Preservation of Beam Quality in ERLs

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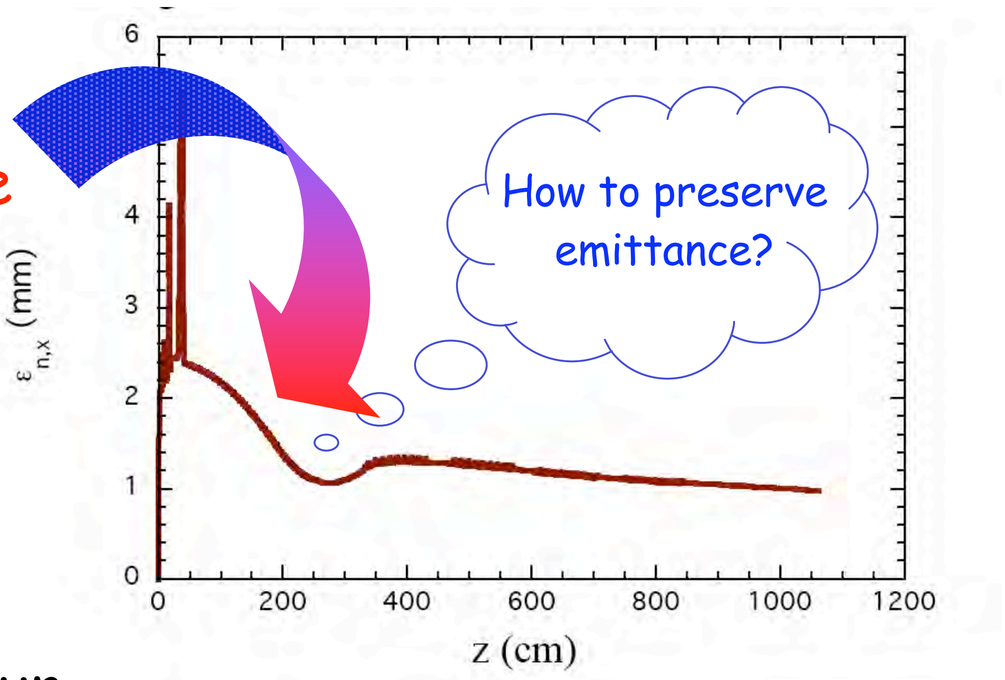
Motivation

- 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,

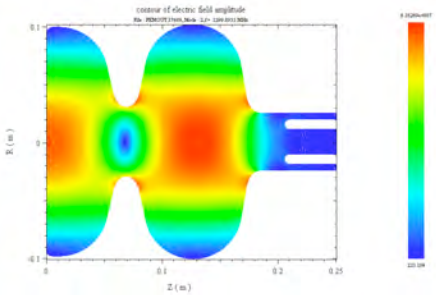
M. Ferrario, J.B. Rosenzweig, G. Travish, J. Sekutowicz, W. D. Möller

Merger is going here

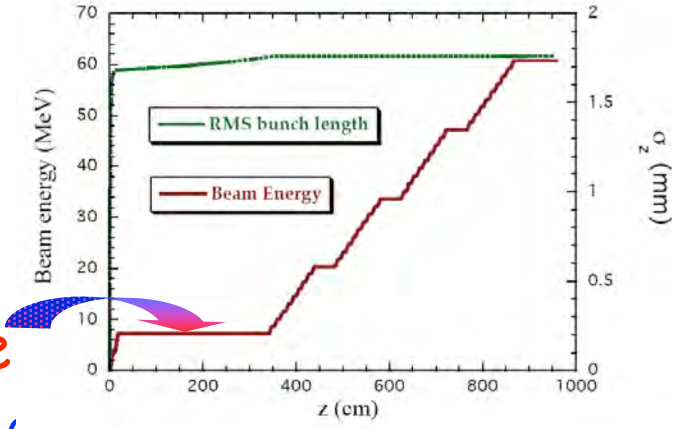


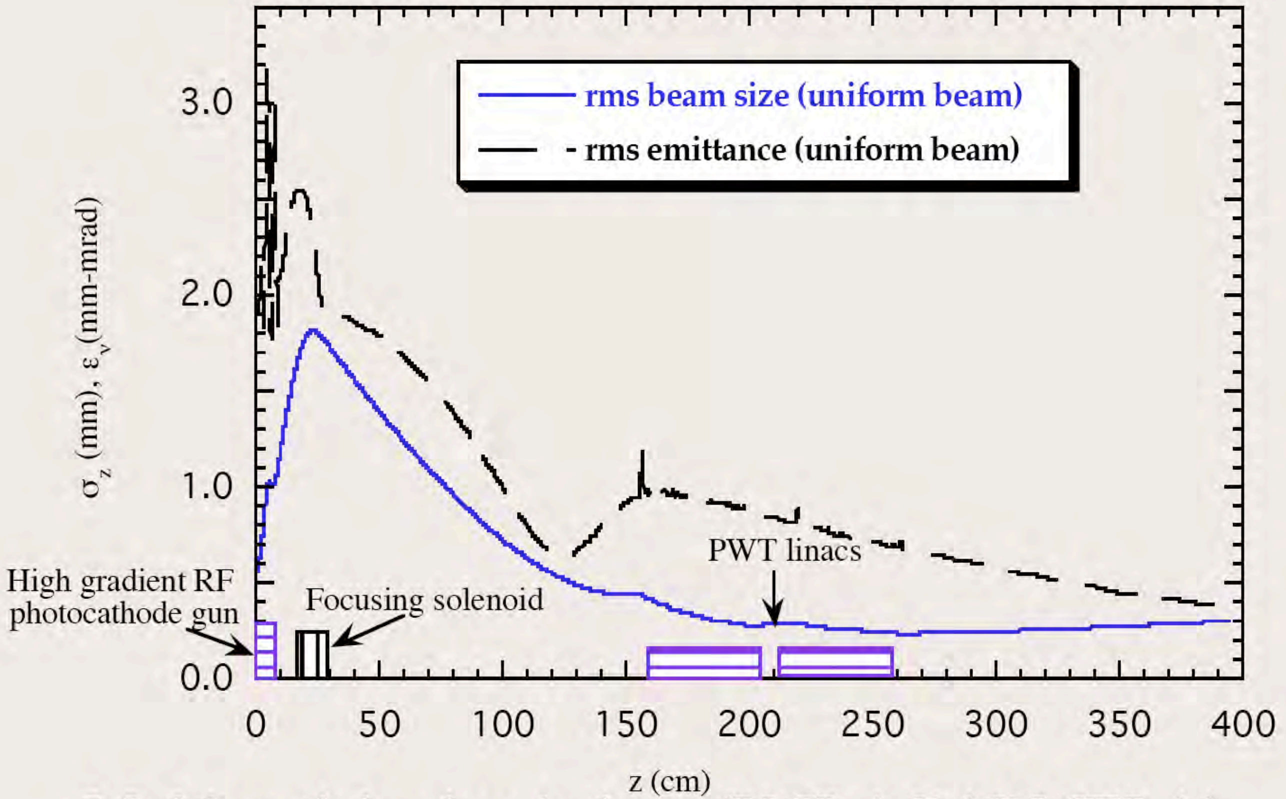
How to preserve emittance?

1.6 cell gun



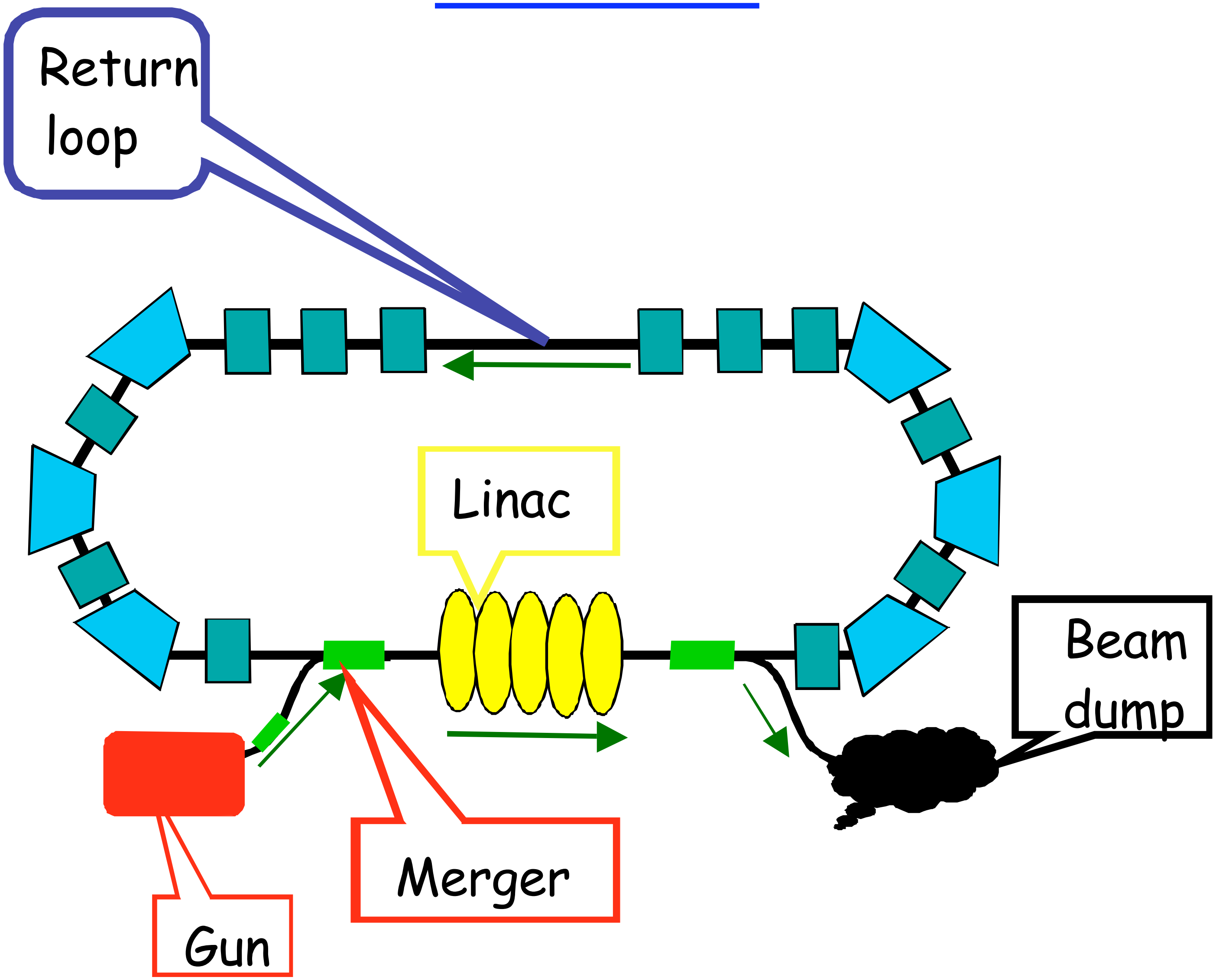
Merger is going here





Multiparticle simulations (UCLA PARMELA)
Showing emittance oscillations and minimization

