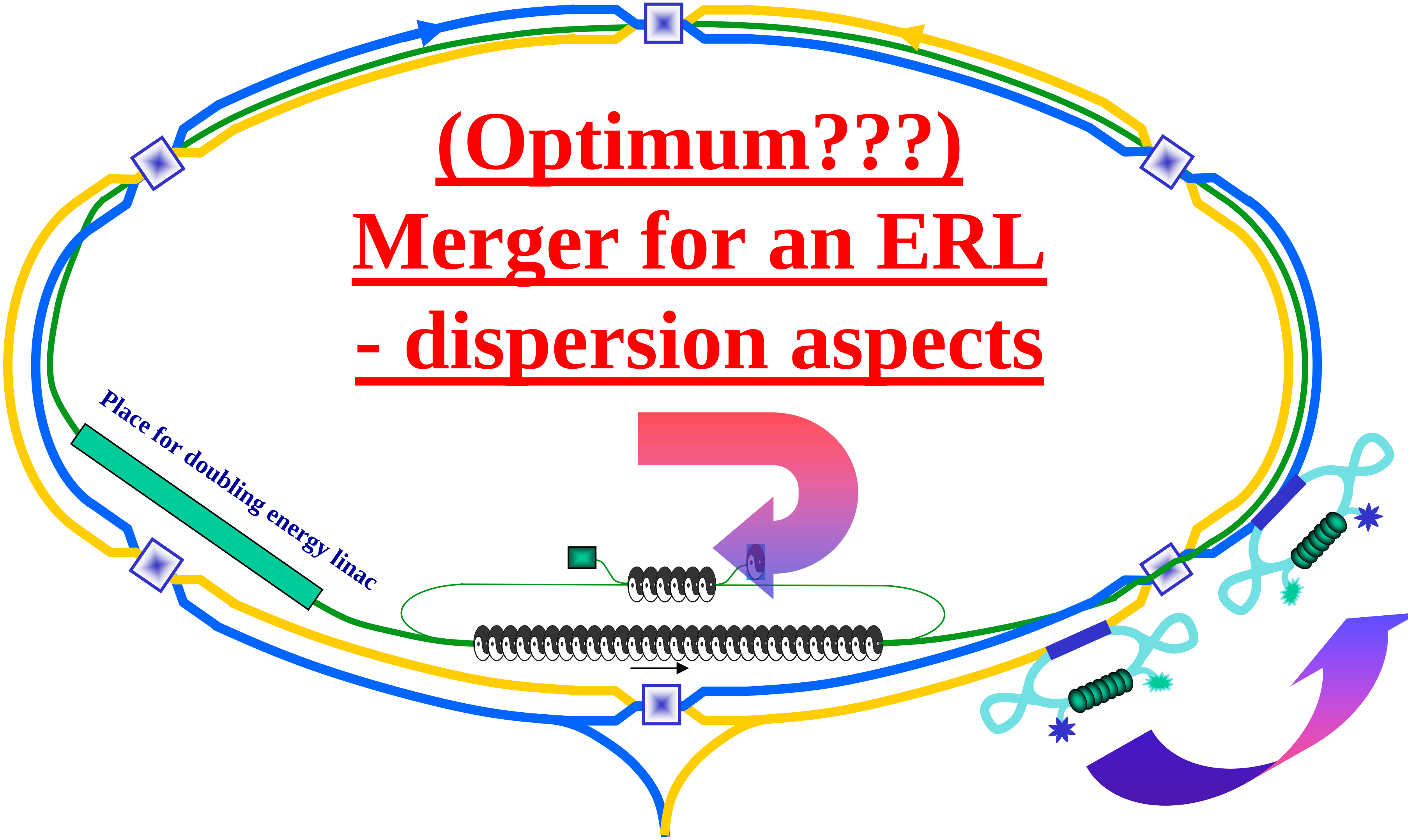
(Optimum???) Merger for an ERL - dispersion aspects



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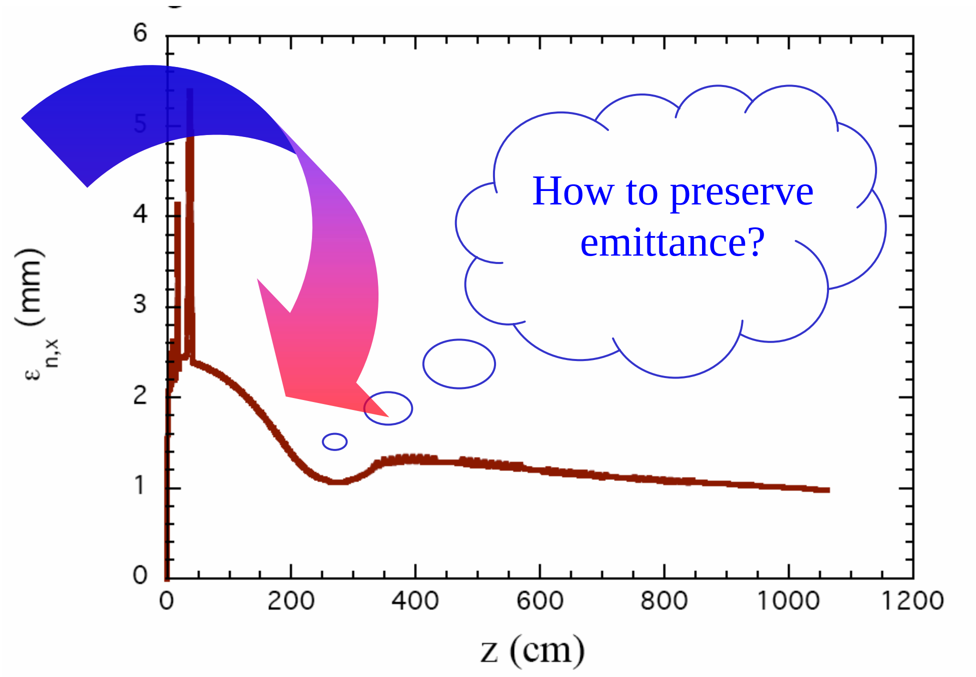
Motivation

- Each ERL has at least one merging system, which includes dipoles ↑ Potential for the mixing of longitudinal and transverse motions
- Low energy injection into high current ERL is strongly desirable: (a) no residual radiation; (b) less MWs in RF power ↑ Strong space charge effects in a merger
- Emittance compensation schemes do not allow using a strong focusing in a merger ↑ Necessity to use of a smooth optics

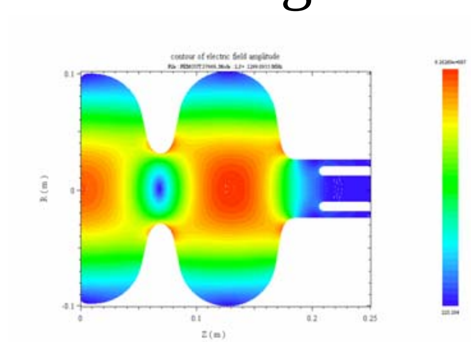
EPAC 2004: AN ULTRA-HIGH BRIGHTNESS, HIGH DUTY FACTOR, SUPERCONDUCTING RF PHOTOINJECTOR,

