Emittance Exchange Program at KEK STF

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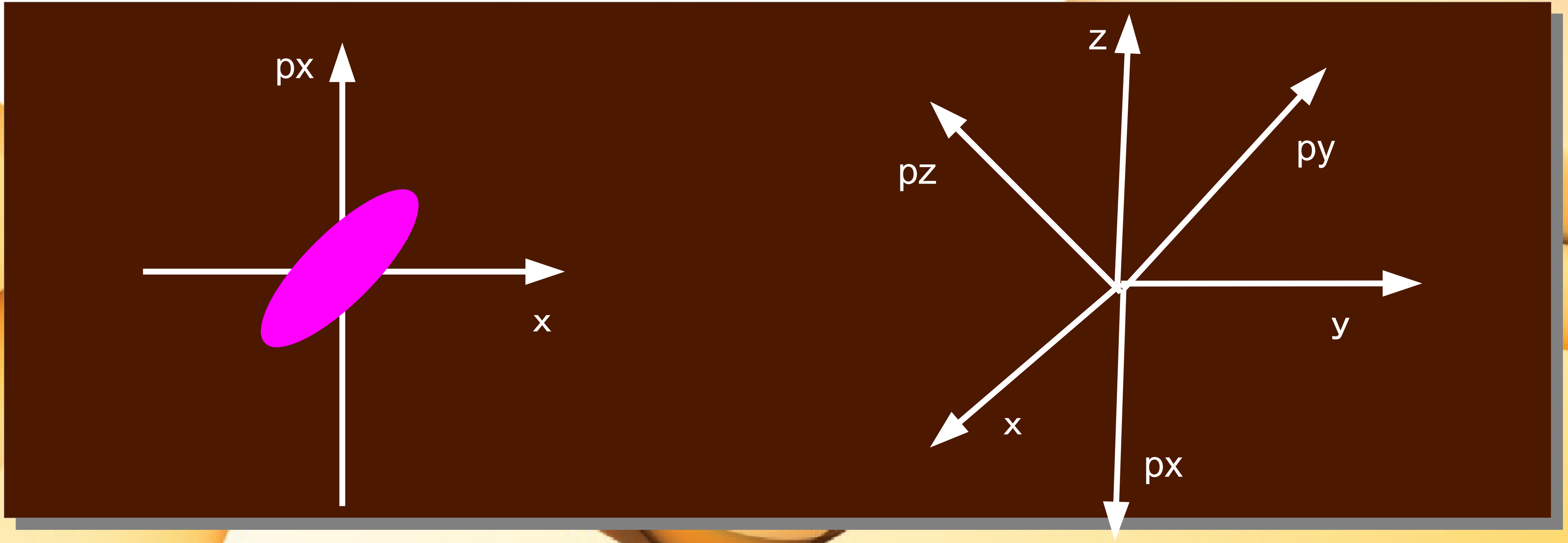
Content

- Introduction
- Emittance Exchange
- Experimental Program at KEK-ATF and WFA-ANL.
- Summary

Introduction

- Particles occupie the are of the phase-space: emittance.
- Emittance is invariant.
- In principle, the emittance is the volume in 6D phase-space.
- The 6D emittance is invariant (Loisville's theorem).



Louisville's theorem

- 6D emittance is invariant.
- 2D emittance (ex, ey, ez) are not invariant.
- Can the partioning of x, y, and z be modified as we want? (Emittance Exchange).

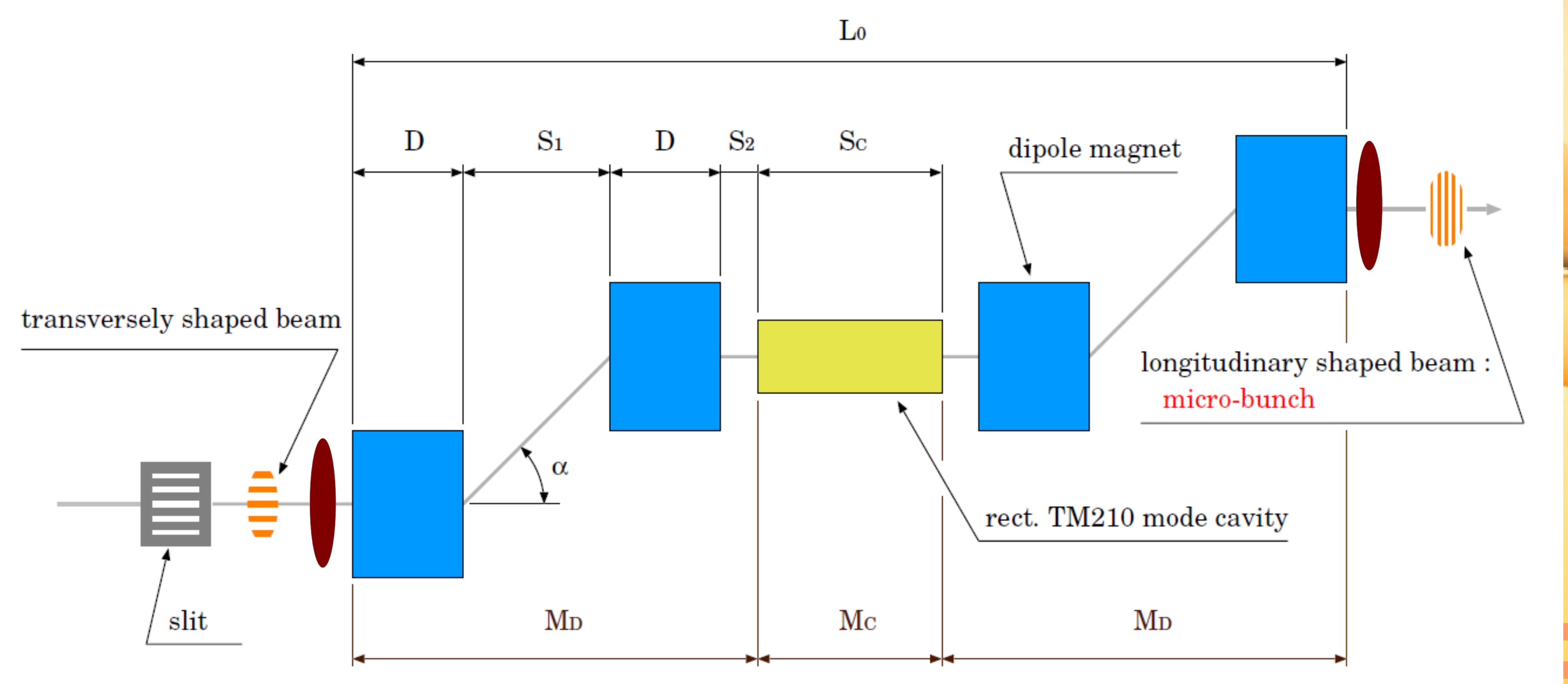
Emittance	ex	ey	ez	ex*ey*ez
No coupling	conserved	convserved	conserved	Invariant
With coupling	varied	varied	varied	Invarian

