = 0.5 A

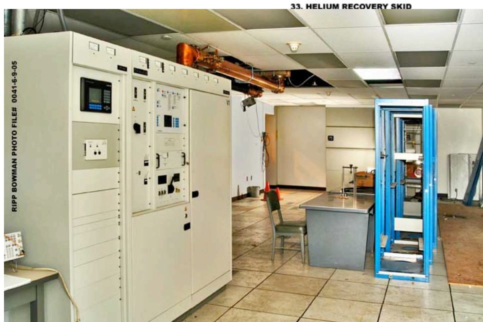
ε_n ~ 2 mm mrad @ 1.4 nC

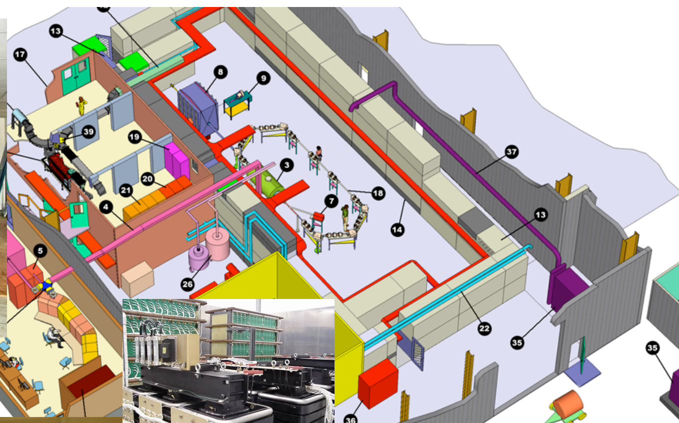
Single Loop, SRF Gun

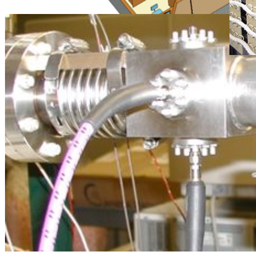
5 cell SRF linac, 703.75 MHz

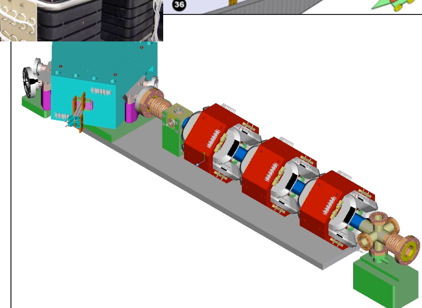


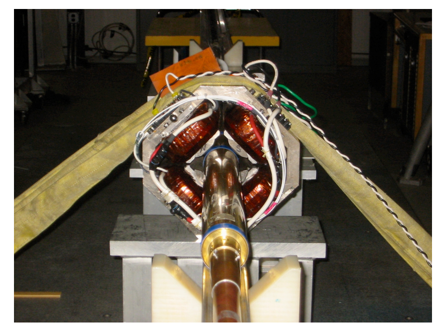












RHIC
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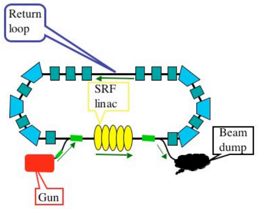

PoP test using BNL R&D ERL: Au ions in RHIC with 40 GeV/n, L_{cooler} = 14 m

N per bunch	$1\ 10^9$	Z, A	79, 197
Energy Au, GeV/n	40	γ	42.63
RMS bunch length, nsec	3.2	Relative energy spread	0.037%
Emittance norm, μm	2.5	$\beta_\perp$, m*	8
Energy e^-, MeV	21.79	Peak current, A	60
Charge per bunch, nC	4 x 1.4	Bunch length, RMS, psec	83
Emittance norm, μm	4	Relative energy spread	0.15%
$\beta_\perp$, m	5	L_1 (lab frame) ,m	4
ω_{pe}, CM, Hz	$5.03\ 10^9$	Number of plasma oscillations	0.256
$\lambda_{D\perp}$, μm	611	$\lambda_{D\|\|}$, μm	3.3
λ_{FEL}, μm	**18**	**λ_w, cm**	**5**
a_w	**0.555**	**L_{Go}, m**	**0.67**
Amplitude gain =150, L_w , m	**6.75 (7)**	**L_{G3D}, m**	**1.35**
L_2 (lab frame) ,m	3	Cooling time, local, minimum	0.05 minutes
N_{turns}, Ñ, 5% BW	$8\ 10^6 > 6\ 10^4$	Cooling time, beam, min	2.6 minutes