An ERL



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

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

$$\zeta = s - v_b t$$

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

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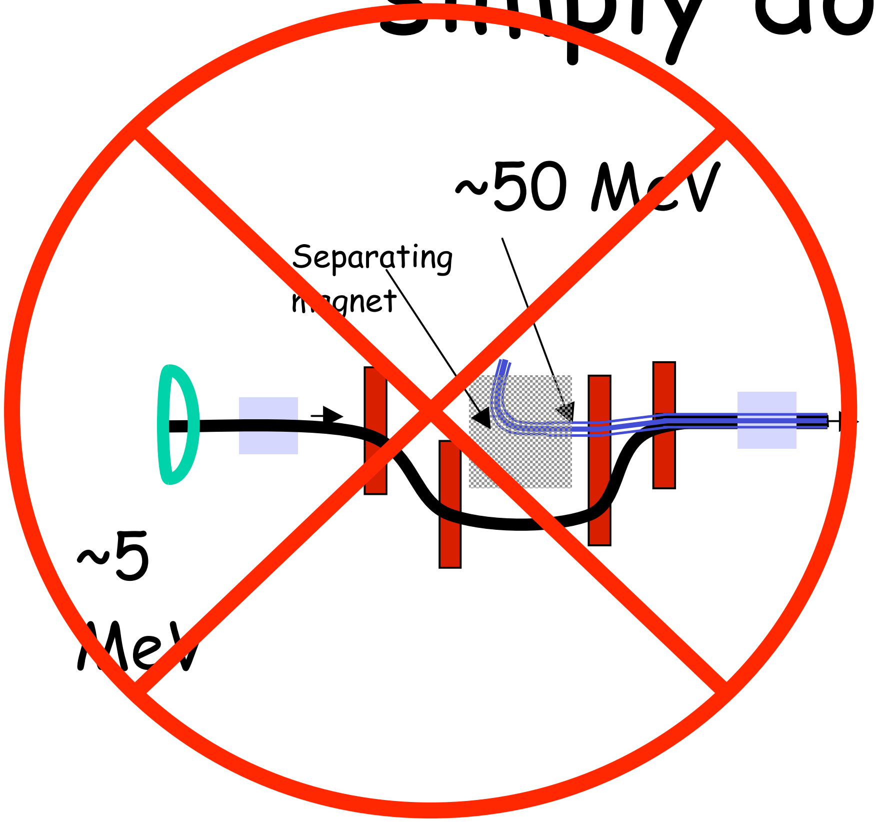
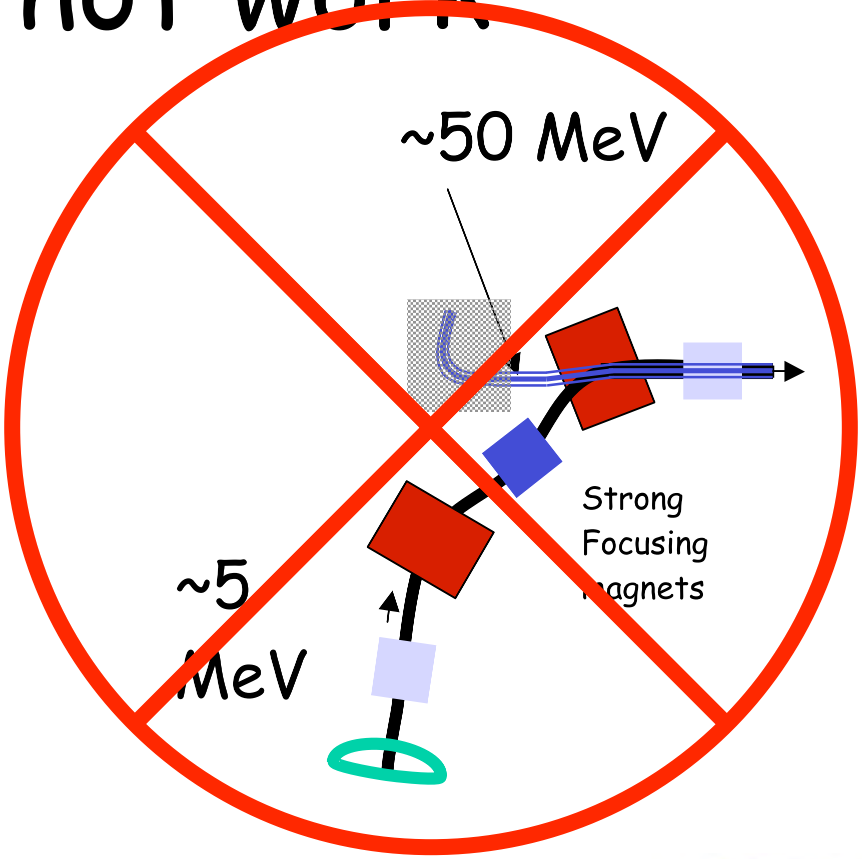
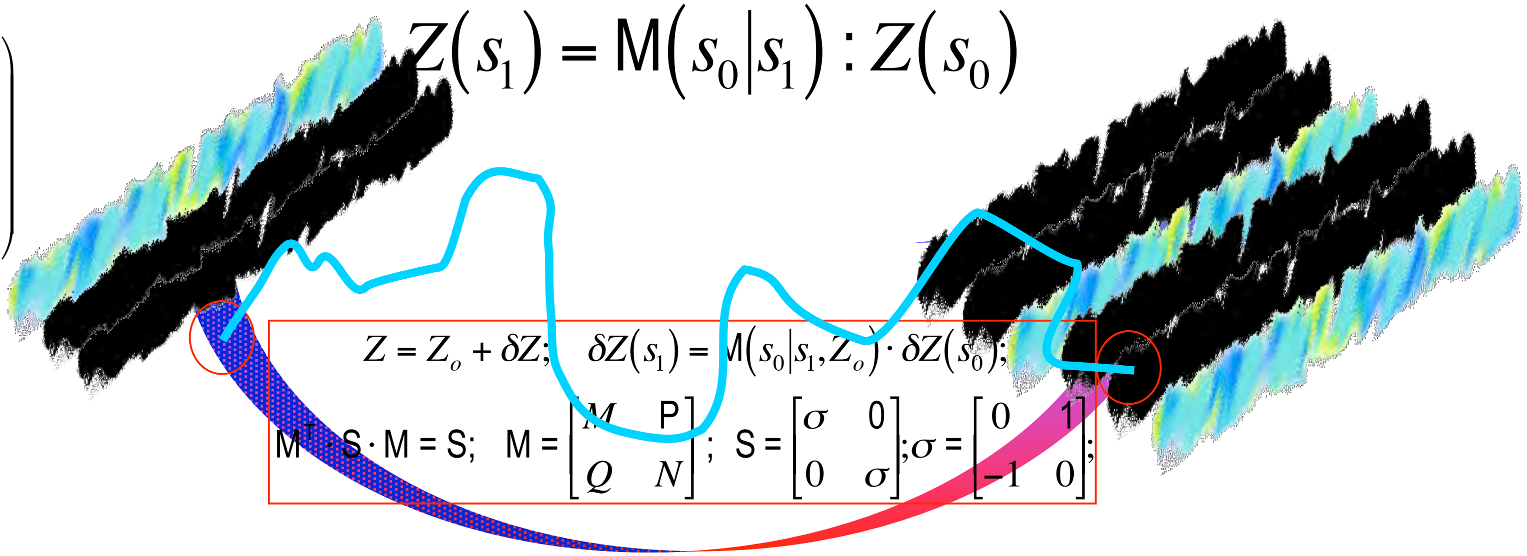
Simple-minded merger for ERL - an achromatic system simply does not work





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

$$Z = \begin{pmatrix} x \\ x' \\ \xi \\ \delta \end{pmatrix}$$



$$Z(s_1) = \mathrm{M}(s_0|s_1) : Z(s_0)$$

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

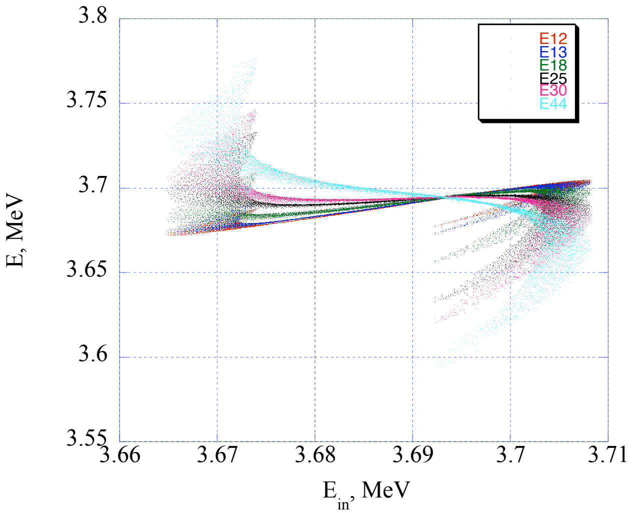
$$\mathrm{M}^{\mathrm{T}} \cdot \mathrm{S} \cdot \mathrm{M} = \mathrm{S}; \quad \mathrm{M} = \begin{bmatrix} M & \mathrm{P} \\ Q & N \end{bmatrix}; \quad \mathrm{S} = \begin{bmatrix} \sigma & 0 \\ 0 & \sigma \end{bmatrix}; \sigma = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix};$$

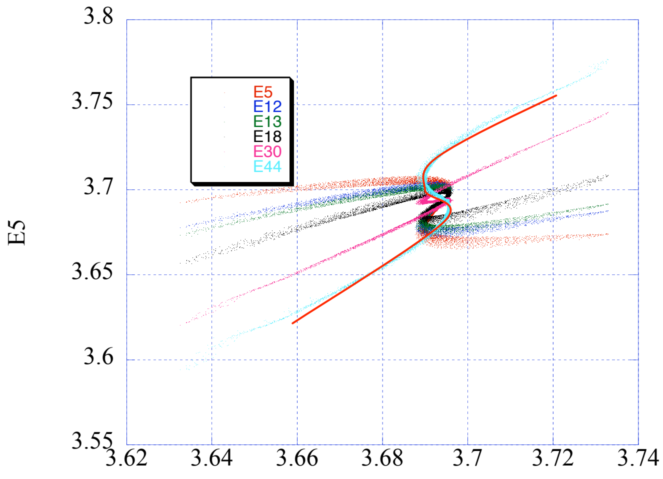
Decoupling separates the bending form the emittance compensation:

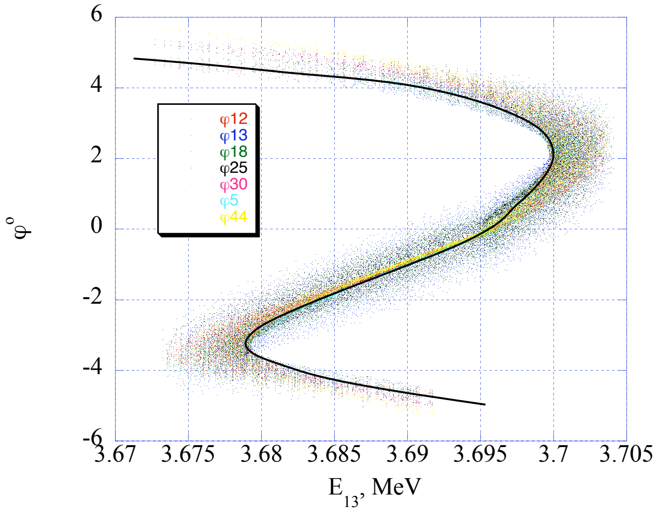
$$M^{\mathrm{T}} \sigma \mathrm{P} + \mathrm{Q}^{\mathrm{T}} \sigma N = 0 \quad \Rightarrow \mathrm{P} = \sigma M^{-1\mathrm{T}} \mathrm{Q}^{\mathrm{T}} \sigma N \quad \Rightarrow \mathrm{Q} \equiv 0!!!!$$

Mess or what?

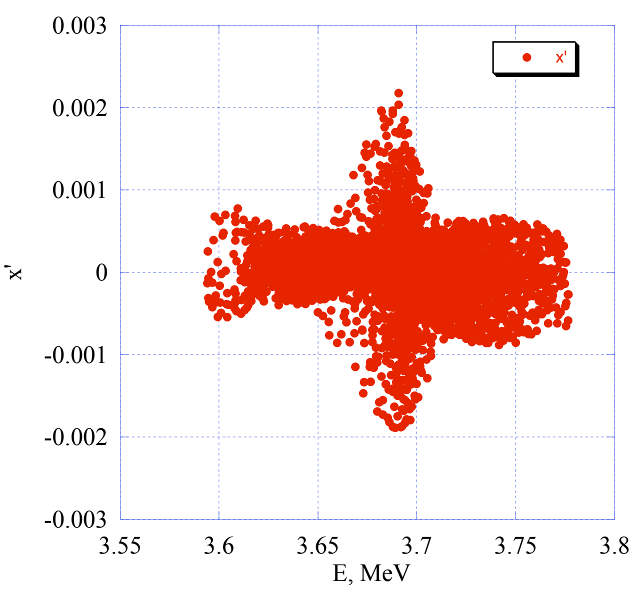
1.5 cell SRF gun



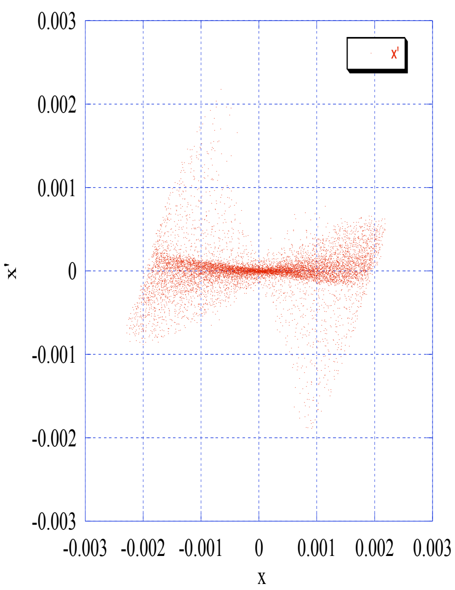




dist1nc_#44



dist1nc_#44



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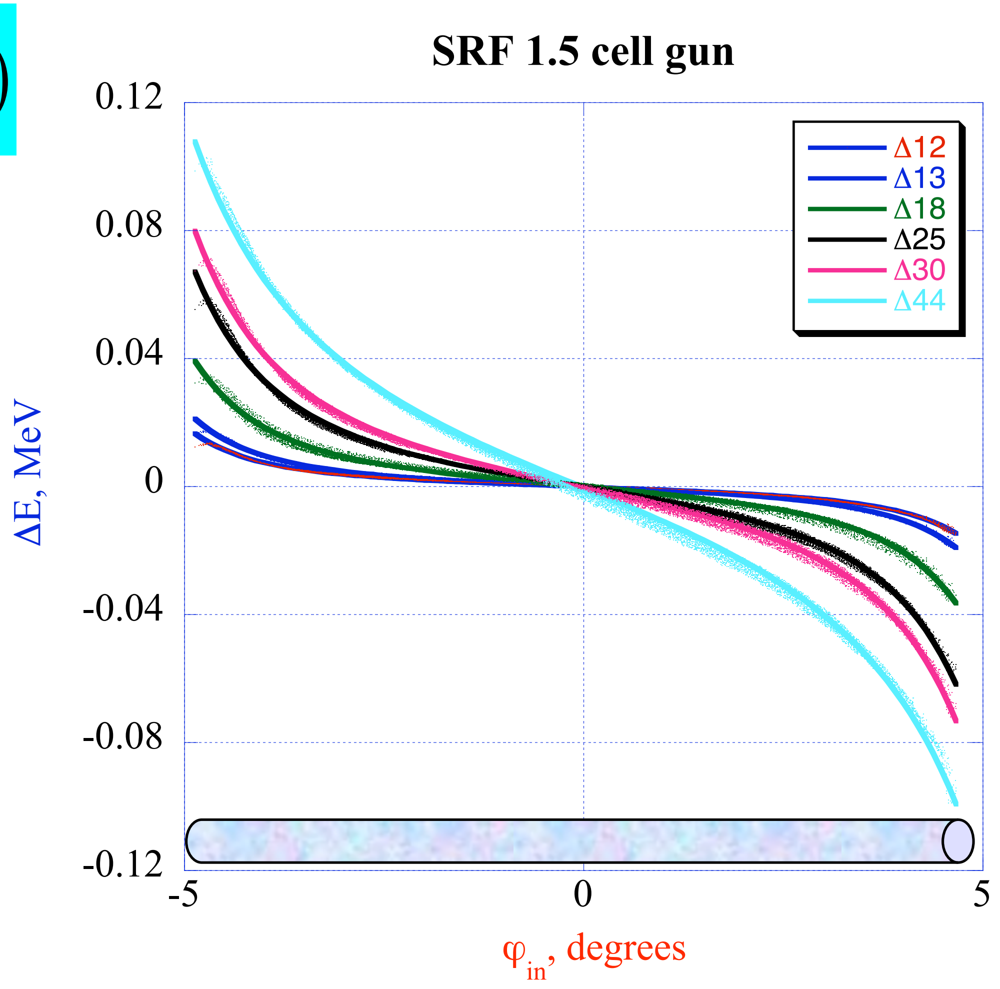
Something is predictable

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



Almost ideal fit to the field of evenly charged cylinder

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

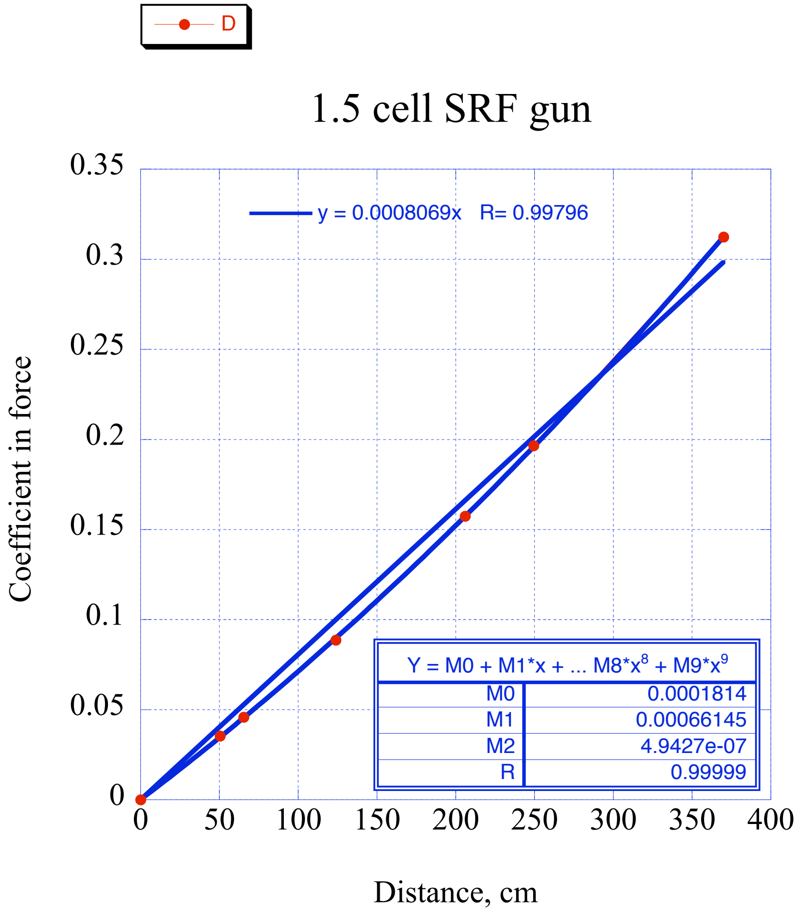
There is a lot of well ordered correlations

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

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

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

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

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

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

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

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

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

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

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 $\delta' = g(\zeta)$

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

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

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

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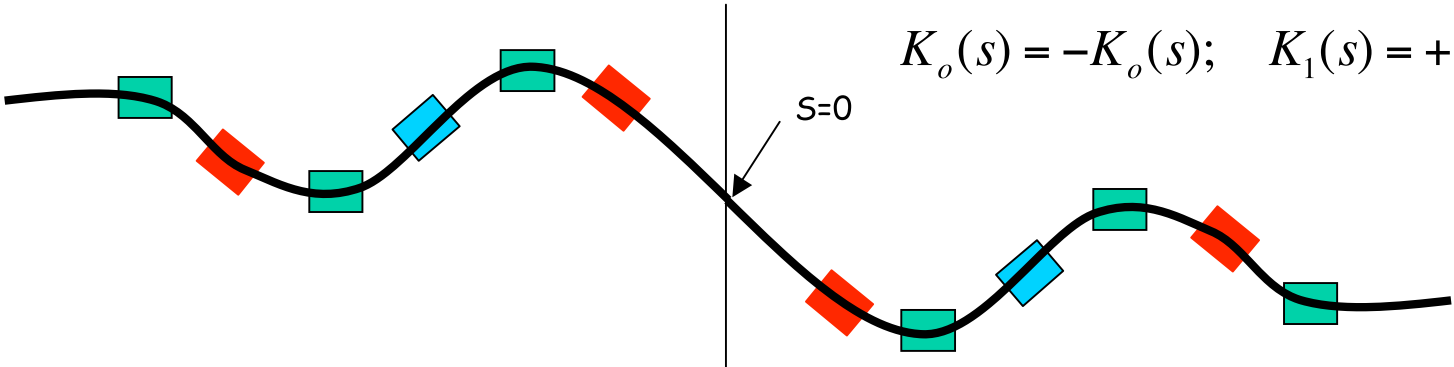
System with bilateral symmetry (ZigZag):

Concept - cont.