XY-Z　Emittance Exchange

TLEX(Transverse to Longitudinal Emitatnce eXchange)

XY-Z Emittance Exchange

- TLEX can be made with chicane or two doglegs and a dipole mode RF cavity.
- The phase spaces of X(transverse direction in deflecting plane) and Z (longitudinal direction) are swapped.



Transfer Matrix of a Dogleg

One dog-leg section

$$M_D(\eta, \xi, L) = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Dispersion

$$\eta = S_1 \frac{\sin\alpha}{\cos^2\alpha} + \frac{2D}{\sin\alpha}\left(\frac{1}{\cos\alpha} - 1\right)$$

Momentum compaction

$$\xi = S_2 \frac{\sin^2\alpha}{\cos^3\alpha} + \frac{2D}{\sin\alpha - \alpha}$$

Effective length

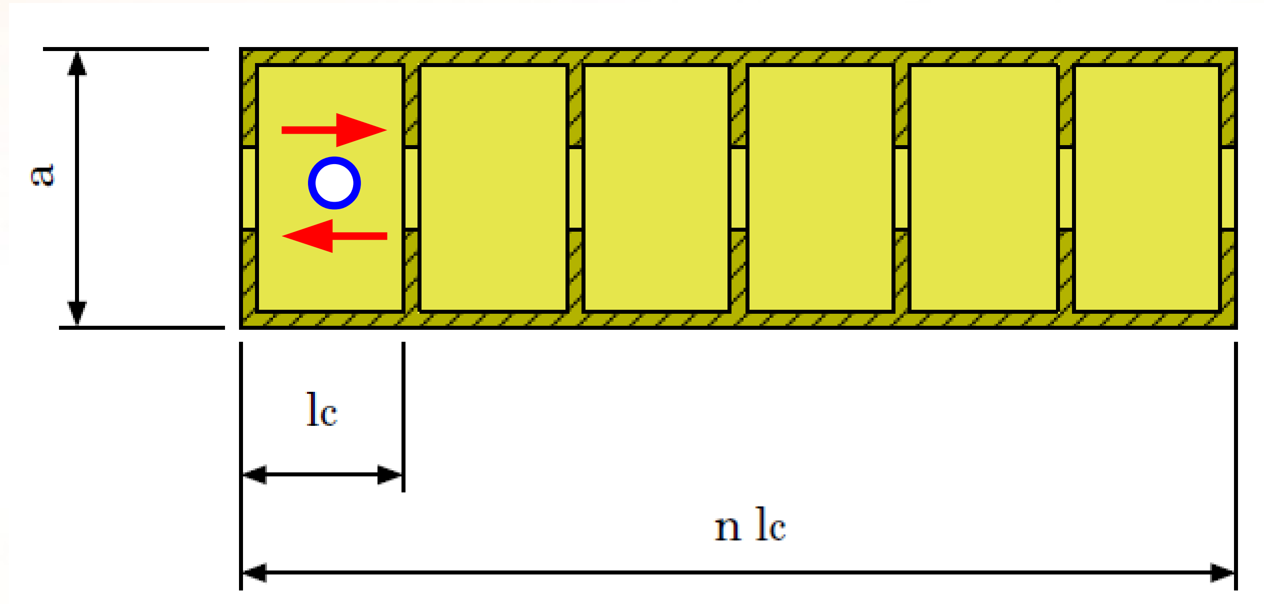
$$L = S_1 \frac{1}{\cos^3\alpha} + \frac{2D}{\cos\alpha} + S_2$$