M. Ferrario, J.B. Rosenzweig, G. Travish, J. Sekutowicz, W. D. Möller

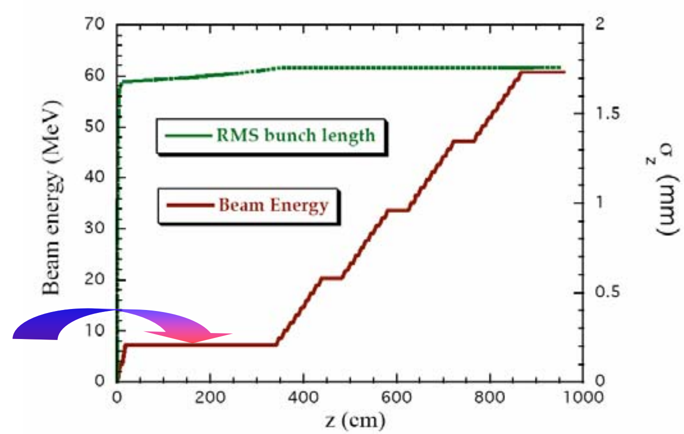
Merger is going here



1.6 cell gun



Merger is going here



QuickTime™ and a
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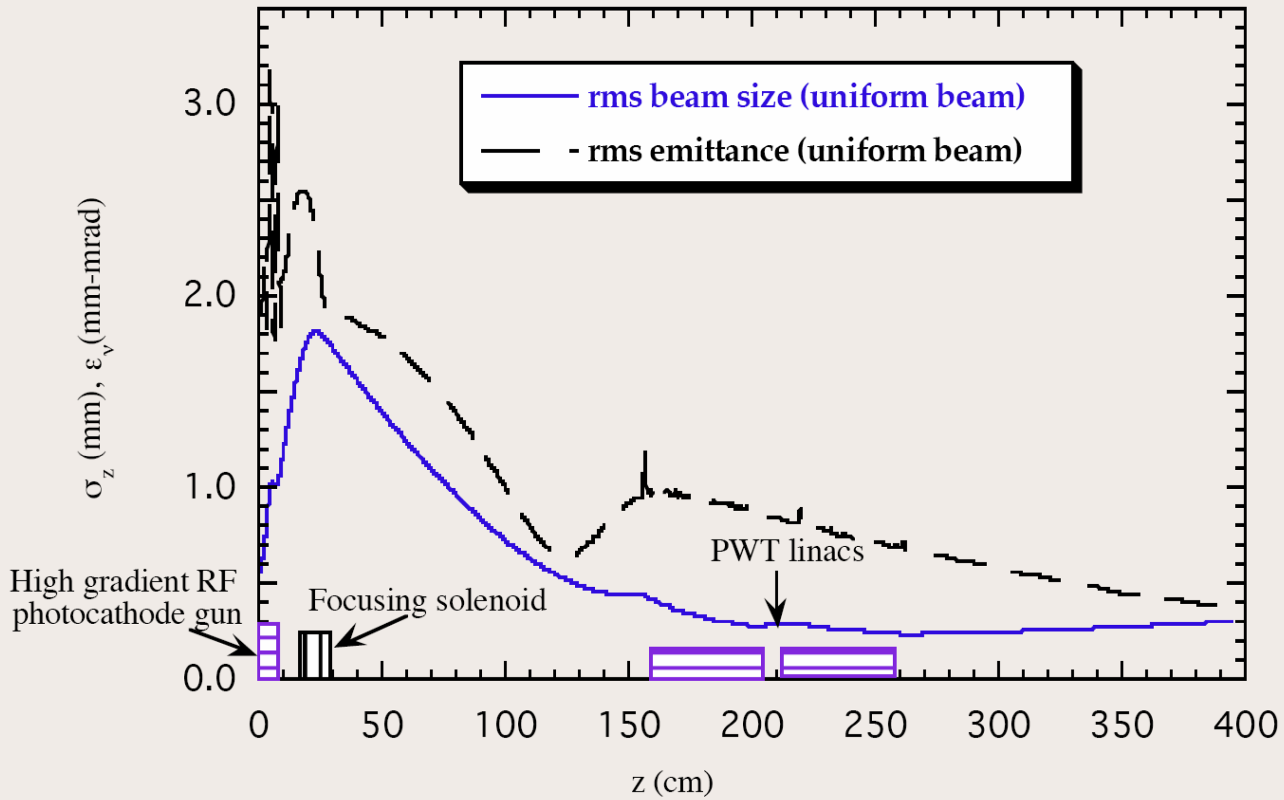
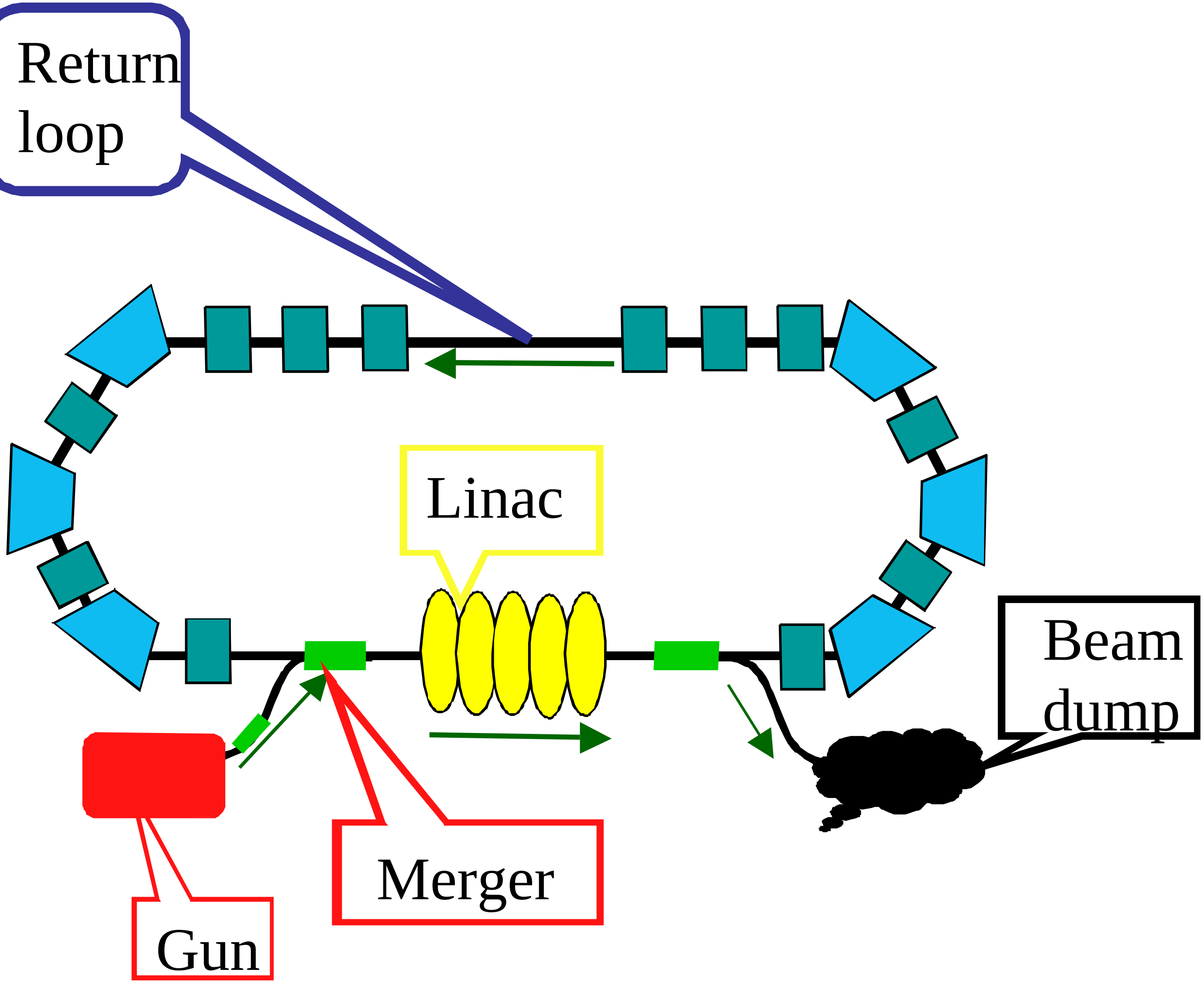
are needed to see this picture.



Multiparticle simulations (UCLA PARMELA)

Showing emittance oscillations and minimization

An ERL



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Emittance compensation

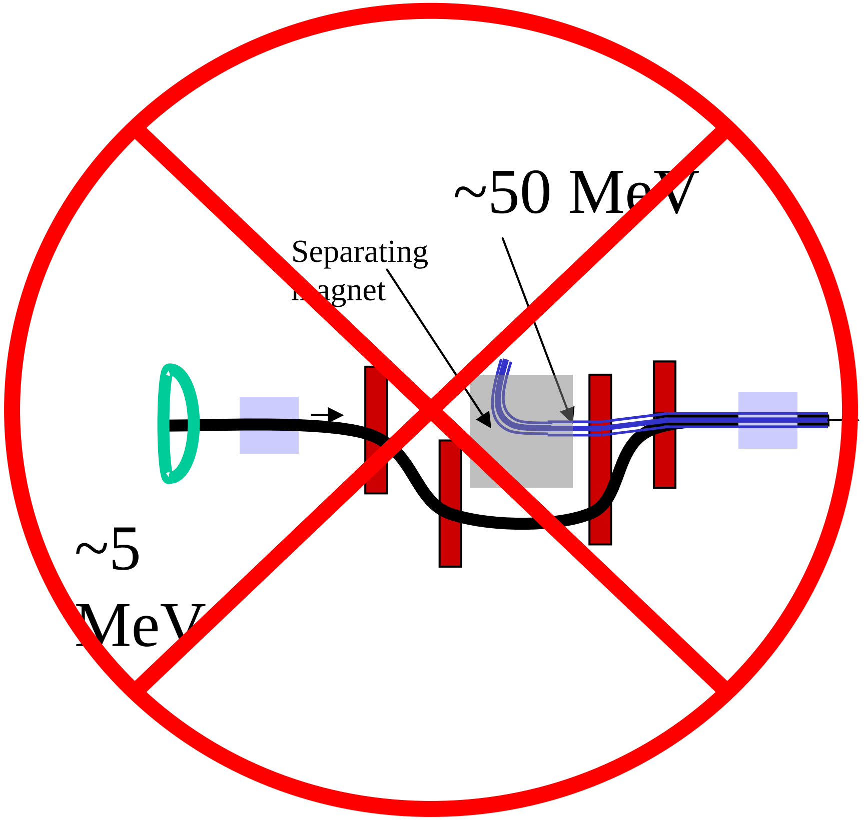
- After initial acceleration, space-charge field is mainly transverse (beam is long in rest frame).
- Both radial and longitudinal forces scale as γ^{-2}
- Transverse force dependent almost exclusively on local value of current density I/σ^2