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

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

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

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

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

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)

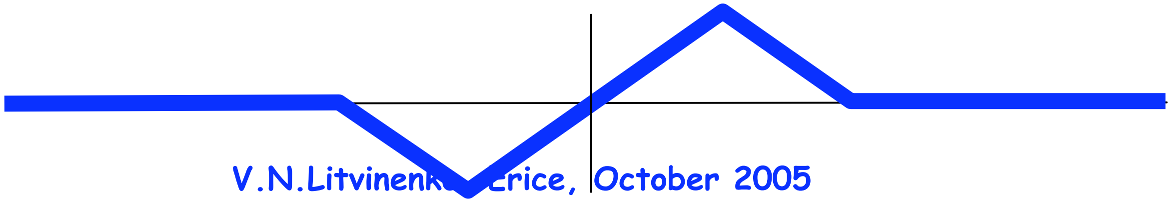
$$K_o(s) = -K_o(s); \quad K_1(s) = +K_1(s)$$

only one condition remains

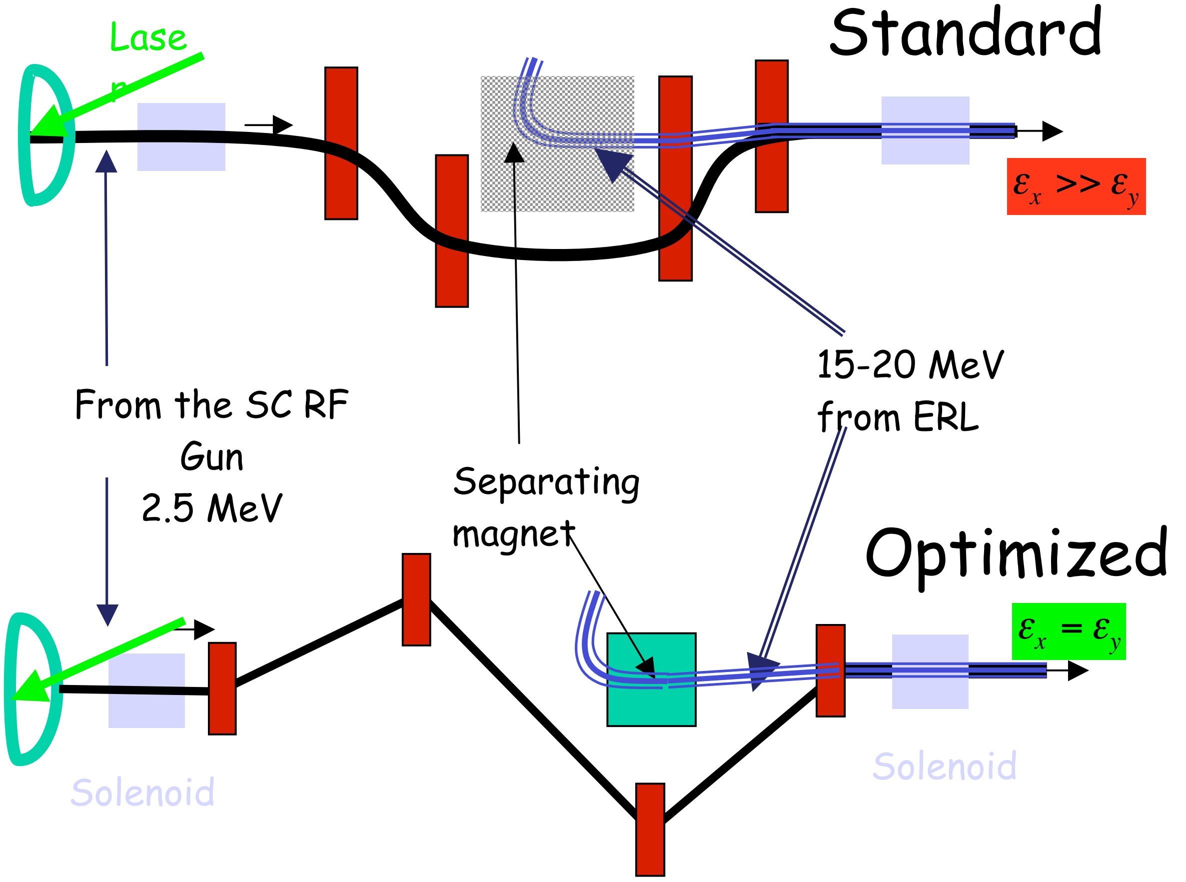
$$\sum_{k=1}^{K} s_k \cdot \theta_k = 0$$