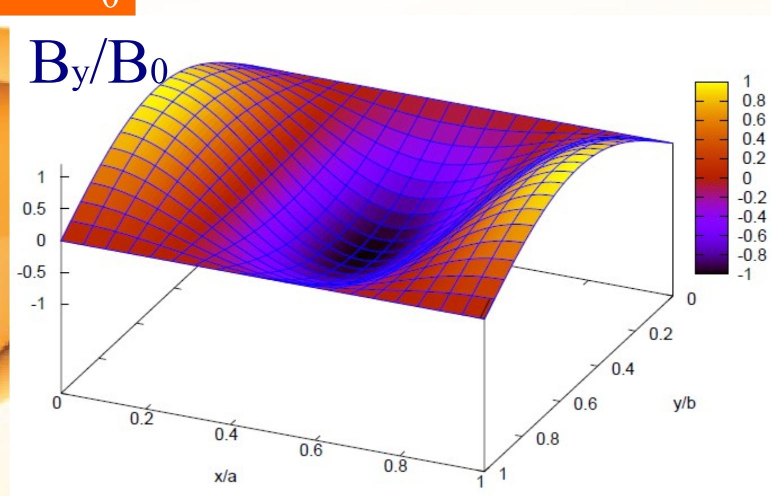
Transfere Matrix of Diple RF

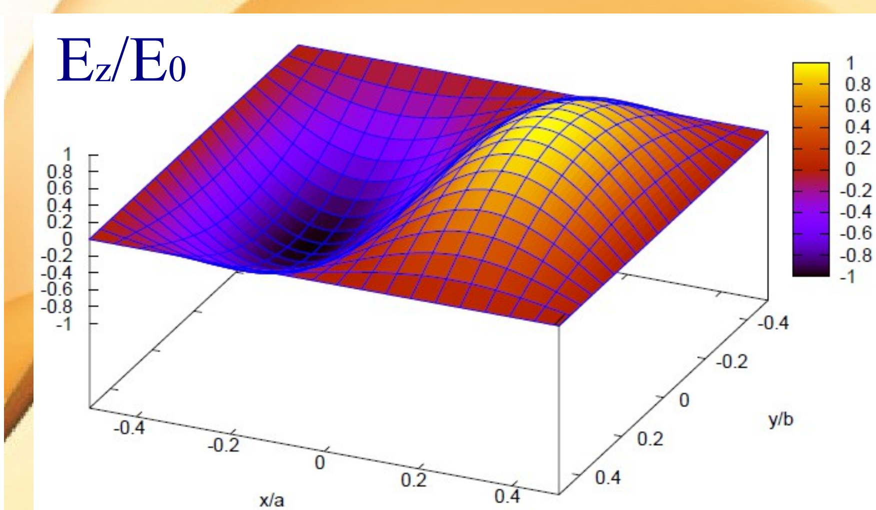
TM011cavity

$$M_C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$$

$$k = \frac{V_0}{aE_0}$$







Matrices -EEX section-

$$M_{EEX} = M_D(\eta,\xi,L)\, M_C\, M_D(\eta,\xi,L)$$

$$= \begin{bmatrix} 0 & 0 & -L/\eta & \eta - L\xi/\eta \\ 0 & 0 & -1/\eta & -\xi/\eta \\ -\xi/\eta & \eta - L\xi/\eta & 0 & 0 \\ -1/\eta & \frac{-L}{\eta} & 0 & 0 \end{bmatrix}$$

matching condition $1 + \eta k = 0$

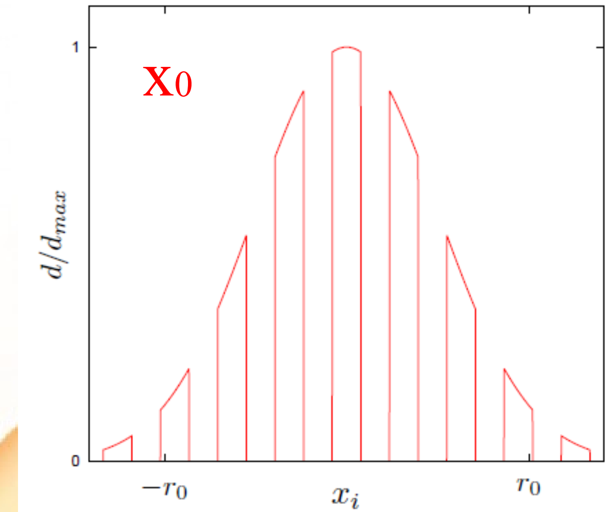
compression factor

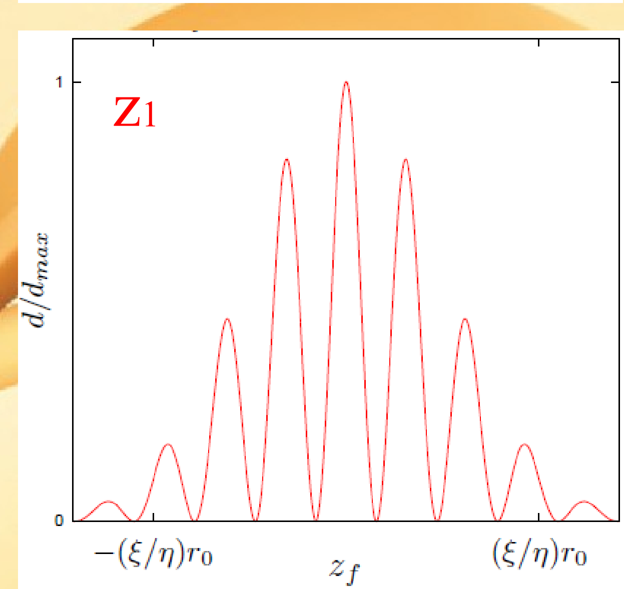
dillution factor

$$z_1 = -\frac{\xi}{\eta} x_0 + \left(\eta - L\frac{\xi}{\eta}\right) x'$$

$$\delta_1 = -\frac{1}{\eta} x_0 - \frac{L}{\eta} x'$$

x-z space exchange
by the 4D space rotation.