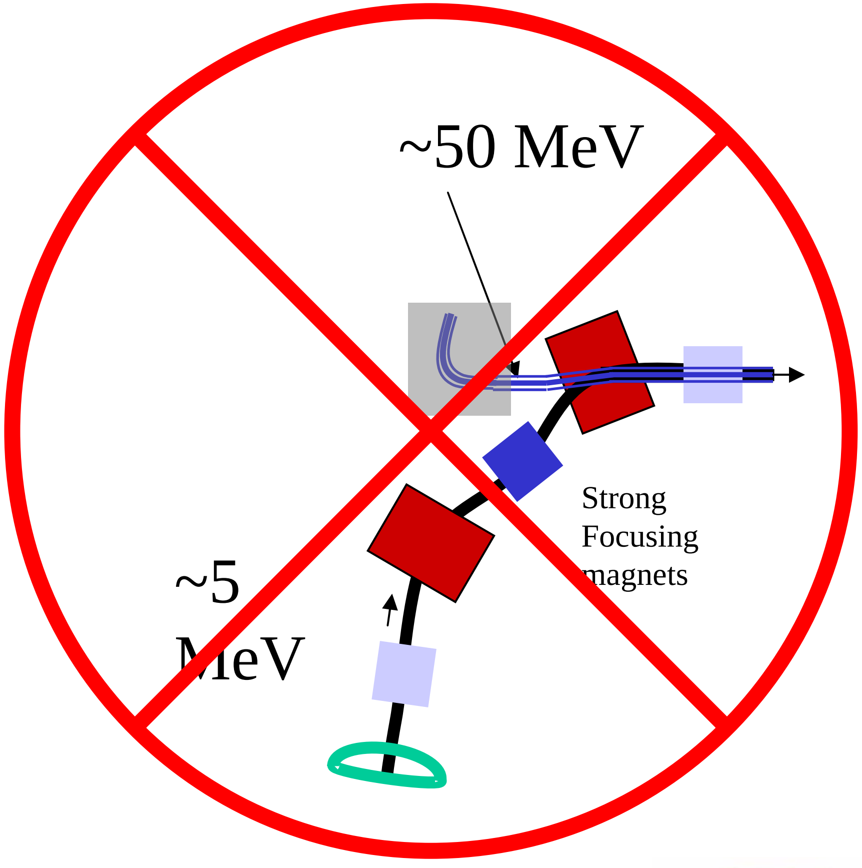
$$\sigma_x''(\zeta,s) + \kappa_\beta^2 \cdot \sigma_x(\zeta,s) = \frac{r_e \lambda(\zeta)}{2\gamma^3 \sigma_x(\zeta,s)} + \frac{\varepsilon_{n,x}^2}{2\gamma \sigma_x{}^3(\zeta,s)}$$

$$\zeta = s - v_b t$$

$$I(\zeta) = \lambda(\zeta) \cdot v_b$$

Simple-minded merger for ERL - an achromatic system simply does not work

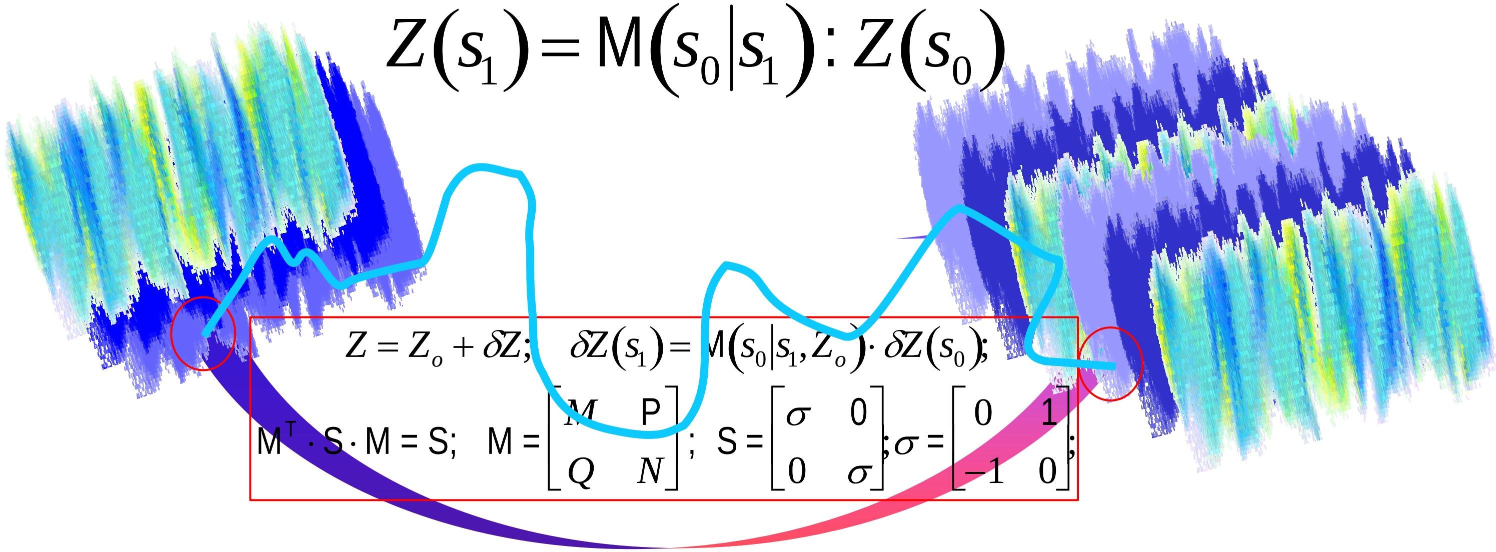




QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

New Emittance spoilers - nonlinear coupling between longitudinal motion and transverse motion in the bending plane

$$Z = \begin{pmatrix} x \\ x' \\ \xi \\ \delta \end{pmatrix} \qquad Z(s_1) = \mathrm{M}(s_0|s_1) : Z(s_0)$$



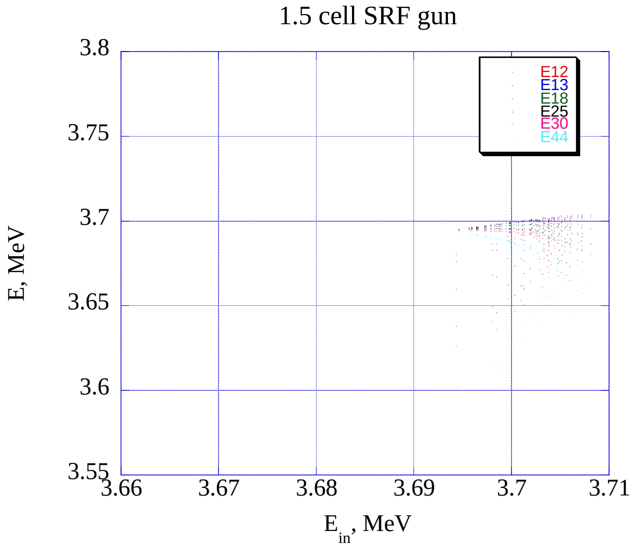
$$Z = Z_o + \delta Z; \quad \delta Z(s_1) = \mathrm{M}(s_0|s_1, Z_o) \cdot \delta Z(s_0);$$

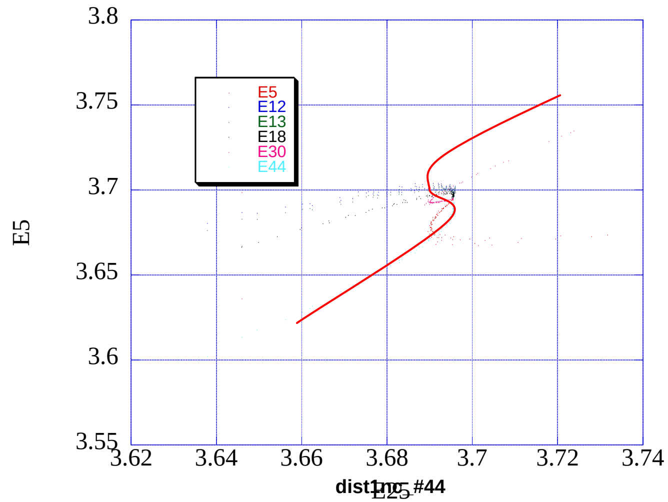
$$\mathrm{M}^{\mathrm{T}} \cdot \mathrm{S} \cdot \mathrm{M} = \mathrm{S}; \quad \mathrm{M} = \begin{bmatrix} M & \mathrm{P} \\ Q & N \end{bmatrix}; \quad \mathrm{S} = \begin{bmatrix} \sigma & 0 \\ 0 & \sigma \end{bmatrix}; \sigma = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix};$$

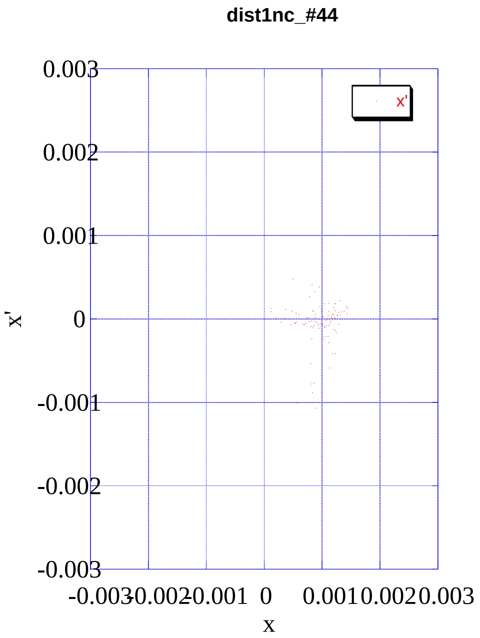
Decoupling separates the bending form the emittance compensation:

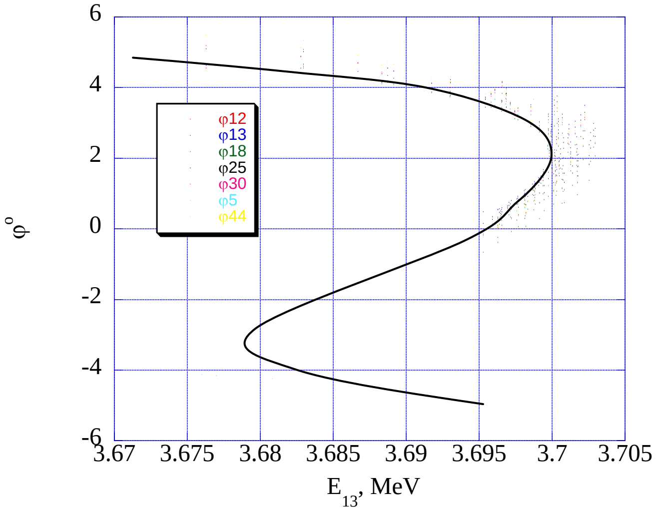
$$M^{\mathrm{T}} \sigma \mathrm{P} + \mathrm{Q}^{\mathrm{T}} \sigma N = 0 \quad \Rightarrow \mathrm{P} = \sigma M^{-1\mathrm{T}} \mathrm{Q}^{\mathrm{T}} \sigma N \quad \Rightarrow \mathrm{Q} \equiv 0!!!!$$

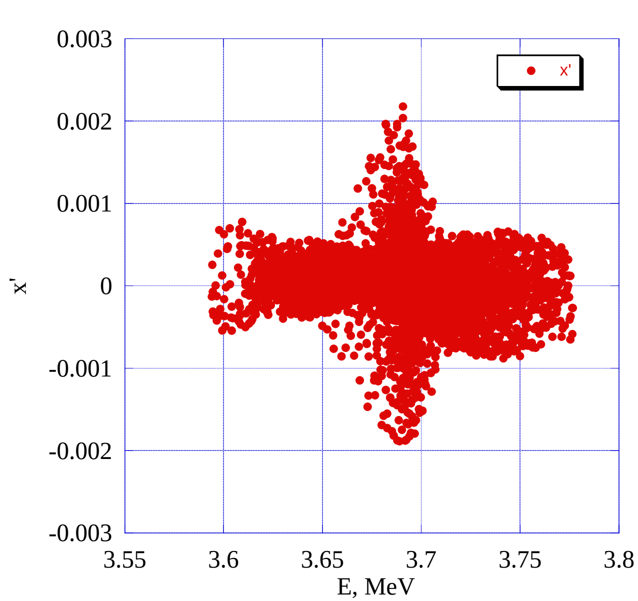
Mess or what?











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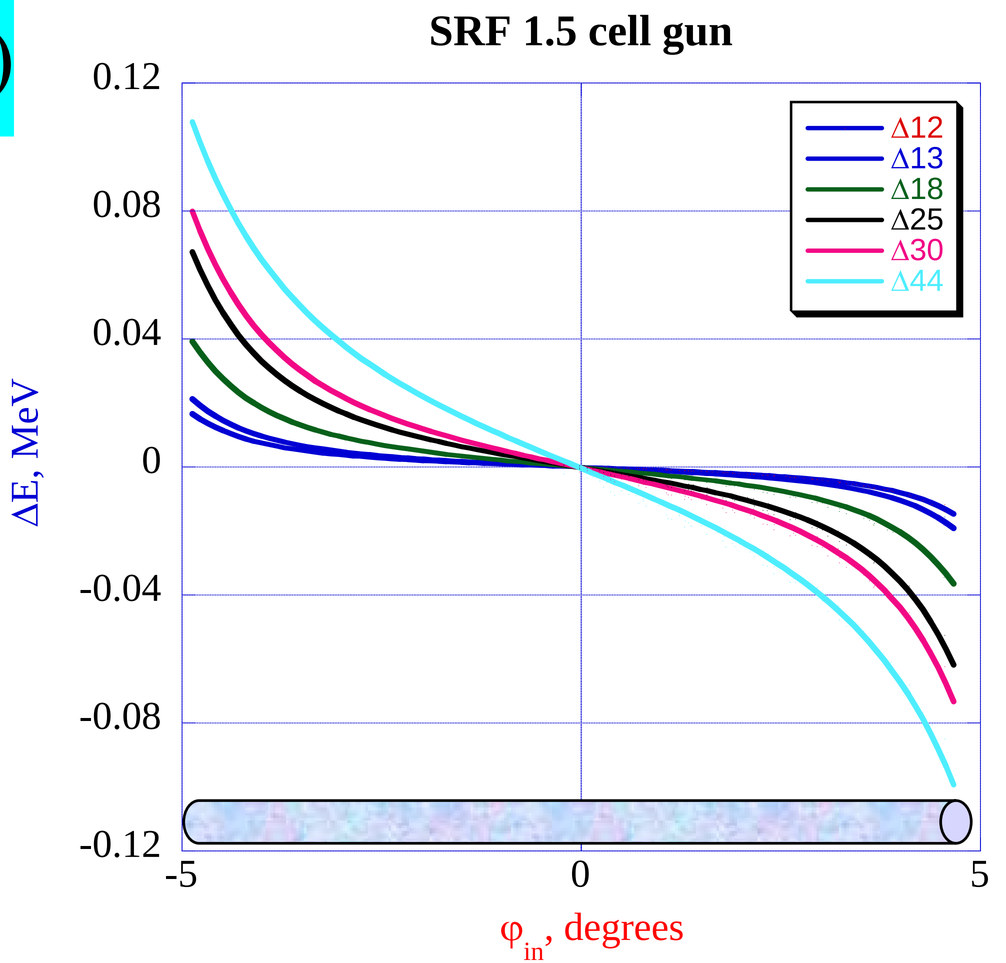
Something is predictable

$$\frac{dE}{ds} \cong f(\zeta_i)$$



Almost ideal fit to the field of evenly charged cylinder

$$\frac{dE}{ds} \cong eE(\zeta); \quad E(\zeta) = \frac{2Q}{r^2 \cdot 2l}\left(2\zeta - \sqrt{r^2 + (\zeta + l)^2} + \sqrt{r^2 + (\zeta - l)^2}\right)$$

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

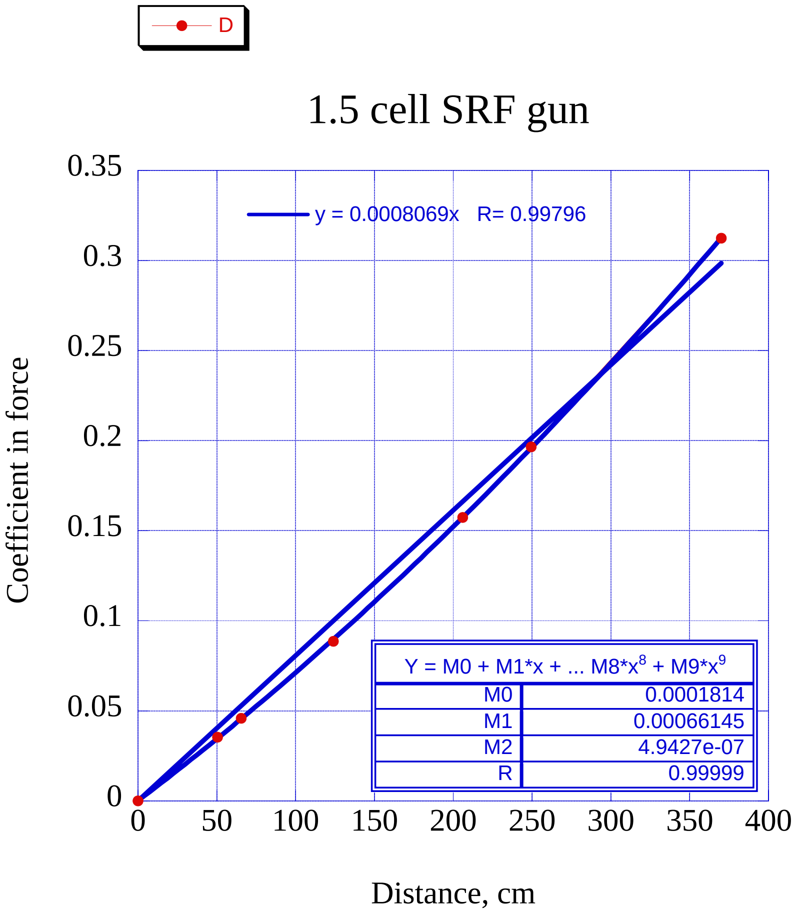
There is a lot of well ordered correlations

$$\Delta E \cong \Delta E_i + f(\zeta_i)\cdot(s+\alpha\cdot s^2)$$

Thus, energy dependence vs s for any electron depends on two parameters - initial energy and initial phase

In general, we seek a general 2-parameter parametrization

$$E_i(s) = a_i \cdot g_1(s) + b_i \cdot g_2(s)$$



Concept

$$X = \begin{bmatrix} x \\ x' \end{bmatrix}; \quad \frac{d}{ds} X \equiv X' = D(s)\cdot X$$

$$free \;\; oscillations \;\; X(s) = M(s)\cdot X(0)$$

$$M' = D(s)\cdot M; \; \det M = 1; \; M(0) = \hat{1}$$

$$\delta = \frac{E - E_o}{E_o}$$

$$\frac{d}{ds}\Psi \equiv \Psi' = D(s)\cdot\Psi + K_o(s)\cdot\delta(s)\cdot\begin{bmatrix} 0 \\ 1 \end{bmatrix}; \; \Psi(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \Rightarrow$$

$$\underline{\underline{\Psi(s) = M(s)\cdot A(s)}} \quad \Rightarrow \quad A' = K_o\cdot\delta\cdot M^{-1}\cdot\begin{bmatrix} 0 \\ 1 \end{bmatrix};$$

$$M^{-1}(s) = \begin{bmatrix} m_{22} & -m_{12} \\ -m_{21} & m_{11} \end{bmatrix} \quad \Rightarrow \quad A' = K_o\cdot\delta\cdot\begin{bmatrix} -m_{12} \\ m_{11} \end{bmatrix};$$

$$A(s) = \begin{bmatrix} -\int_0^s K_o(s')\cdot\delta(s')m_{12}(s')ds' \\ \int_0^s K_o(s')\cdot\delta(s')m_{11}(s')ds' \end{bmatrix} \quad \Rightarrow \quad A = 0!$$