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

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



Standard and optimized merging systems



Laser

Standard

$\varepsilon_x >> \varepsilon_y$

From the SC RF
Gun
2.5 MeV

15-20 MeV
from ERL

Separating
magnet

Optimized

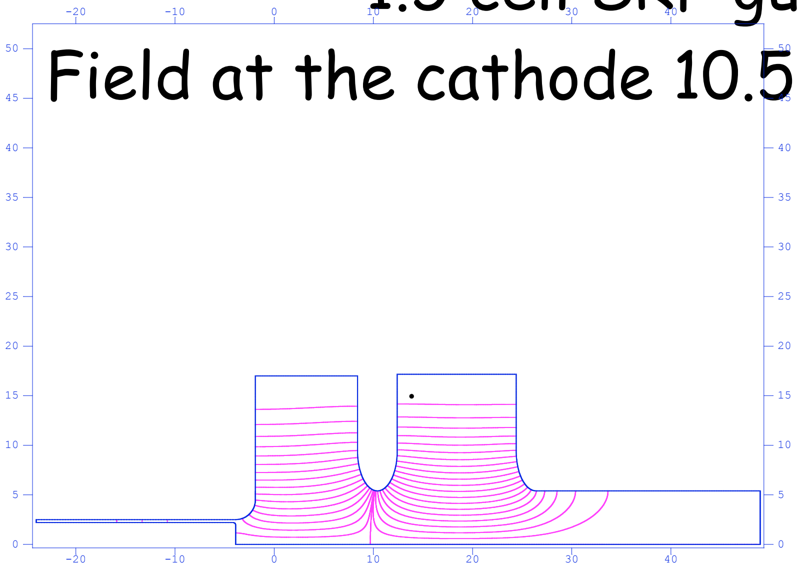
$\varepsilon_x = \varepsilon_y$

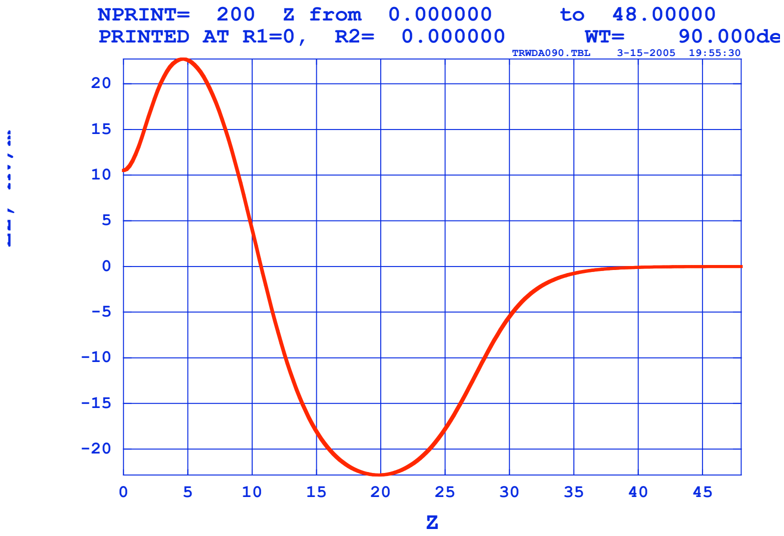
Solenoid

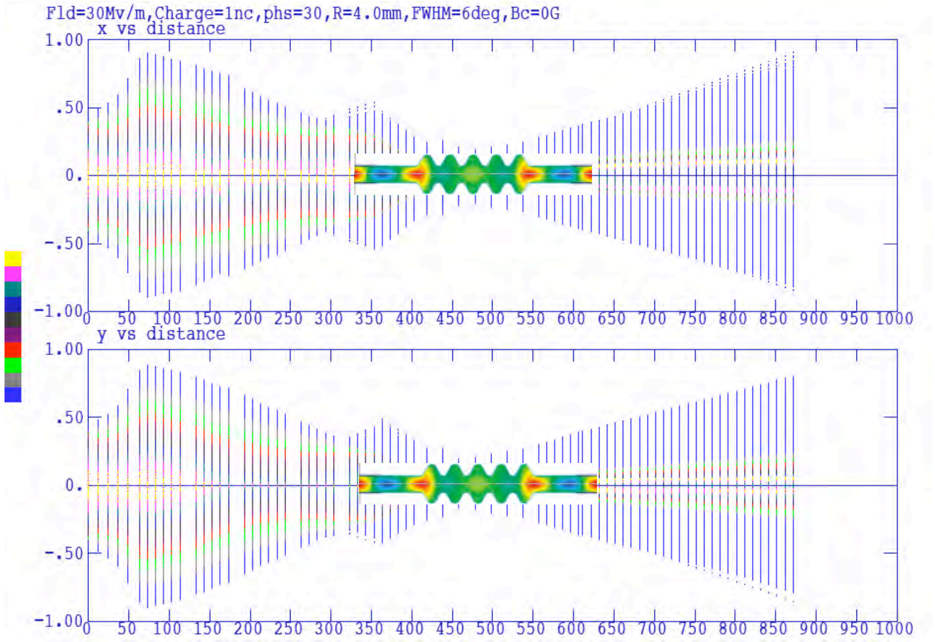
Solenoid

1.5 cell SRF gun - for simulations

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







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

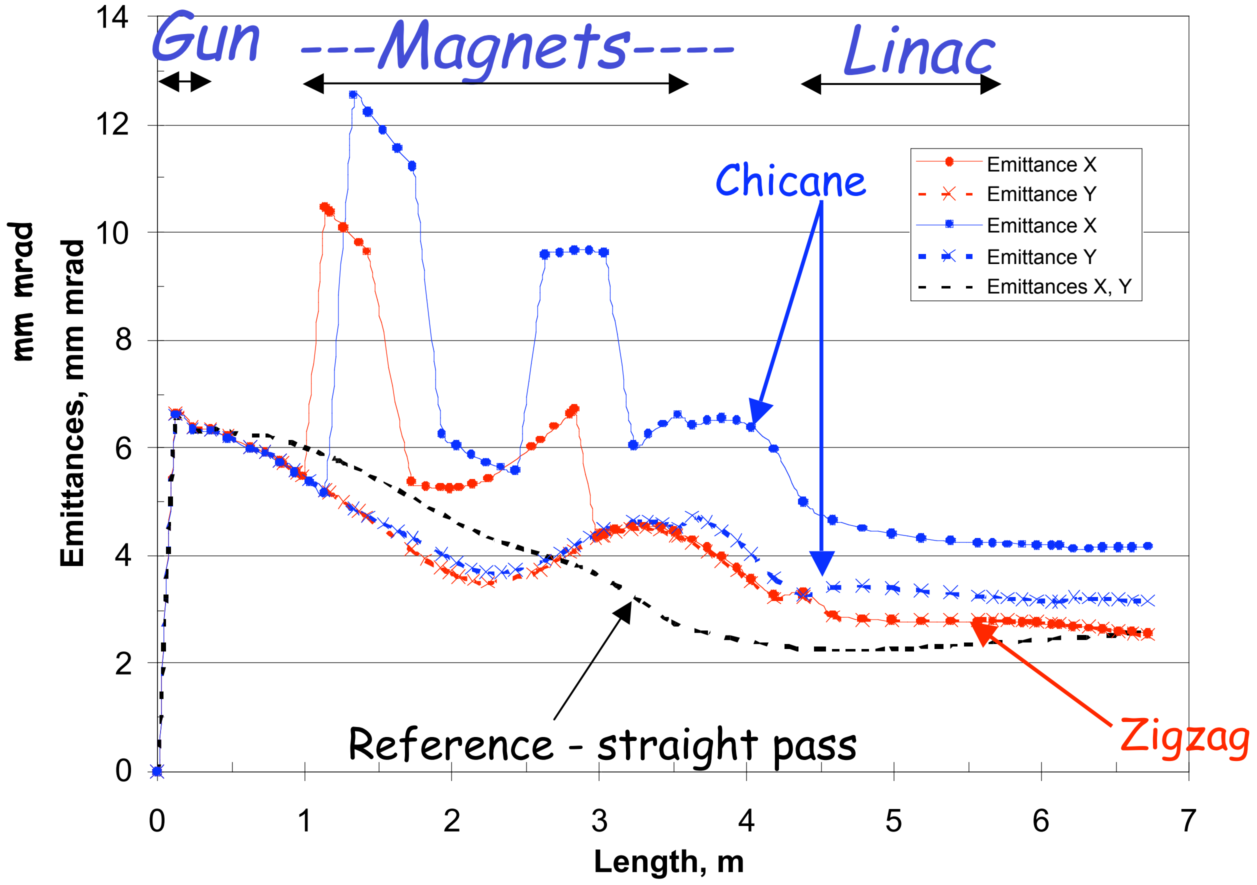
Lattice *10^o bend, 40 cm drift, -20^o bend, 81.6 cm,*
20^o bend, 40 cm drift, 10^o bend

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.

First test



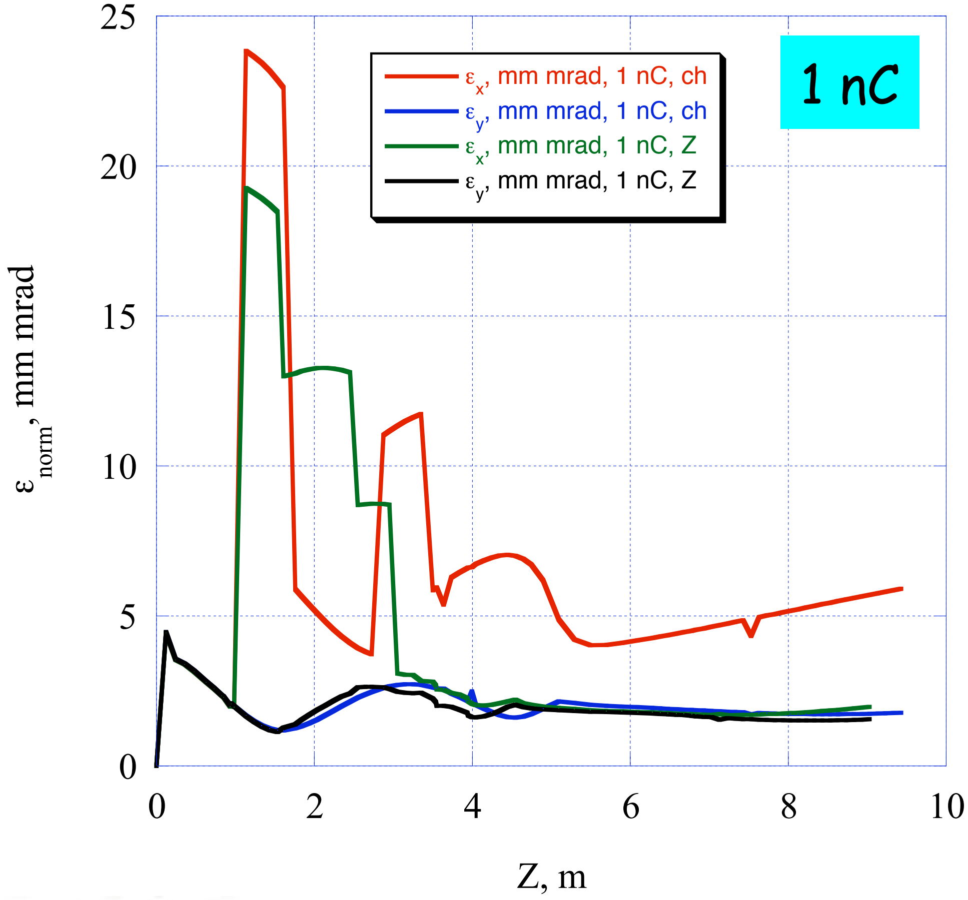
Results of Parmela simulation for 1 nC.

Beer-can distribution, **1.5 cell gun**, Q=1, 2, 4 nC
Pulse length 12°, 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;

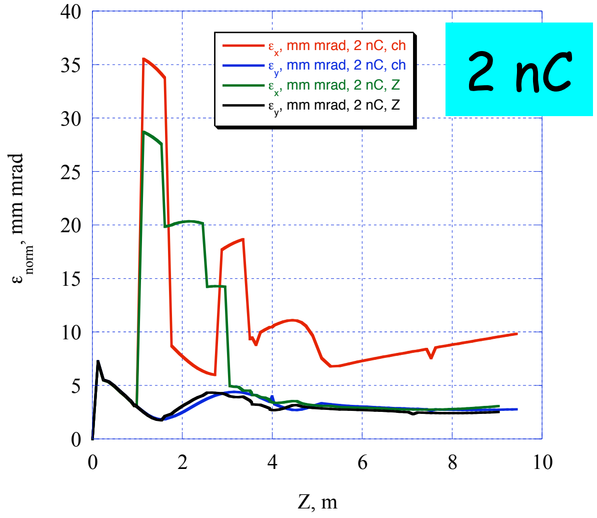
Chicane: $\varepsilon_{x\ norm}$ > **4** mm mrad, $\varepsilon_{y\ norm}$ = 1.7 mm mrad



1.5 Cell gun

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

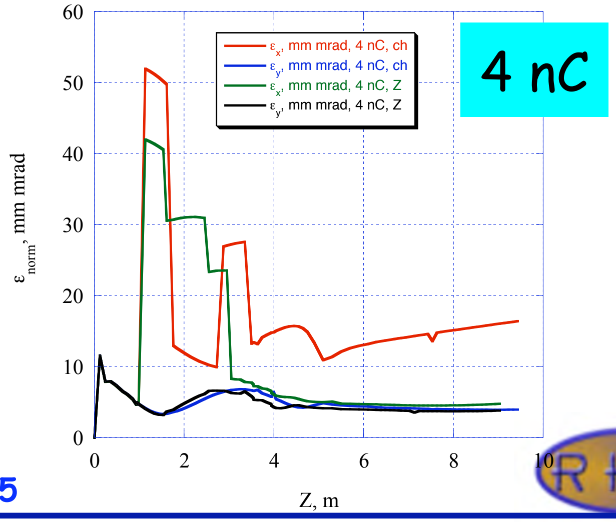
Chicane: $\varepsilon_{x\ norm}$ > **7** mm mrad, $\varepsilon_{y\ norm}$ = 2.7 mm mrad



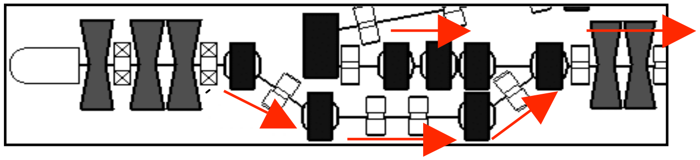
1.5 Cell gun

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

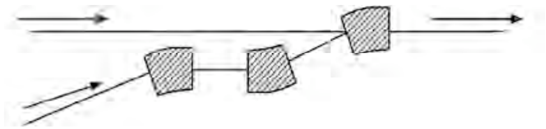
Chicane: $\varepsilon_{x\ norm}$ > **11** mm mrad, $\varepsilon_{y\ norm}$ = 3.9 mm mrad