XY Emittance Exchange

RFTB(Round to Flat Beam Transformation)

Magnetized Beam

- Beam Generation in solenoid field (B_z)
- Canonical momentum by Vector potential has the angular momentum.
- By the fringe field, the canonical momentum becomes the kinetic momentum .
- The x-py and y-px correlated beam is obtained.
- The ex and ey are quite bad and the beam is useless in a usual sense.

Vector Potential

$$A_x = -\frac{B_0}{2} y \qquad A_y = \frac{B_0}{2} x$$

Magnetized Beam

$$\vec{P}_c = \vec{P} - e\vec{A} \qquad \vec{P}_c \sim \frac{eB_o}{2} \begin{pmatrix} y \\ -x \end{pmatrix}$$

In sigma matrix

$$\Sigma_0 = \sigma^2 \begin{bmatrix} 1 & 0 & 0 & -\kappa \\ 0 & \kappa^2 & \kappa & 0 \\ 0 & \kappa & 1 & 0 \\ -\kappa & 0 & 0 & \kappa^2 \end{bmatrix} \quad \kappa \equiv \frac{eB_0}{2mc}$$

Restoration Matrix

- By ignoring the intrinsic emittance, the beam at the exit of the solenoid field is

$$\vec{Y}_0 = \vec{S}\,\vec{X}_0 \qquad \vec{S} = \begin{pmatrix} 0 & \frac{2}{eB_0} \\ \frac{-eB_0}{2} & 0 \end{pmatrix}$$

- Beam transfer with a matrix M is

$$\begin{pmatrix} X_1 \\ Y_1 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} = M \begin{pmatrix} 1 \\ S \end{pmatrix} X_0$$

- If the condition is satisfied, Y_1 is independent from X_0.

$$M_{21} + M_{22} S = 0$$

E. Thrane, LINAC2002

Restoration Matrix

- The solution is the skew Q channel composed from three quadrupoles.

$$M = R^{-1} Q(q_3) O(D) Q(q_2) O(D) Q(q_1) R$$

$$R = \frac{1}{\sqrt{2}} \begin{pmatrix} I & I \\ -I & I \end{pmatrix} \quad Q(q) = \sqrt{2} \begin{pmatrix} Q(q) & 0 \\ 0 & Q(-q) \end{pmatrix} X_0$$

- The skew quadrupole strengths are given by the initial sigma matrix.

$$q_1 = \pm \sqrt{\frac{-Ds_{11} + s_{12} + 2D^2 s_{21} + 2Ds_{22}}{2D^2 s_{12}}}$$

$$q_2 = -\frac{s_{12} + 2D\, s_{22}}{D^2 (1 + q_1 s_{12})}$$

$$q_3 = \frac{-q_1 - q_2 - D\, q_1 q_2 s_{11} - s_{21}}{1 + (2Dq_1 + Dq_2) s_{11} + D^2 q_2 (q_1 + s_{21})}$$