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Concept - cont.

$$\delta = \frac{E - E_o}{E_o}$$

Parametrization for all electrons in the bunch

$$\delta_i(s) = a_i \cdot g_1(s) + b_i \cdot g_2(s) \Rightarrow \quad 4 \text{ "}Achromat\text{" } conditions$$

$$\int_0^s K_o(s') \cdot g_1(s) \cdot m_{11}(s') ds' = 0; \int_0^s K_o(s') \cdot g_2(s) \cdot m_{11}(s') ds' = 0;$$

$$\int_0^s K_o(s') \cdot g_1(s) \cdot m_{12}(s') ds' = 0; \int_0^s K_o(s') \cdot g_2(s) \cdot m_{12}(s') ds' = 0;$$

Simple examples: “frozen” longitudinal motion

$$\delta' = g(\zeta)$$

$$\delta_i(s) = \delta_{i0} + s \cdot g(\zeta_i) \Rightarrow \quad 4 \text{ "}Achromat\text{" } conditions$$

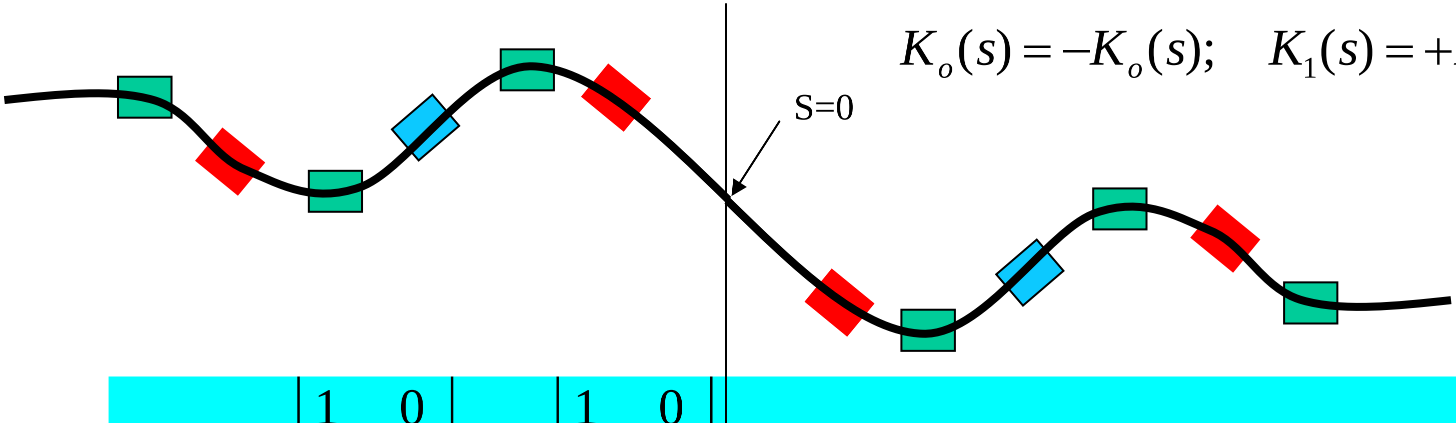
$$\int_0^s K_o(s') \cdot m_{11}(s') ds' = 0; \qquad \int_0^s K_o(s') \cdot s \cdot m_{11}(s') ds' = 0;$$

$$\int_0^s K_o(s') \cdot m_{12}(s') ds' = 0; \qquad \int_0^s K_o(s') \cdot s \cdot m_{12}(s') ds' = 0;$$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

System with bilateral symmetry (ZigZag): Concept - cont.

$$K_o(s) = -K_o(s); \quad K_1(s) = +K_1(s)$$



$$M(-s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} M(s) \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \Rightarrow m_{11}(-s) = m_{11}(s); m_{12}(-s) = -m_{12}(s)$$

$$K_o(-s)\cdot m_{11}(-s) = -K_o(s)\cdot m_{11}(s) \quad \Rightarrow \int_{-L}^{L} K_o(s')\cdot m_{11}(s')ds' \equiv 0$$

$$K_o(-s)\cdot(-s)\cdot m_{12}(-s) = -K_o(s)\cdot(s)\cdot m_{12}(s) \quad \Rightarrow \int_{-L}^{L} K_o(s')\cdot m_{12}(s')s'\cdot ds' \equiv 0$$

2 conditions are automatically satisfied

$$\int_0^L K_o(s')\cdot m_{12}(s')ds' = 0;$$

$$\int_0^L K_o(s')\cdot s\cdot m_{11}(s')ds' = 0;$$

2 conditions remain -> Two elements

RHIC

Concept - cont.

No focusing

$$m_{11} = 1; \quad m_{12} = s;$$

$$\delta_i(s) = \delta_{i0} + s \cdot g(\zeta_i) \Rightarrow \quad 3 \text{ "Achromat" conditions}$$

$$\int_0^S K_o(s') \cdot ds' = \sum_k \theta_k = 0; \qquad \int_0^S K_o(s') \cdot s' \cdot ds' = \sum_k s_k \cdot \theta_k = 0;$$

$$\int_0^S K_o(s') \cdot s' \cdot ds' = \sum_k s_k \cdot \theta_k = 0; \quad \int_0^S K_o(s') \cdot s'^2 \cdot ds' = \sum_k s_k{}^2 \cdot \theta_k = 0;$$

In such system with bilateral symmetry (ZigZag)

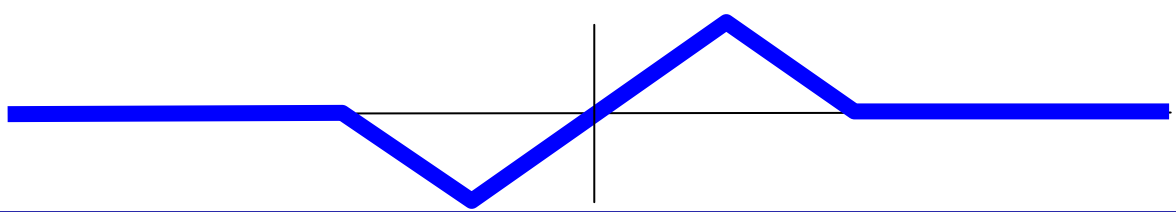
$$K_o(s) = -K_o(s); \quad K_1(s) = +K_1(s)$$

only one condition remains

$$\sum_{k=1}^{K} s_k \cdot \theta_k = 0$$

and it is trivial to satisfy in many ways with K=2.

Example: simplest ZigZag $s_2 = 2s_1; \quad \theta_1 = -2\theta_2$



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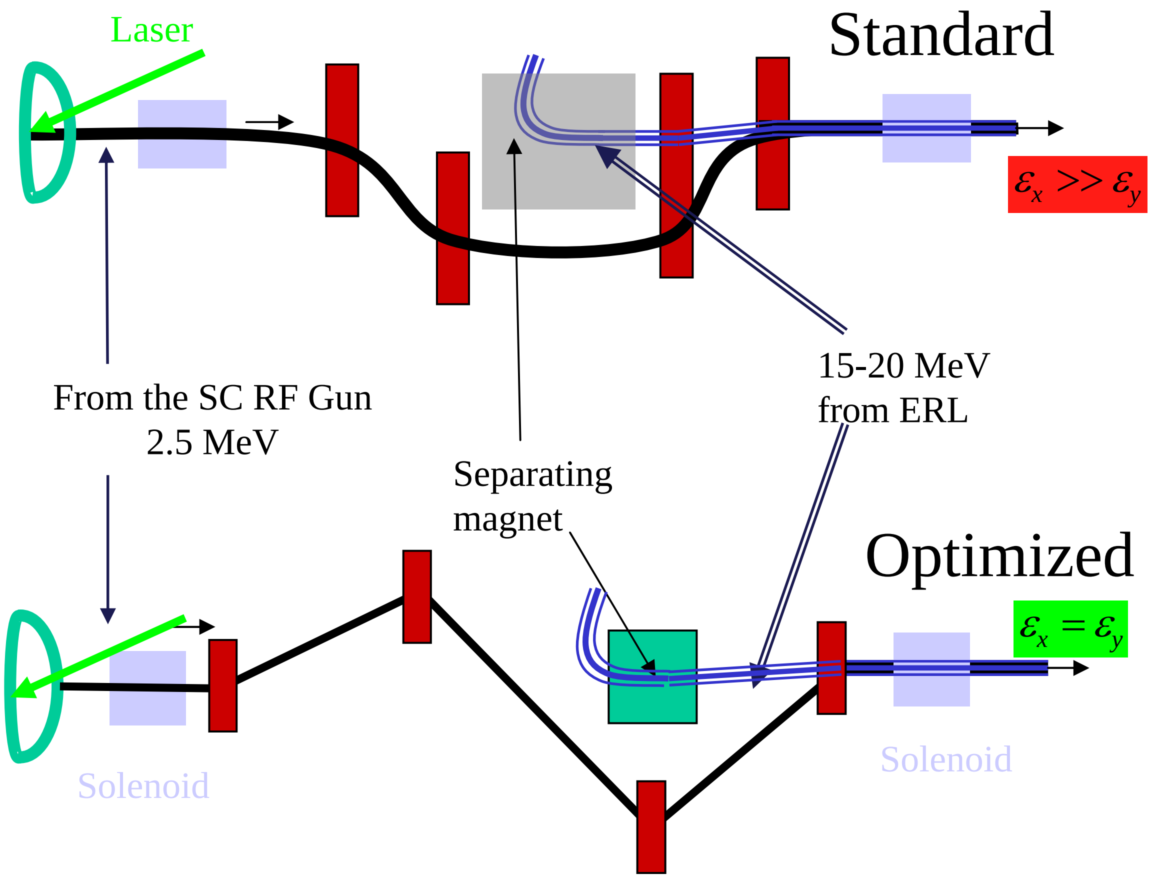
Standard and optimized merging systems