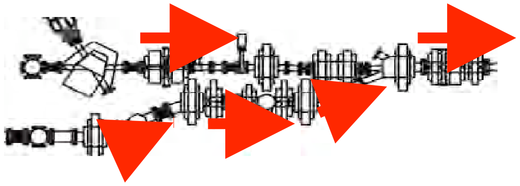
MERGERS USED IN OPERATIONAL ERLS



Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia



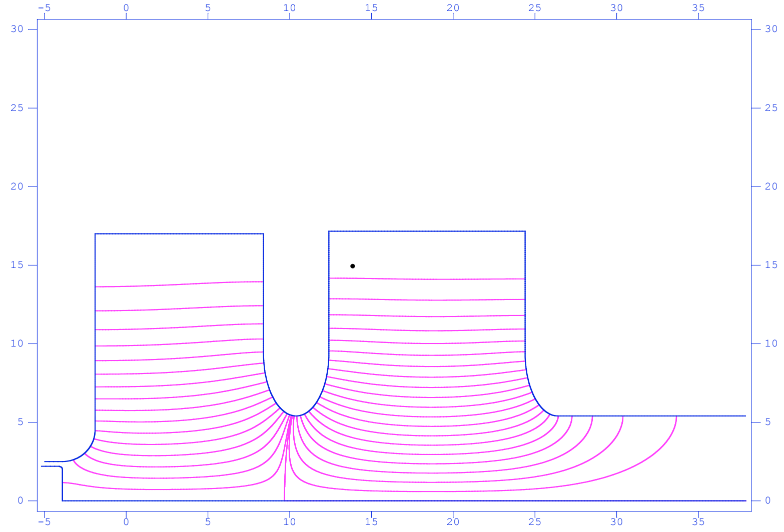
Tomas Jefferson National Accelerator Facility (TJNAF) Newport News, VA, USA



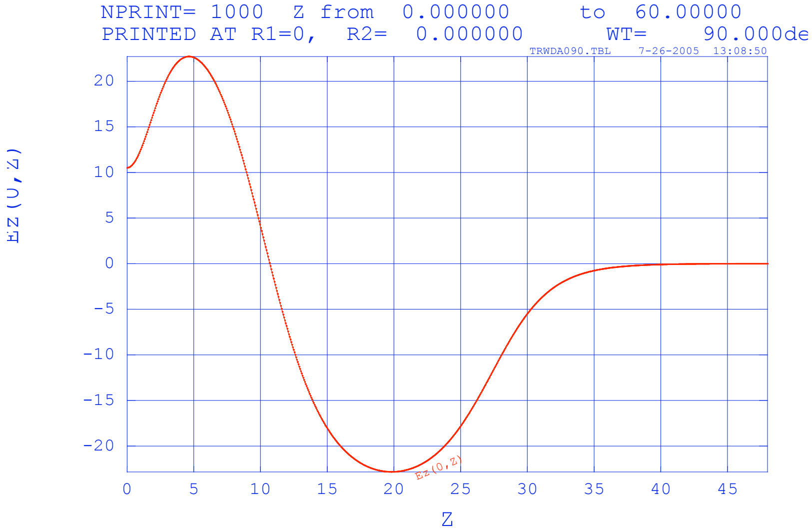
Japan Atomic Energy Research Institute (JAERI), Tokai-mura, Ibaraki, Japan

	BINP	TJNAF	JAERI
Gun type	Thermionic	Photocathode	Thermionic
Inj.energy	2 MeV	9.1 MeV	2.5 MeV
Q_{bunch}	1.5 nC	0.135 nC	0.5 nC
$\Delta T_{bunch},$	150 psec	2 psec	9.4 psec
Merger type	Chicane with quad sstrong focusing	Three dipole strong focusing	Dog-leg, with quads strong focusing
$\varepsilon_{n,h}$ /$\varepsilon_{n,v}$	30/30 μ	10/10 μ	35/26 μ