E. Thrane, LINAC2002

Emittance Ratio

- The emittance after the skew Q-channel is

$$\epsilon_n^{\pm}\sqrt{(\epsilon_n^u)^2+(\gamma\beta L)^2}\pm(\gamma\beta L)$$

$$L=\frac{eB_0\sigma_c^2}{p_z}$$

- If $\epsilon_n^u \leqslant \gamma\beta L$ the emittance and the ration are

$$\epsilon_n^{+}\sim 2\gamma\beta L$$

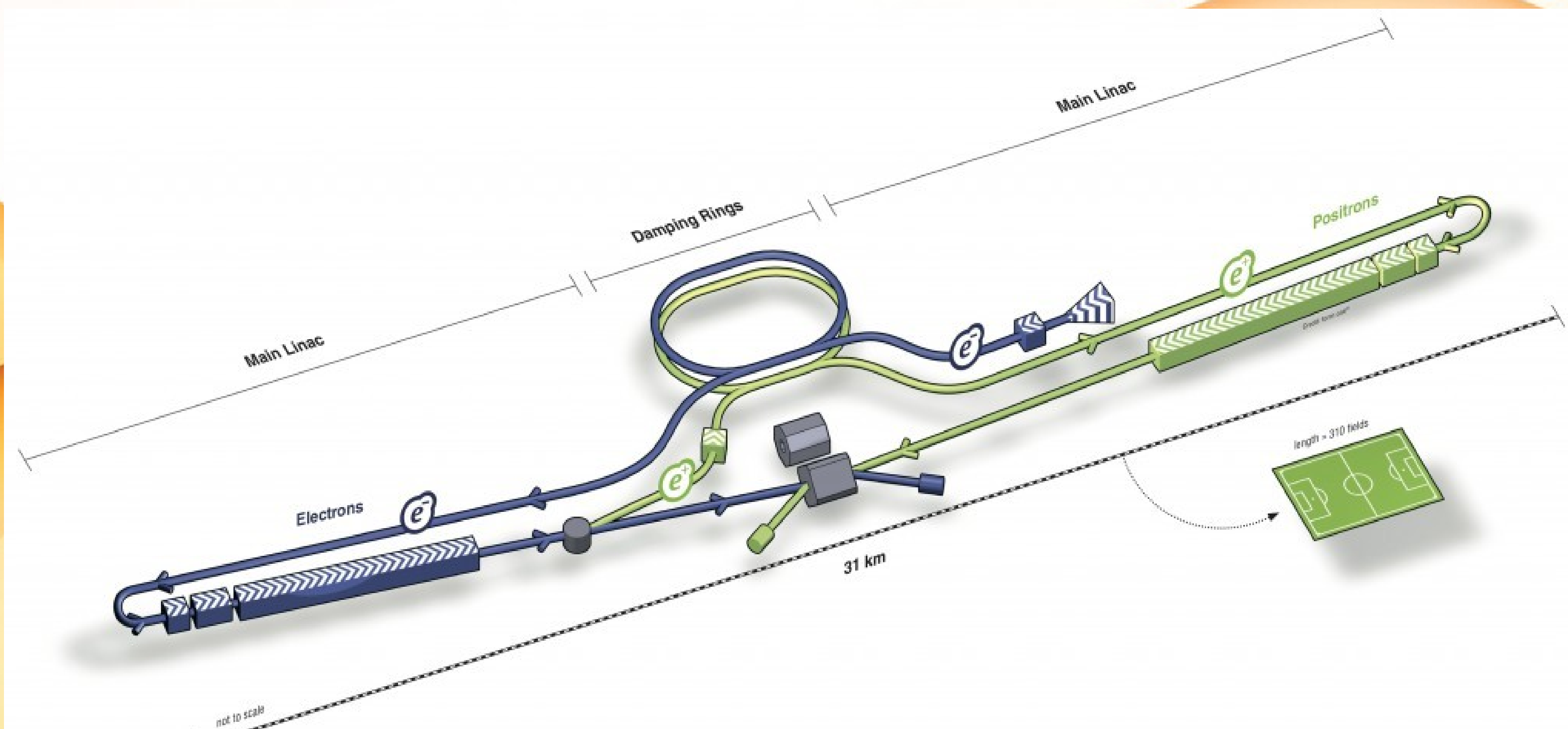
$$\epsilon_n^{-}\sim\frac{(\epsilon_n^u)^2}{(2\gamma\beta L)}$$

$$\frac{\epsilon_n^{+}}{\epsilon_n^{-}}\sim\frac{(\epsilon_n^u)^2}{(2\gamma\beta L)^2}$$

P. Piot, Y.-E. Sun,and K. -J. Kim PRSTAB(9)031001(2006).

Asymmetric Beam for Linear Collider

a)Linear Collider is an only solution for e+e- collision beyond the limit of ring colliders by the huge energy loss by synchrotron radiaon.
b)The beam is “one pass” and the beam current is very limited. In order of 10mA for linear colliders, and in order of A for a modern ring collider .
c)To obtain an enough luminosity, the beam is focused down to nm.



High Aspect Ratio Beam in LC

Event Rate

$$N = \sigma \times L$$

σy«σx(Asymmetric Beam)

Luminosity ↑ $$L = \frac{f_{rep} n_b N^2}{4\pi \sigma_x \sigma_y}$$

Beamstrahlung ↓ $$\frac{\Delta E}{E} \propto \frac{N^2 E}{(\sigma_x^2 + \sigma_y^2)\sigma_z}$$

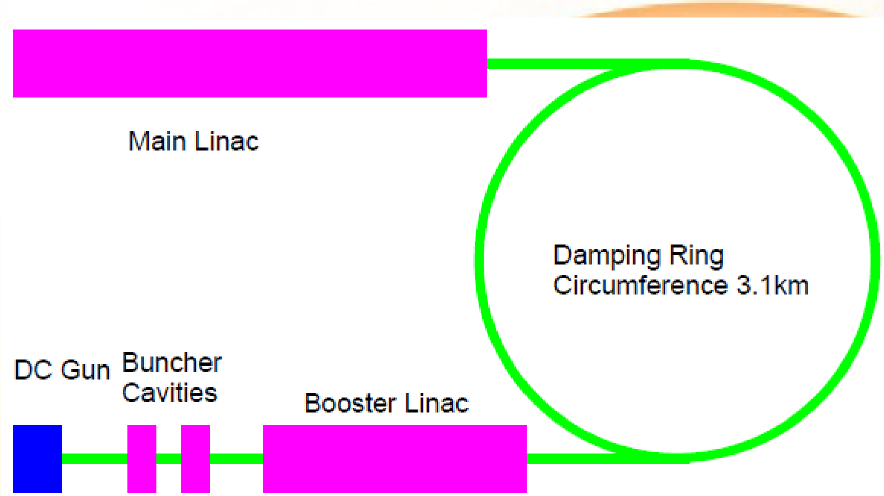
Disruption ↓ $$D_{x,y} = \frac{2Nr_e}{\gamma} \frac{\sigma_z}{\sigma_{x,y}(\sigma_x + \sigma_y)}$$