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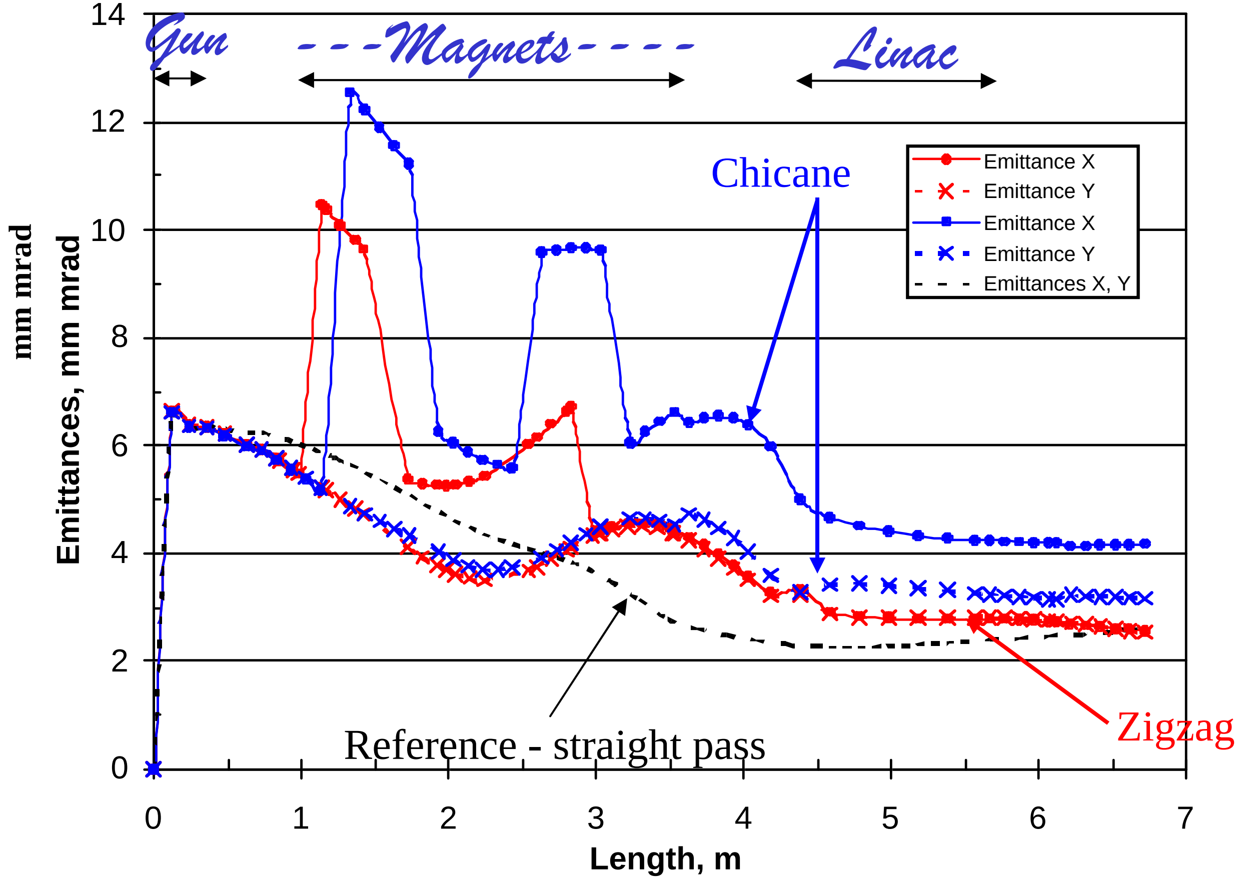
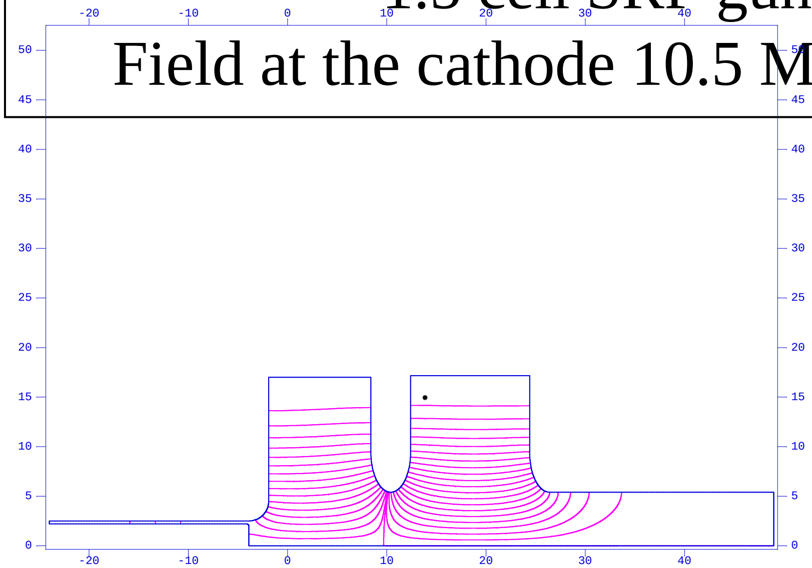
First test

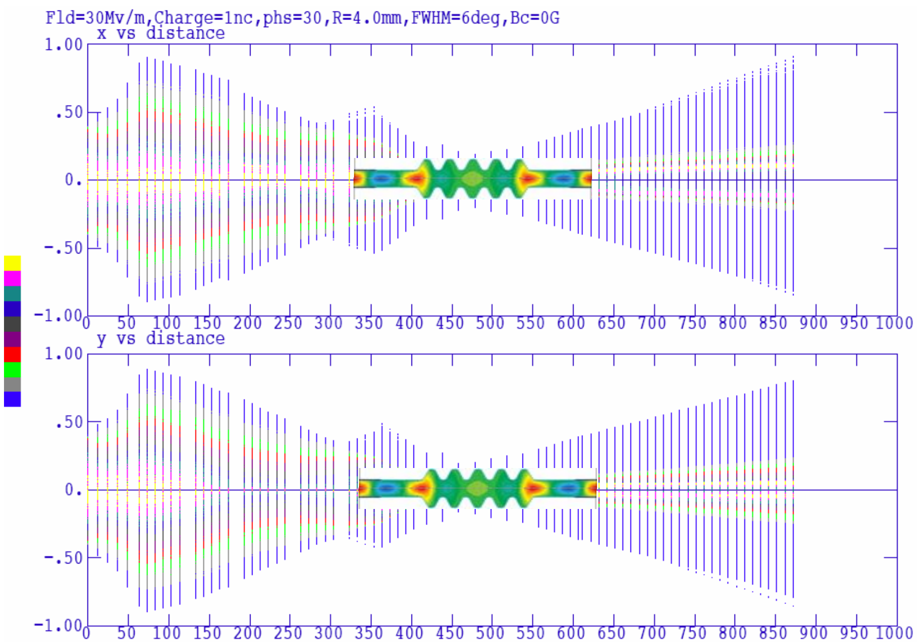


Results of Parmela simulation for 1 nC.

1.5 cell SRF gun - for simulations

Field at the cathode 10.5 MV/m, max field 22.7 MV/m





QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Energy after the 3.7 MeV gun γmc^2=4.2 MeV,

after the linac E=18 MeV.

ZigZag parameters:

all dipoles are chevron, $\rho=1/K_o$ = 15 cm

Lattice *10^o bend, 40 cm drift, -20^o bend, 81.6 cm,*

20^o bend, 40 cm drift, 10^o bend

Chicane parameters: the same radii, the same total focusing and the length:

Lattice *12.4^o bend, 447.5 cm drift, -11.36^o bend,*

96.6 cm, 11.36^o bend, 47.5 cm drift, -12.4^o bend

Both configurations are achromats for particle with constant energy.