1.5 cell GUN

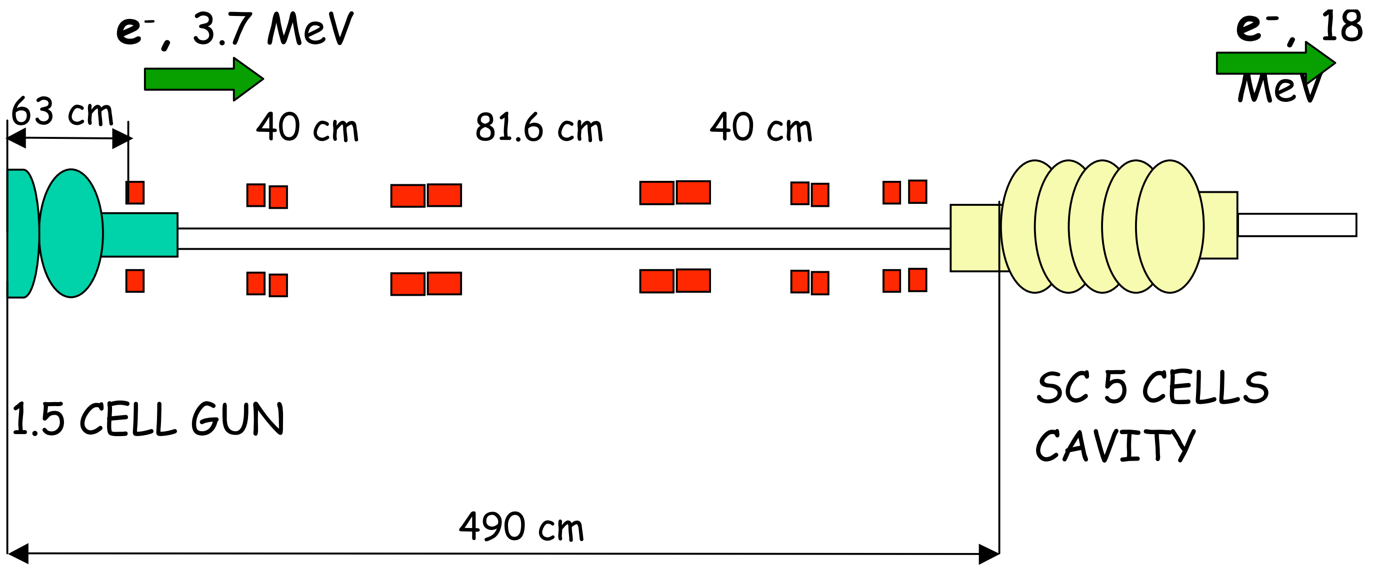


Gun Shape and Electric Field Profile

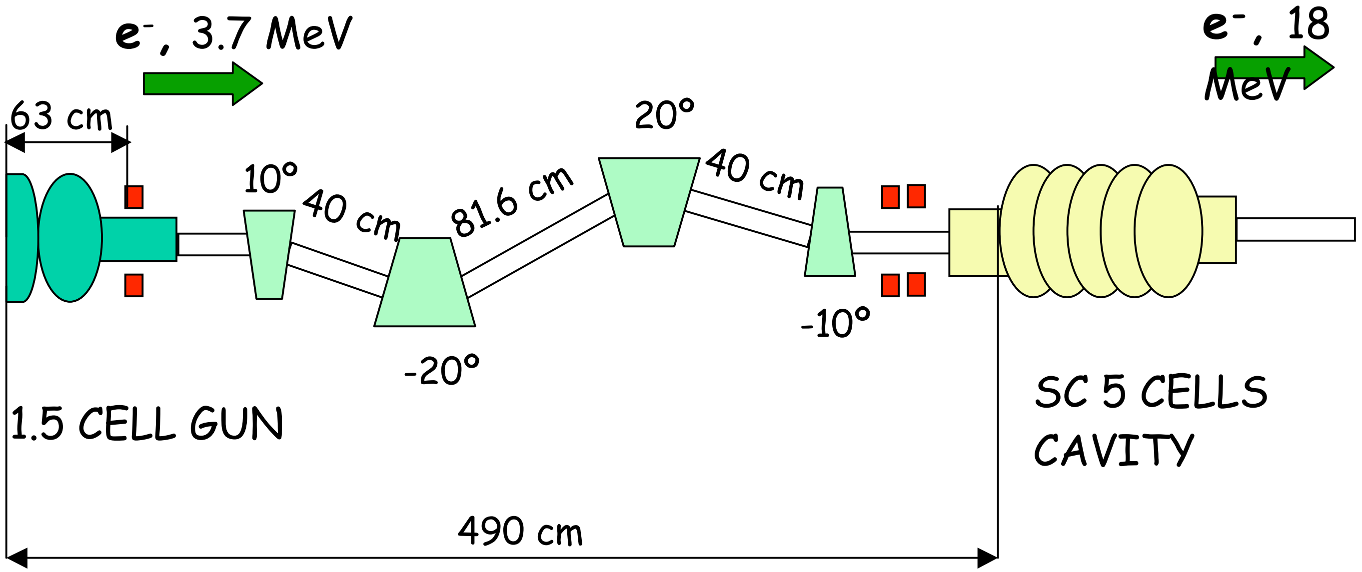


Electric Field @ Cathode 10 MeV/m

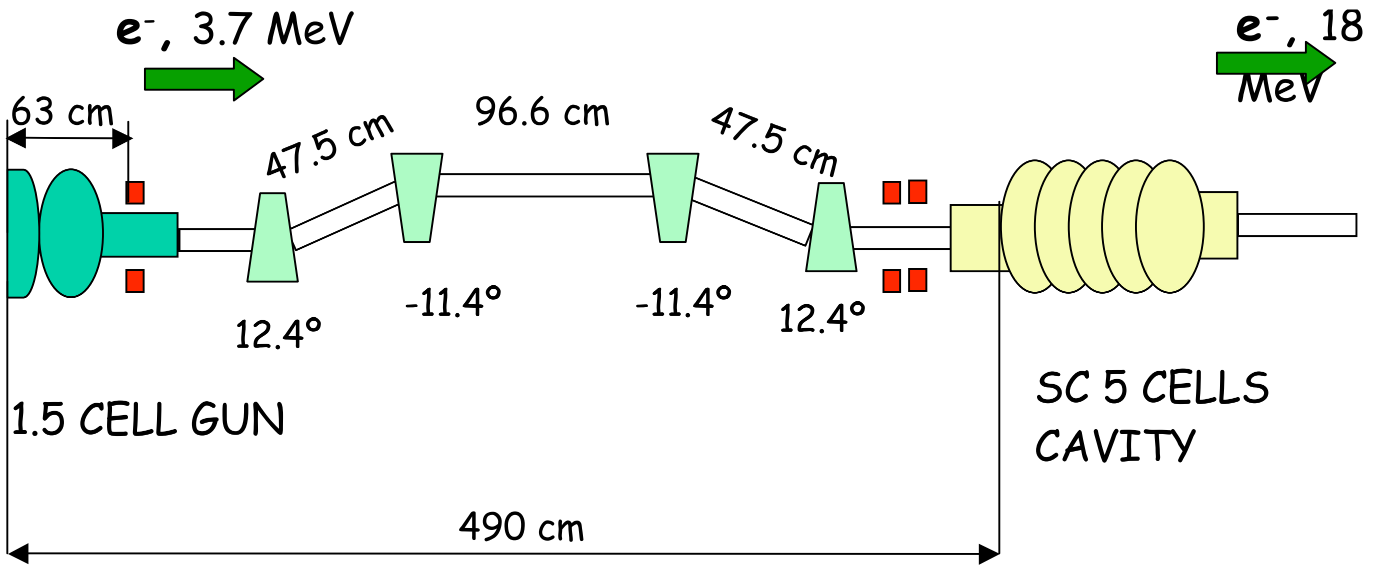
Straight Line



Zig-Zag

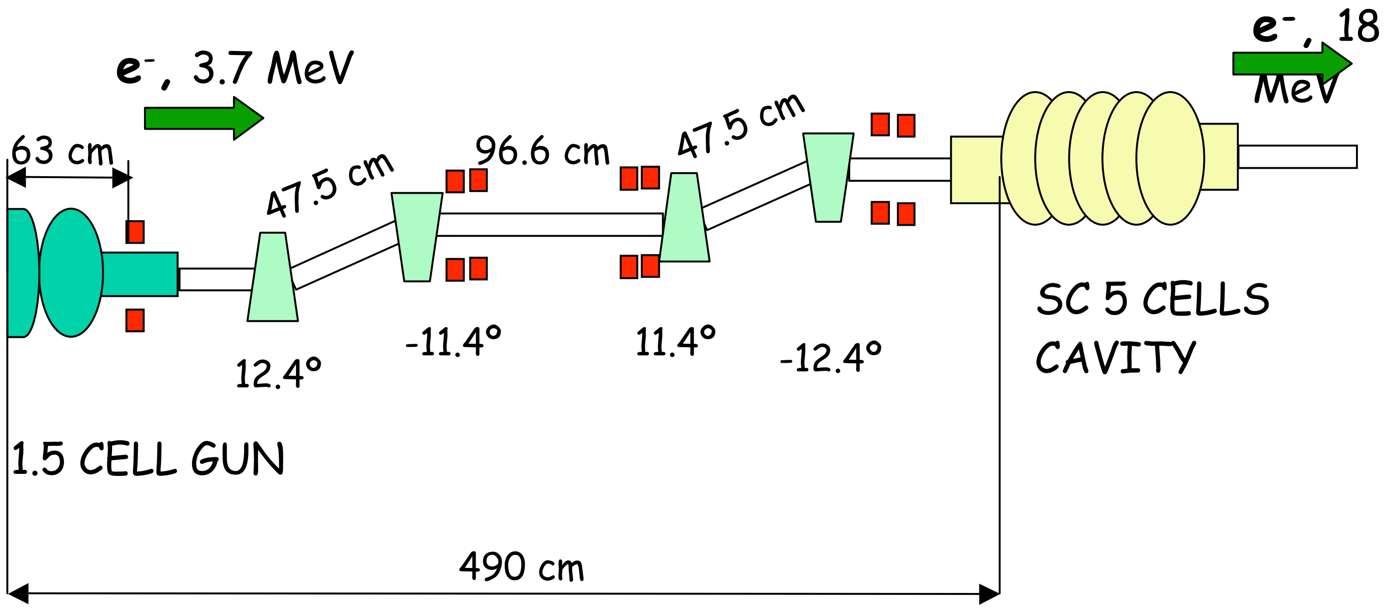

e-, 3.7 MeV
e-, 18 MeV
63 cm
10°
40 cm
81.6 cm
20°
40 cm
-20°
-10°
1.5 CELL GUN
SC 5 CELLS CAVITY
490 cm

Chicane



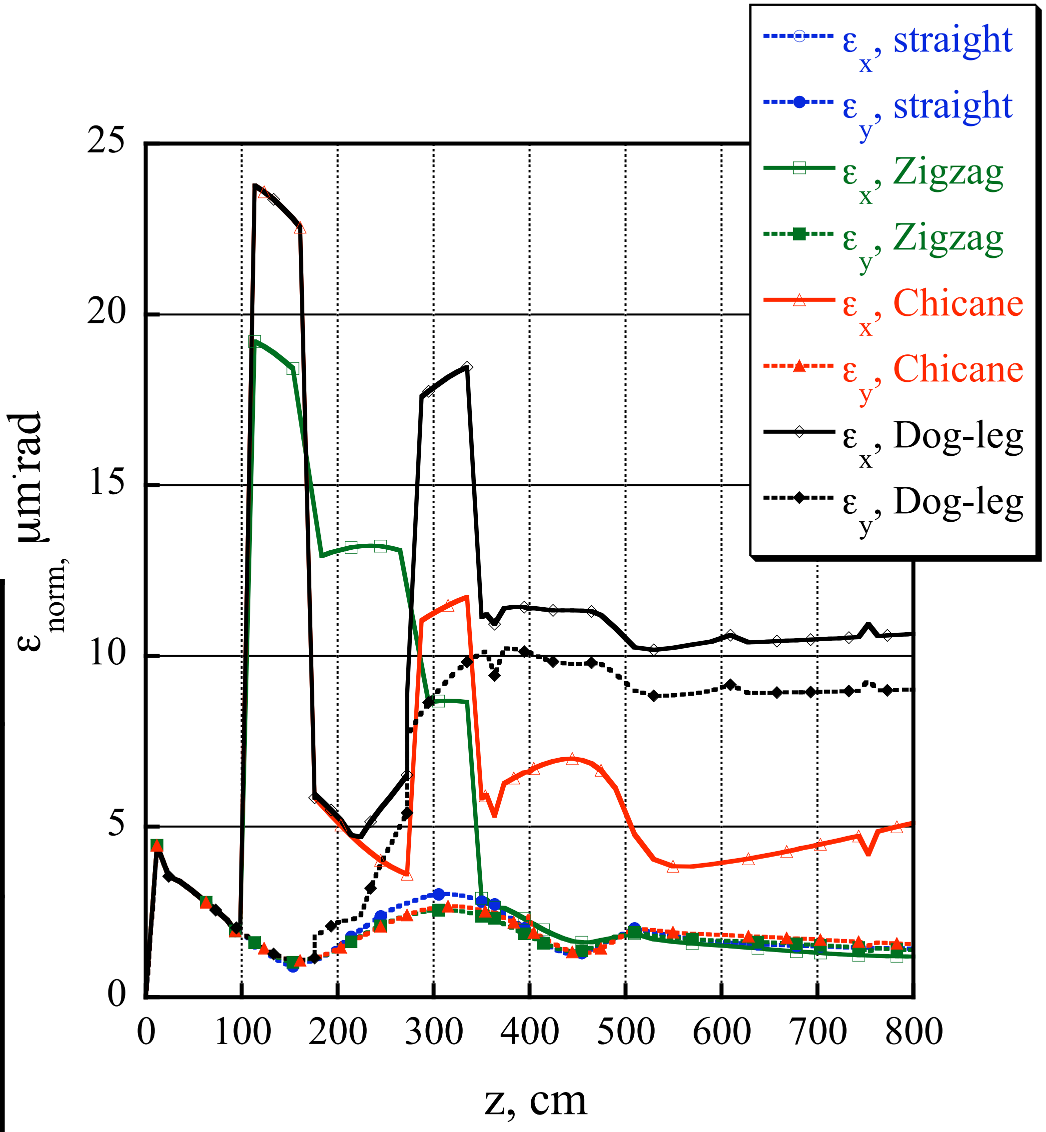
e⁻, 3.7 MeV
e⁻, 18 MeV
63 cm
47.5 cm
96.6 cm
47.5 cm
12.4°
-11.4°
-11.4°
12.4°
1.5 CELL GUN
SC 5 CELLS CAVITY
490 cm

Dog Leg


e⁻, 3.7 MeV
e⁻, 18 MeV
63 cm
47.5 cm
96.6 cm
47.5 cm
12.4°
-11.4°
11.4°
-12.4°
SC 5 CELLS CAVITY
1.5 CELL GUN
490 cm

Comparison

	Straigt line	Zigzag	Chicane	Dog-leg
$Q_{bunch,}$ nC	1.0	1.0	1.0	1.0
$\varepsilon_{n,h}$ μm rad	1.4	1.4	5	11
$\varepsilon_{n,v}$ μm rad	1.4	1.4	1.4	8



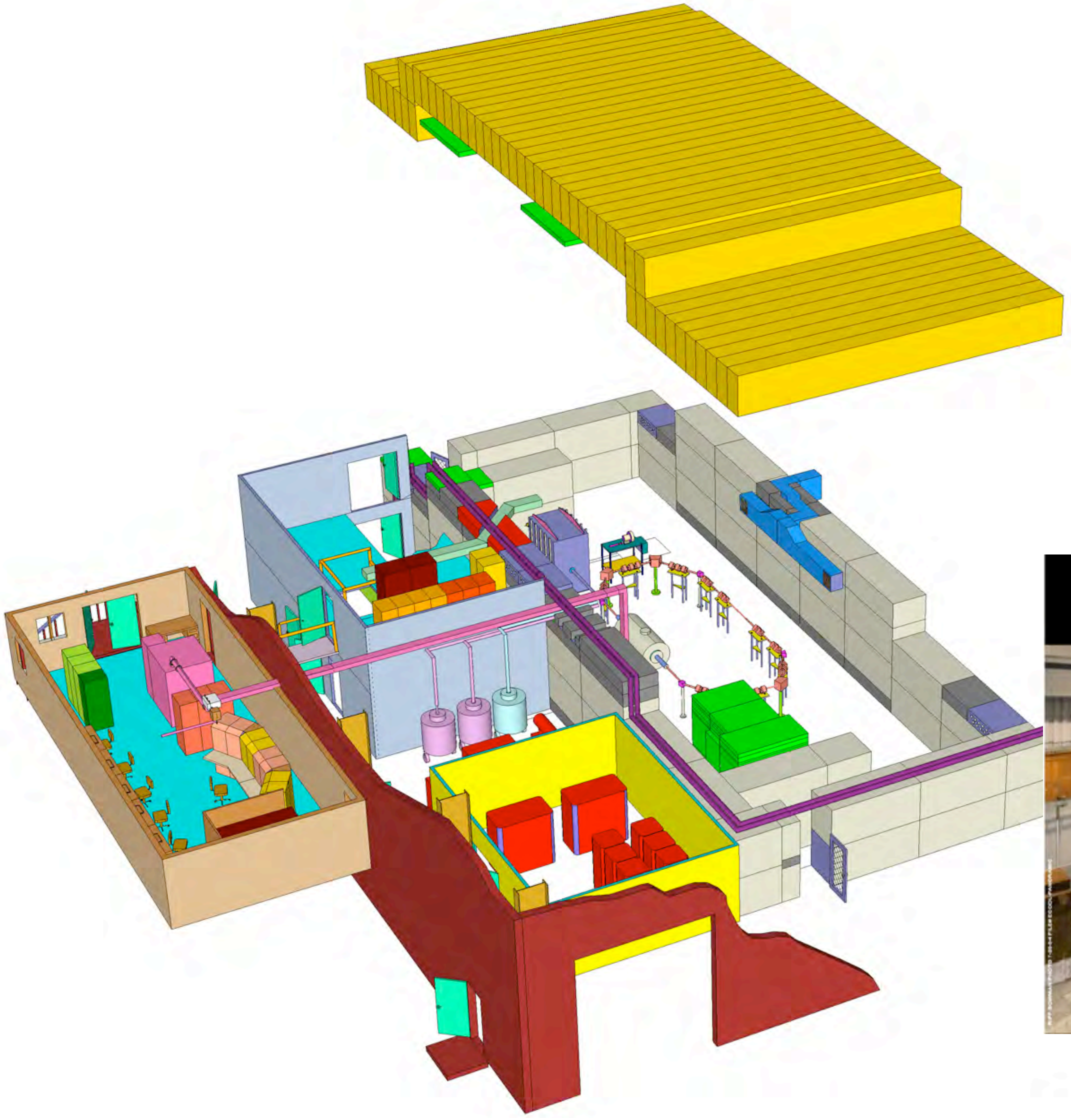
Evolution of horizontal and vertical normalized emittances in the four systems: the axially symmetric system, the Zigzag, the chicane and the Dog-leg.