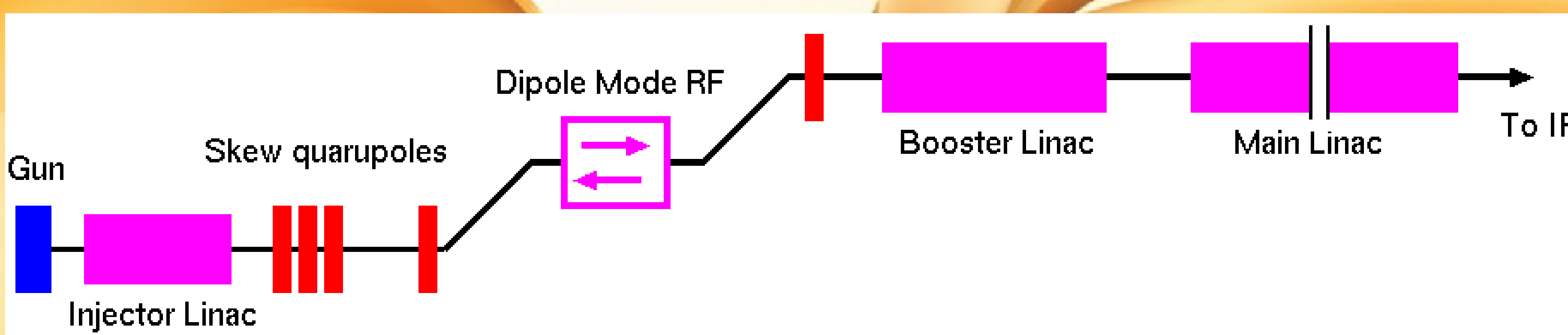
Parameter	Value
Horizontal size	640 nm
Vertical size	5.7 nm
Bunch length	300 μm
Vertical Disruption	19.4
RMS energy by BS	2.4%
Horizontal emi.	10 mm.mrad
Vertical emi.	0.04 mm.mrad

aspect ratio 250
is made up with 3km DR

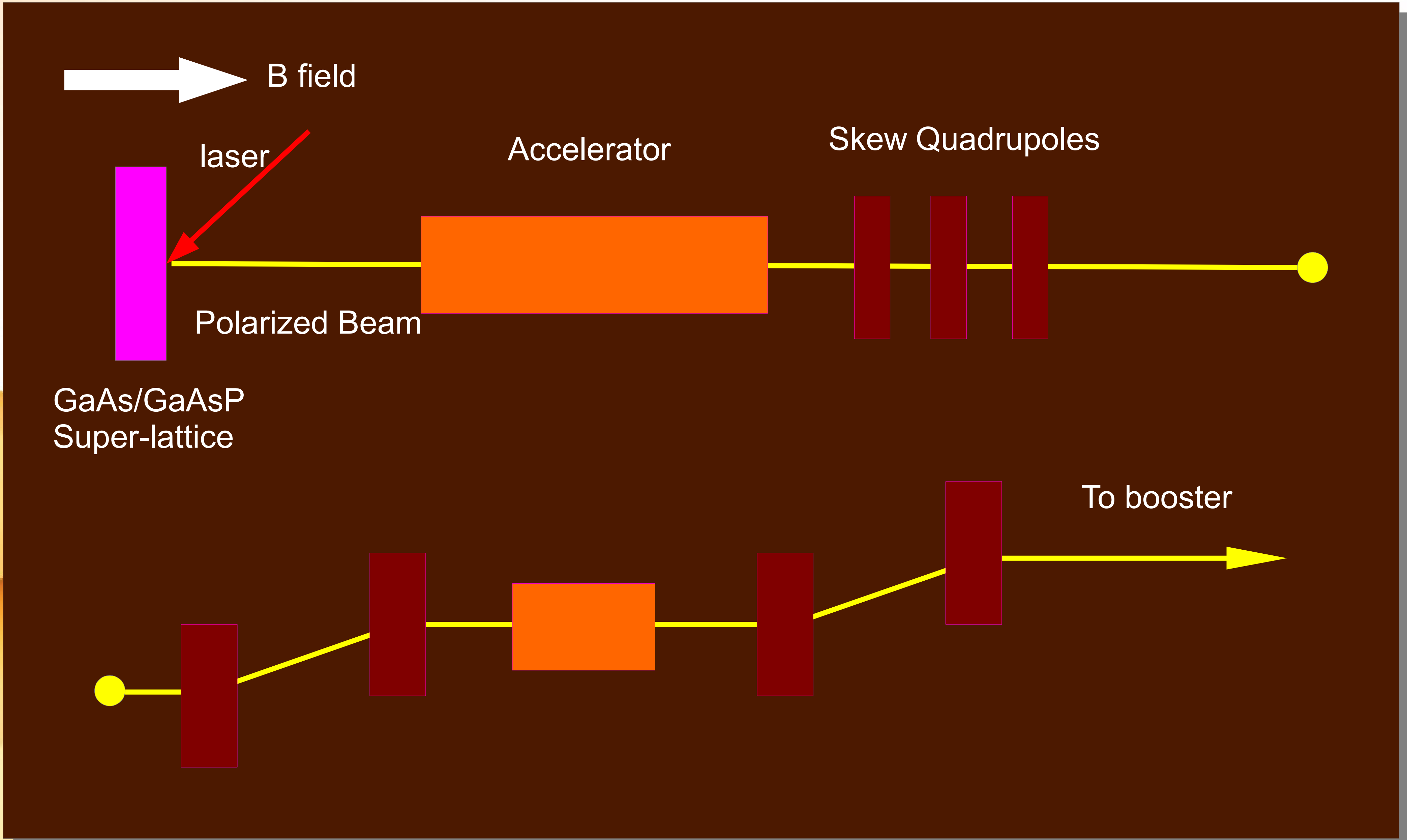
High Aspect Ratio Beam by EMIX

- The high aspect ratio beam is generated by a 3km DR (Damping Ring) in the current design.
- I the beam can be generated directly from the injector with EmiX technique, the design can be much simpler.