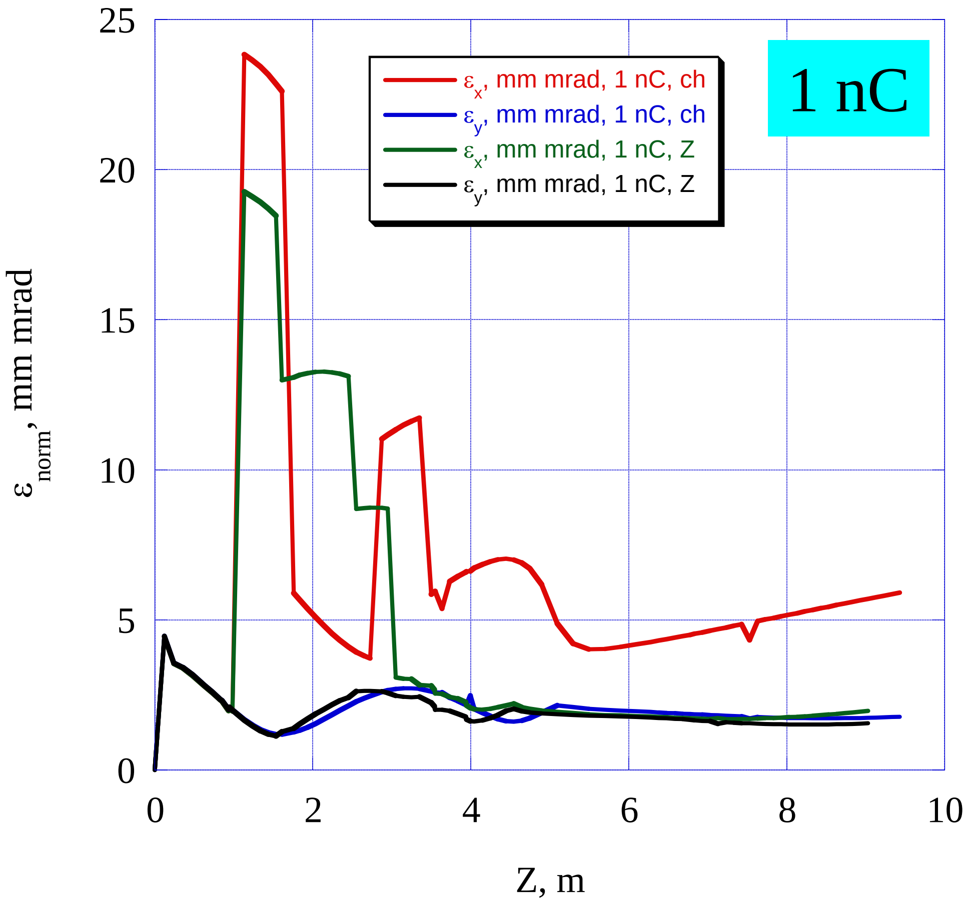
Beer-can distribution, **1.5 cell gun**, Q=1, 2, 4 nC

Pulse length 12^o, r_{cath}=4, 5, 6 mm

1.5 Cell gun

Z-bend: $\varepsilon_{x\ norm}$ = 1.7 mm mrad, $\varepsilon_{y\ norm}$ = 1.5 mm mrad;

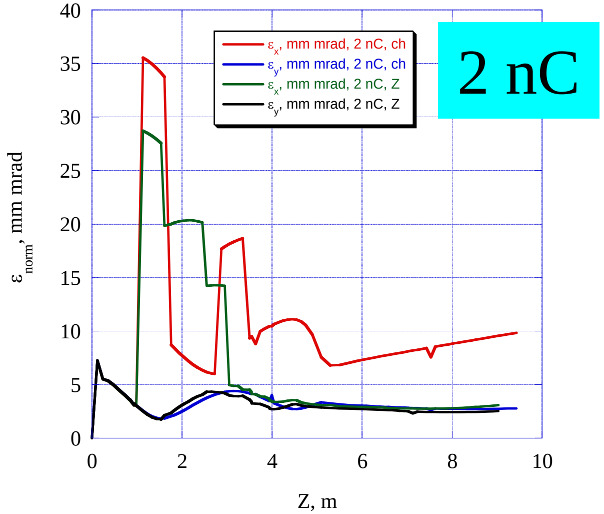
Chicane: $\varepsilon_{x\ norm}$ > **4** mm mrad, $\varepsilon_{y\ norm}$ = 1.7 mm mrad



1.5 Cell gun

Z-bend: $\varepsilon_{x\ norm}$ = 2.8 mm mrad, $\varepsilon_{y\ norm}$ = 2.4 mm mrad;

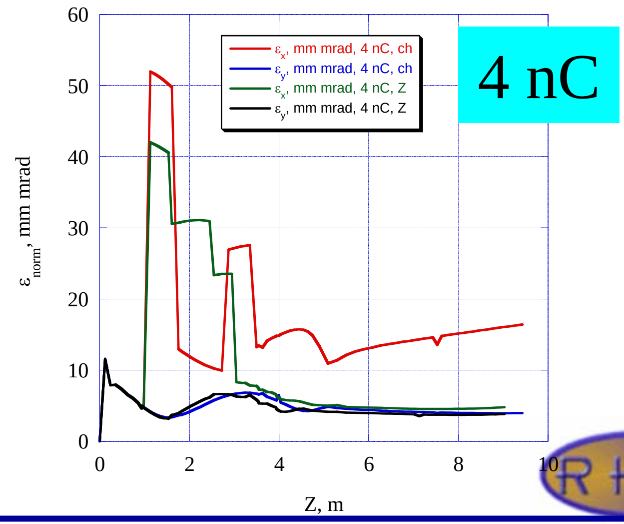
Chicane: $\varepsilon_{x\ norm}$ > **7** mm mrad, $\varepsilon_{y\ norm}$ = 2.7 mm mrad



1.5 Cell gun

Z-bend: $\varepsilon_{x\ norm}$ = 4.5 mm mrad, $\varepsilon_{y\ norm}$ = 3.7 mm mrad;

Chicane: $\varepsilon_{x\ norm}$ > **11** mm mrad, $\varepsilon_{y\ norm}$ = 3.9 mm mrad



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

ZigZag works as a magic

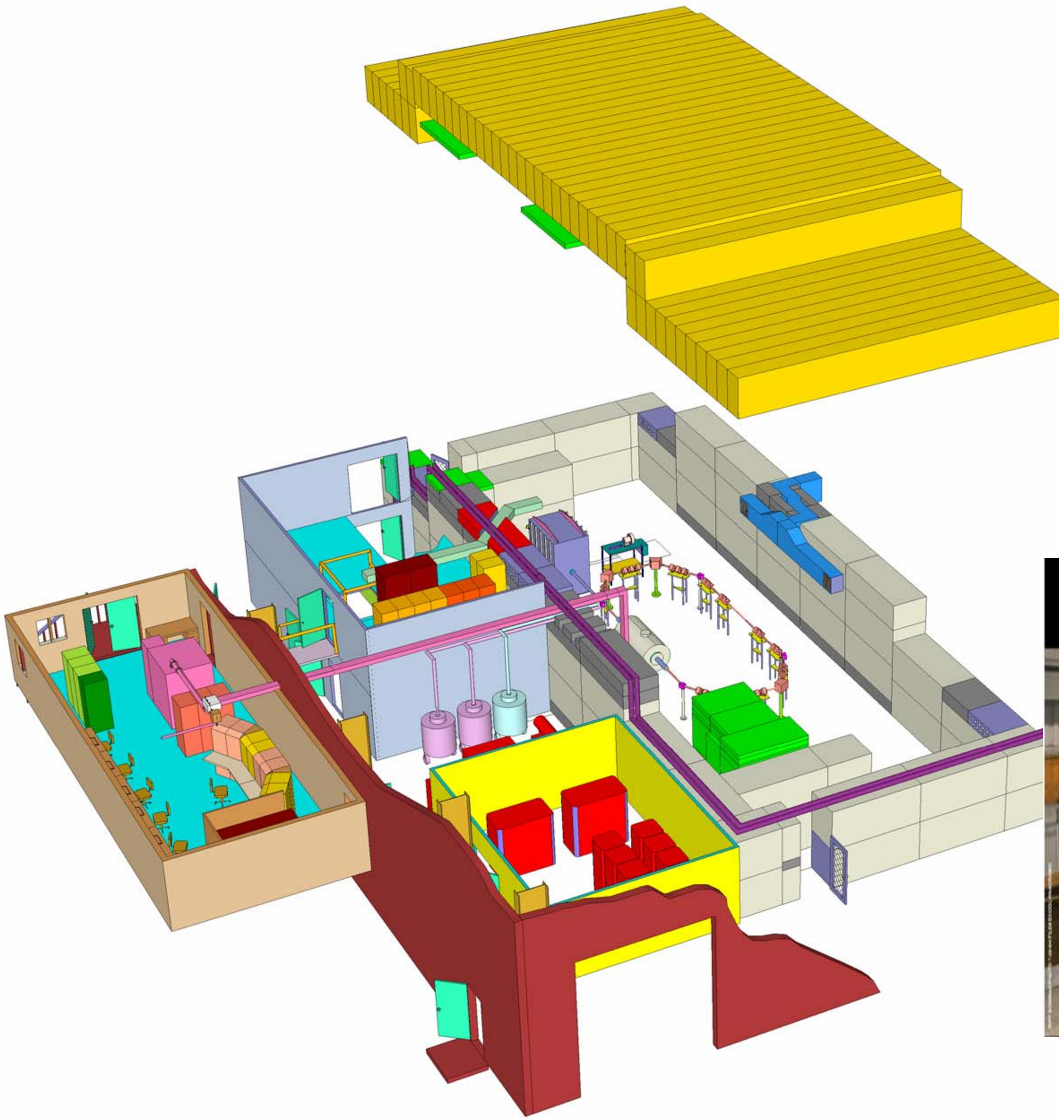
Much better than can be expected from a very-very simple concept