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

R&D ERL in bldg. 912



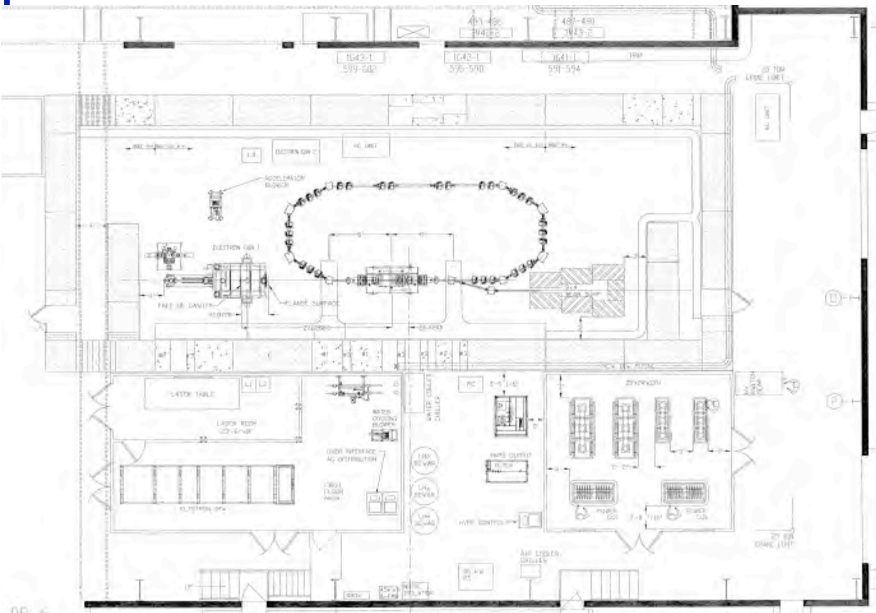
BLDG 912 Oct 03

Bldg 912 July 04

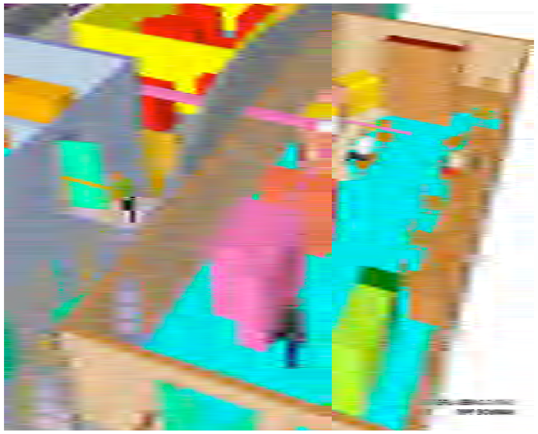
Ripp Bowman 3-7-05
File# Image-1

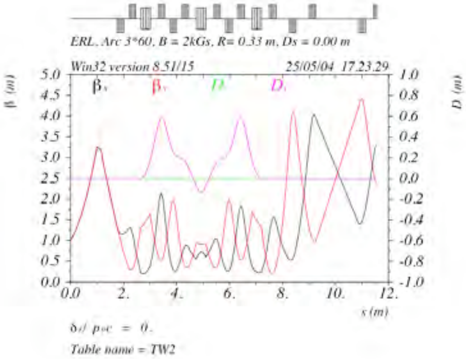
RHIC

R&D ERL in bldg. 912

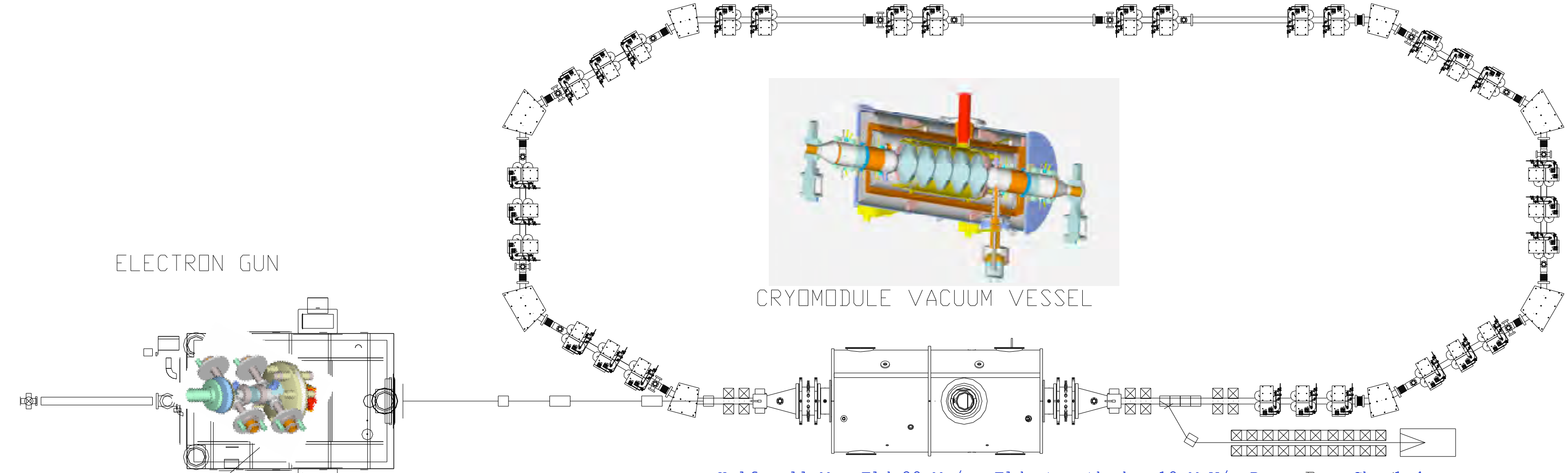


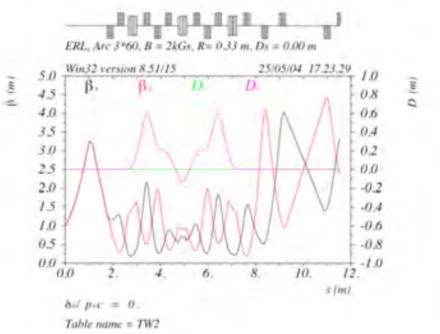
ERL circumference [m]	~ 28
Number of passes	1 to 2
Beam rep-rate [MHz]	9.38 – 351.875
for tuning	1 Hz – 1 kHz
Beam energy [MeV]	20 - 40
Electrons per bunch (max)	10^{11}
Normalized emittance [μm rad]	< 50
RMS Bunch length [m]	0.05
Charge per bunch [nC]	1.3 – 20
Average e-beam current [A]	0.02 – 0.5
Efficiency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

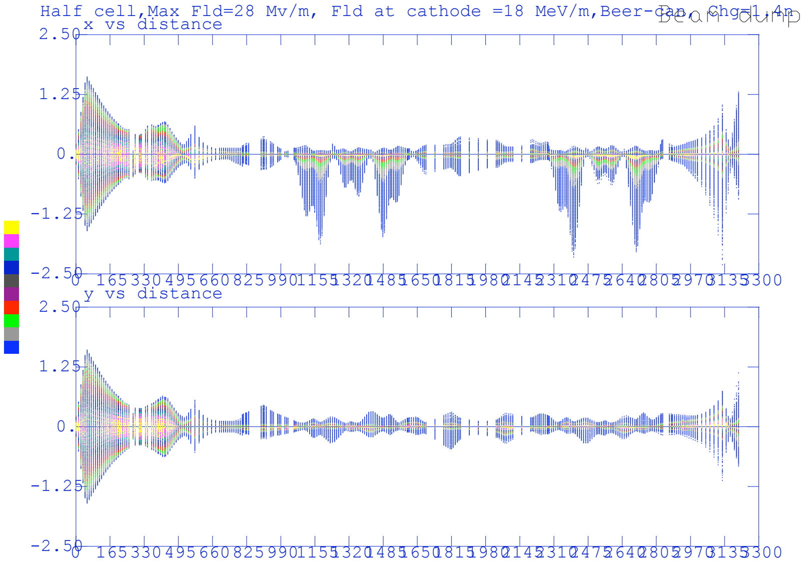




R&D ERL in Bldg.912 - Start-to-End simulations
Half cell, Max Field=28 MV/m, Field at cathode 18 MV/m, Beer-can, Chg=1.4nc,R=2.3 mm, L=12 deg







V.N.Litvinenko, Erice, October 2005

Conclusions

Merger is one distinct element of any ERL, which makes it different from standard axi-symmetric low emittance linear accelerators. Desire to operate electron beams with significant charges per bunch and to lower energy of injection into ERL requires mergers compatible with emittance compensation in space-charge dominated beams. In addition, variation of particles energies along the pass of a merger, caused by the space charge forces of the bunch, introduce additional conditions on the merger lattice.

Mergers used in presently operating ERLs were not designed for operating with very low emittance electron beam, and , therefore, can not be used for ERL operating beams with normalized emittances ~ 1 mm mrad or lower.

The concept of a Zigzag merger, based on a rather simple assumption, promises (at least at the level of the 3-D simulations using PARMELA) to solve some of the challenges presented by future ERL operating with super-bright intense electron beams. Compatibility with emittance compensation schemes and simple geometry of Zigzag mergers promise to be useful in the next generation of ERL. The experimental validity of the Zigzag merger and its performance in ERL will be tested in 20 MeV, 0.5 A ERL which is under construction as Brookhaven national Laboratory.

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