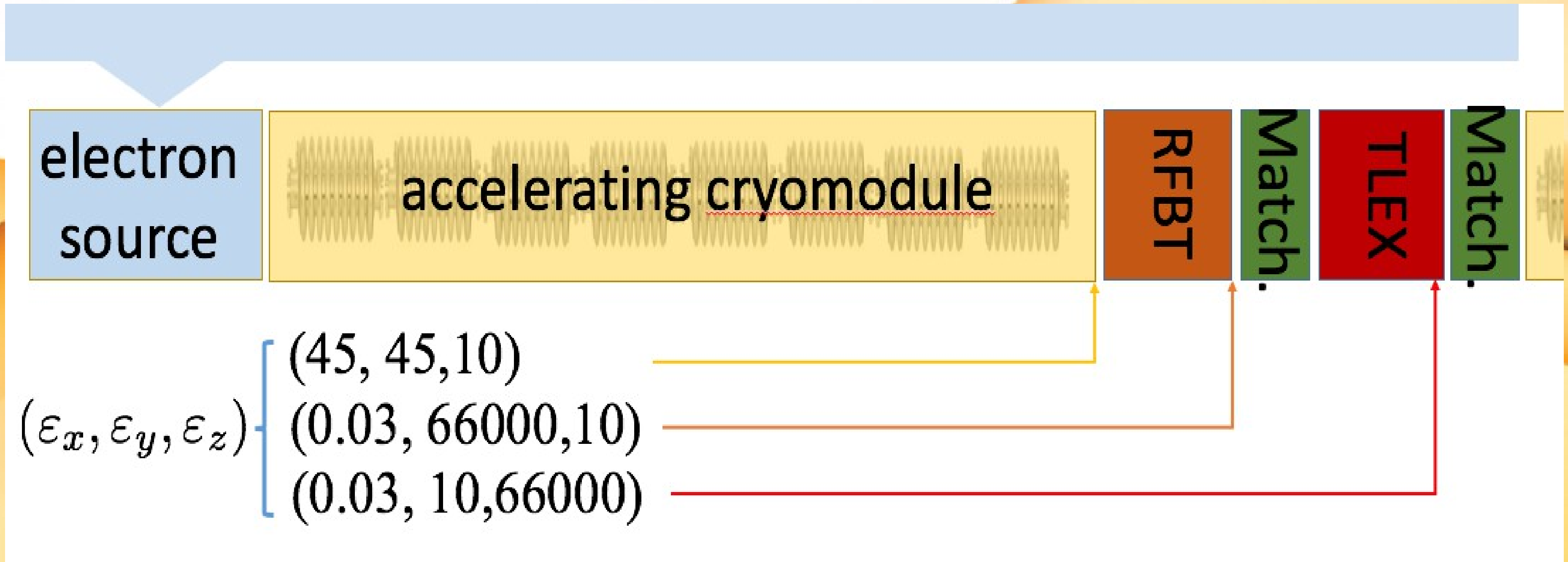


High Aspect Ratio Beam Generation with EmiX



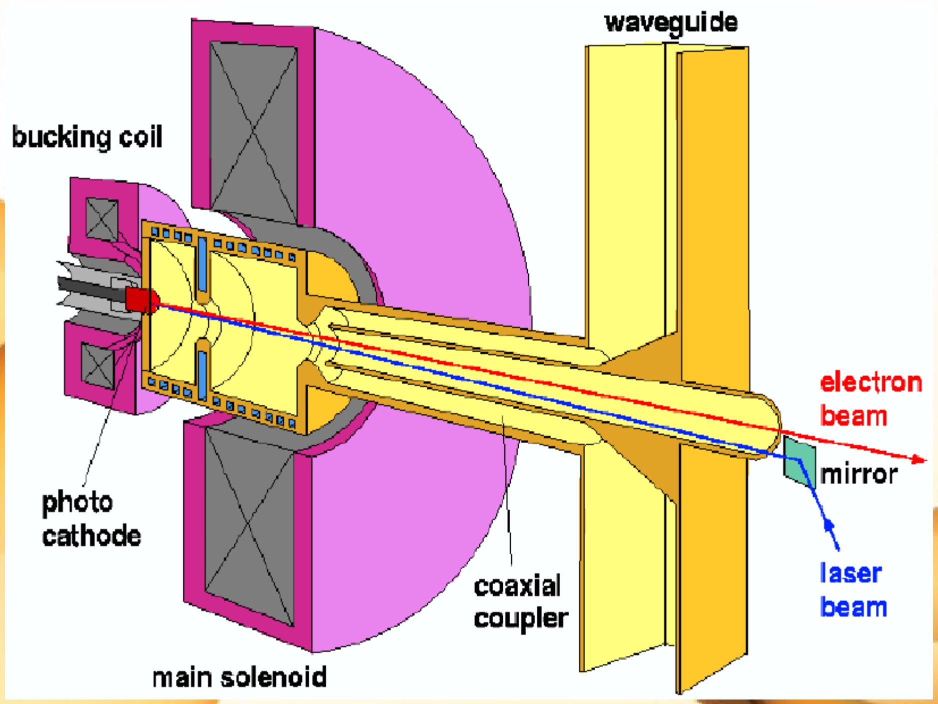
Flat Beam Generation for LC

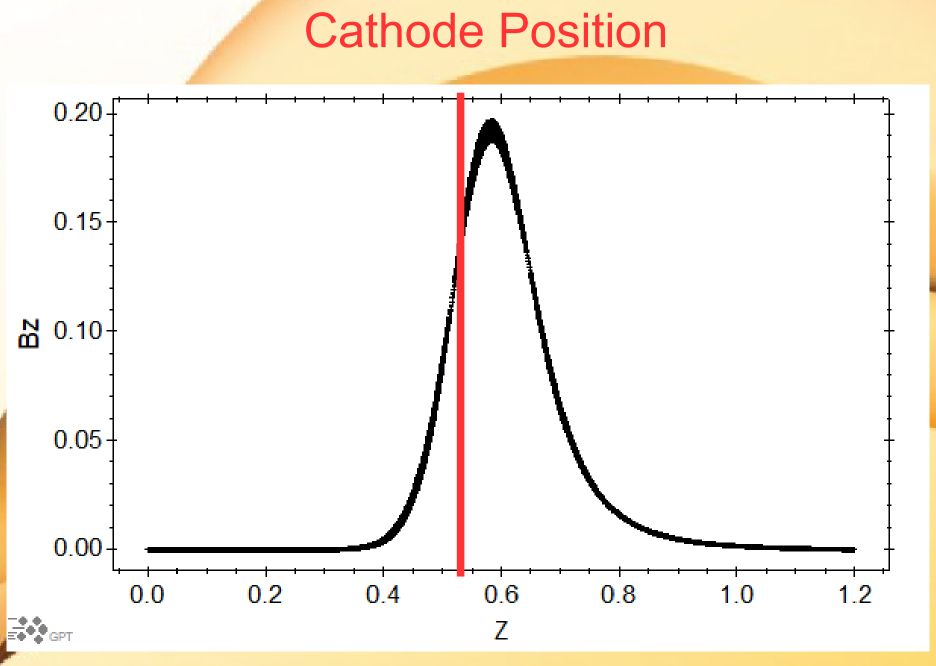
- The flat beam (ex=10um, ey=0.04um) can be generated with RFTB and TLEX.
- The beam is generated in a large size to compensate the space charge non-linearity. ex=ey=45 um.