Most Importantly it is Compatible with Emittance Compensation scheme

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

RHIC

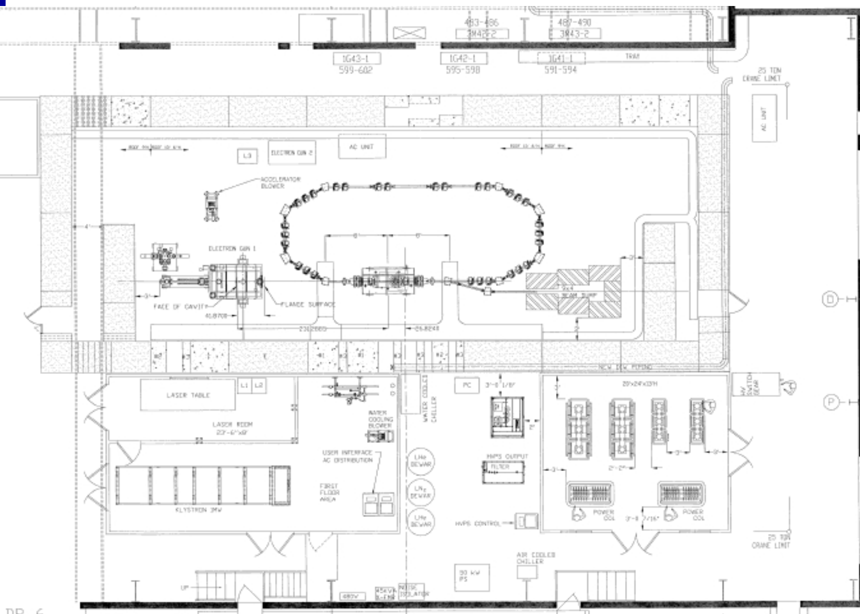
R&D ERL in bldg. 912



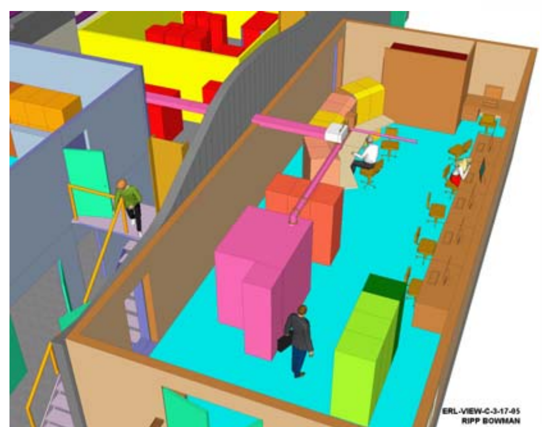
Ripp Bowman 3-7-05
File# Image-1

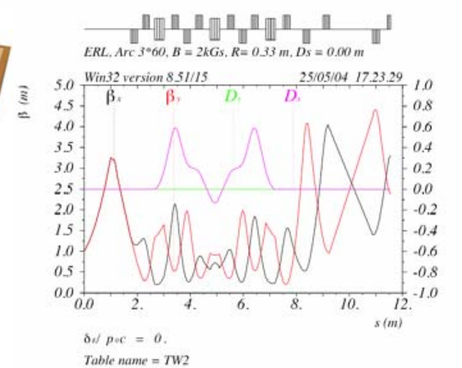
RHIC

R&D ERL in bldg. 912

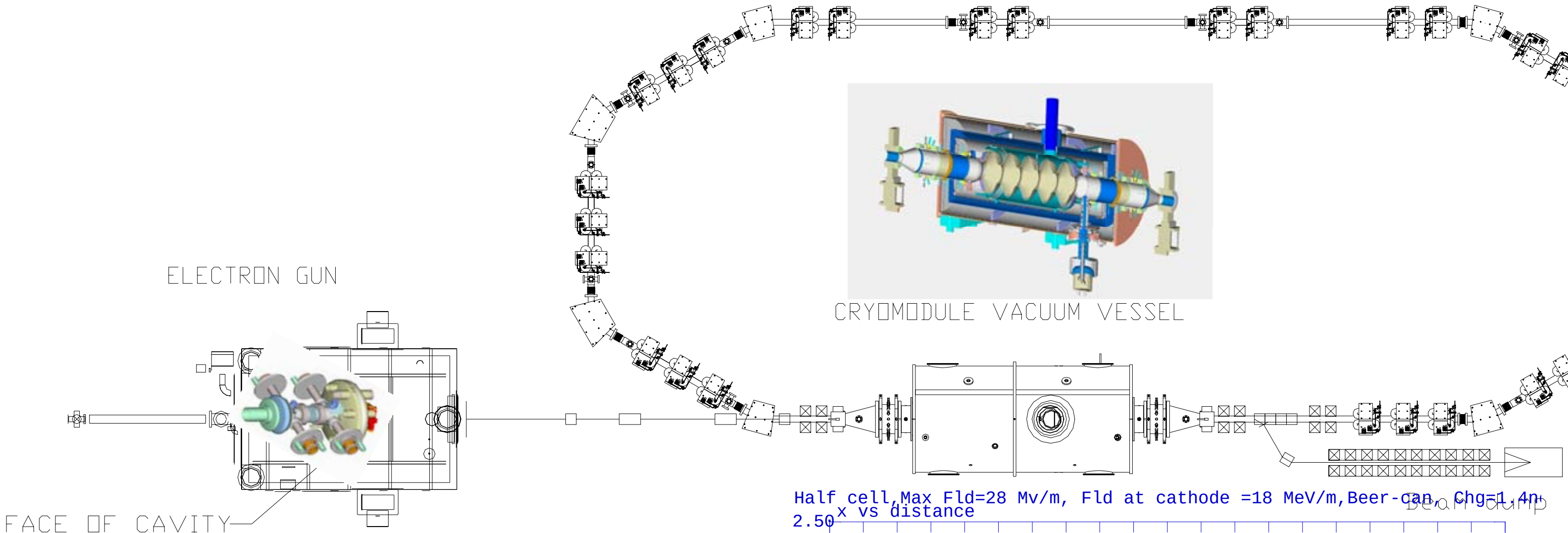


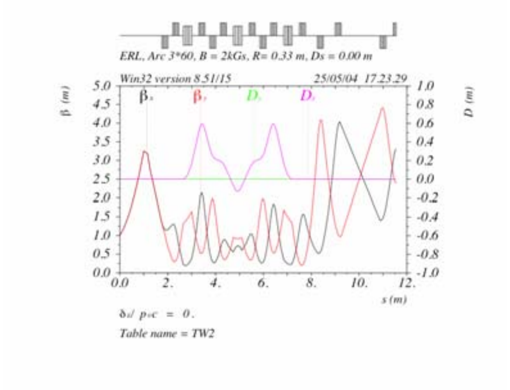
ERL circumference [m]	~ 28
Number of passes	1 to 2
Beam rep-rate [MHz]	**9.38** – **351.875**
for tuning	1 Hz – 1 kHz
Beam energy [MeV]	20 - 40
Electrons per bunch (max)	10^{11}
Normalized emittance [µm rad]	< 50
RMS Bunch length [m]	0.05
Charge per bunch [nC]	**1.3** – **20**
Average e-beam current [A]	0.02 – 0.5
Efficiency of energy recovery	> 99.95%
Efficiency of current recovery	> 99.9995%

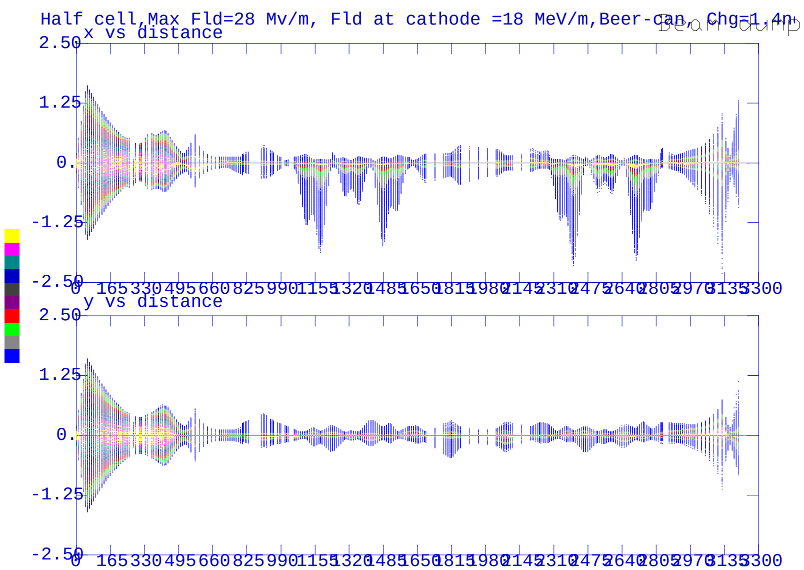




R&D ERL in Bldg.912 - Start-to-End simulations
Half cell, Max Field=28 MV/m, Field at cathode 18 MV/m, Beer-can, Chg=1.4nc,R=2.3 mm, L=12 deg







QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Conclusions

ZigZag works as a magic

Both for low energy and space charge dominated e-beam - works much better than can be expected from a very simple concept

Most Importantly it is Compatible with Emittance Compensation scheme

BNL's 0.5 A average current ERL test-bed in Bldg.912