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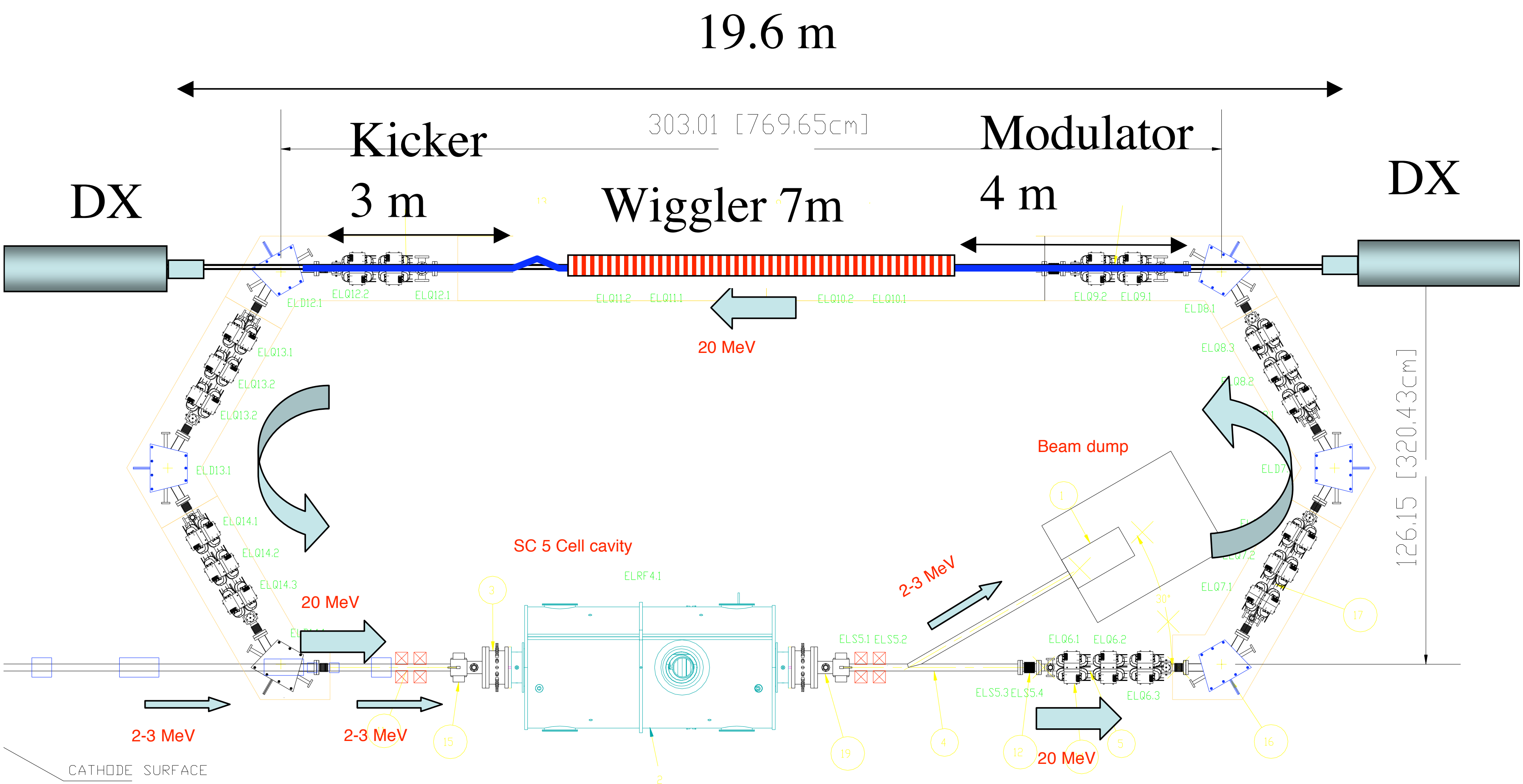
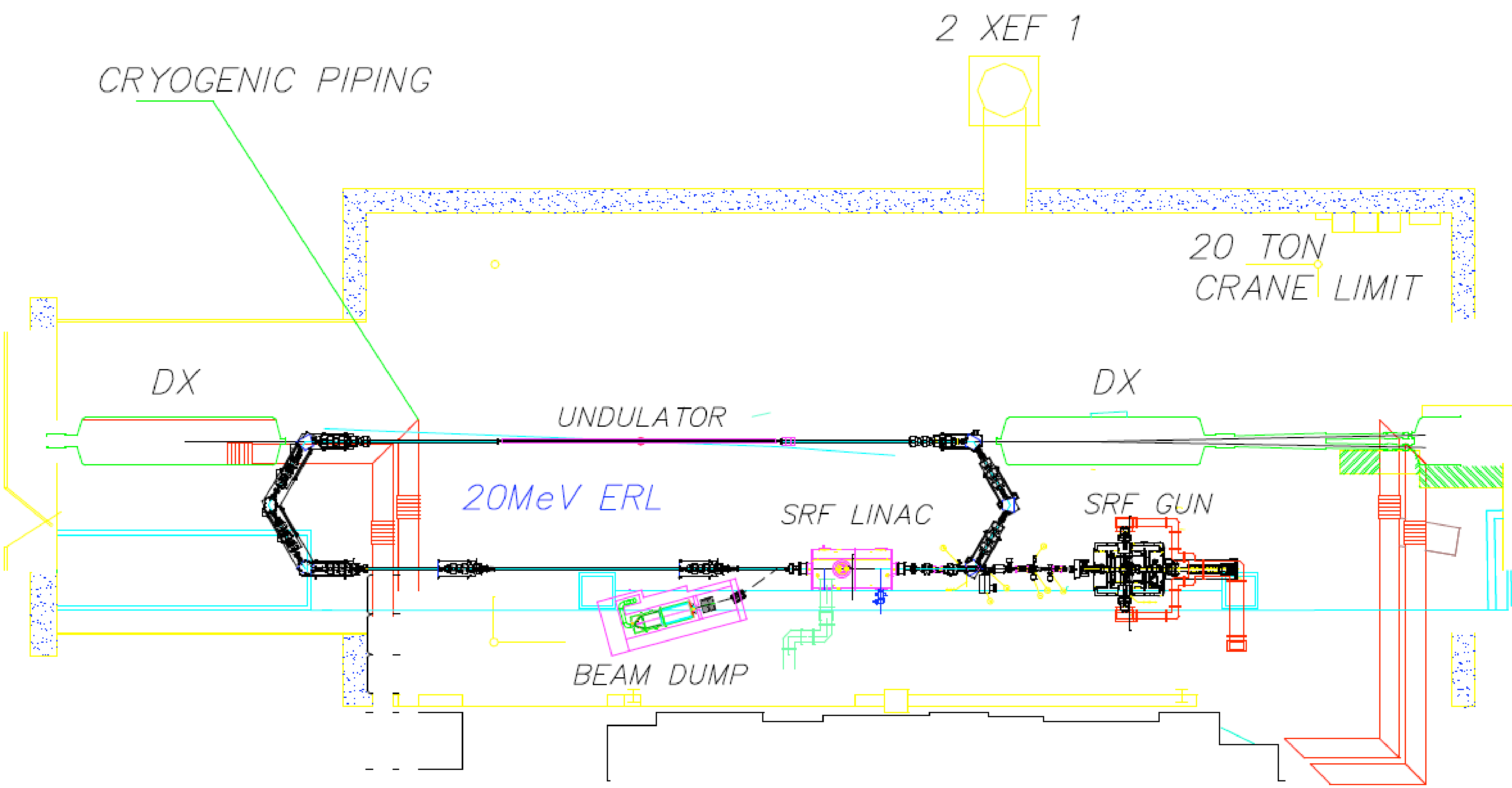
IR-2 layout for Coherent Electron Cooling proof-of-principle experiment



IR-2 for proof-of-principle for CEC



See presentation by D.Kayran at 3:10 p.m., Tue, May 20
Parallel session: Accelerators

Conclusions

- Coherent electron cooling is very promising method for significant increases in luminosity and energy reach in eRHIC
- It could be the key for reducing electron beam current from polarized gun and increased reach in eRHIC c.m. energy
- We plan a proof of principle experiment of coherent electron cooling with Au ions in RHIC at ~ 40 GeV/n and existing R&D ERL as part of EIC R&D

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