- By RFTB, it can be ex=66000um and ey=0.03.
- The ex is too large for LC. It should be exchanged with ez by TLEX.



STF RF Gun

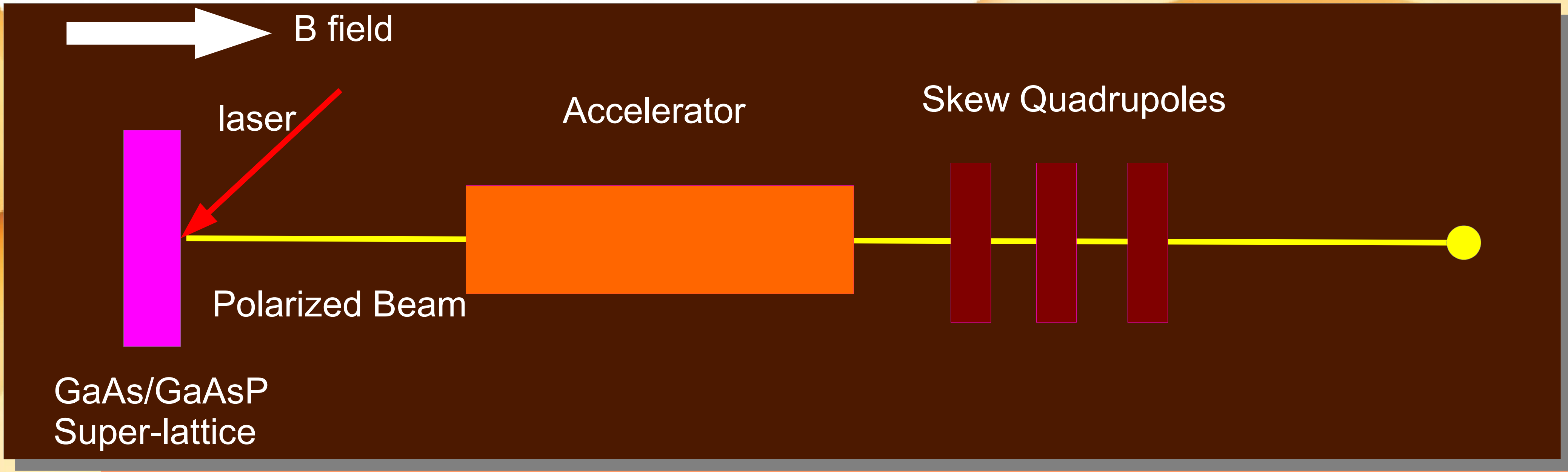
- L-band (1.3 GHz) normal conducting RF gun developed for FLASH/XFEL at DESY.
- By switching current of the bucking coil, solenoid field can be made on the cathode surface.
- In the simulation, that was 0.1 Tesla.



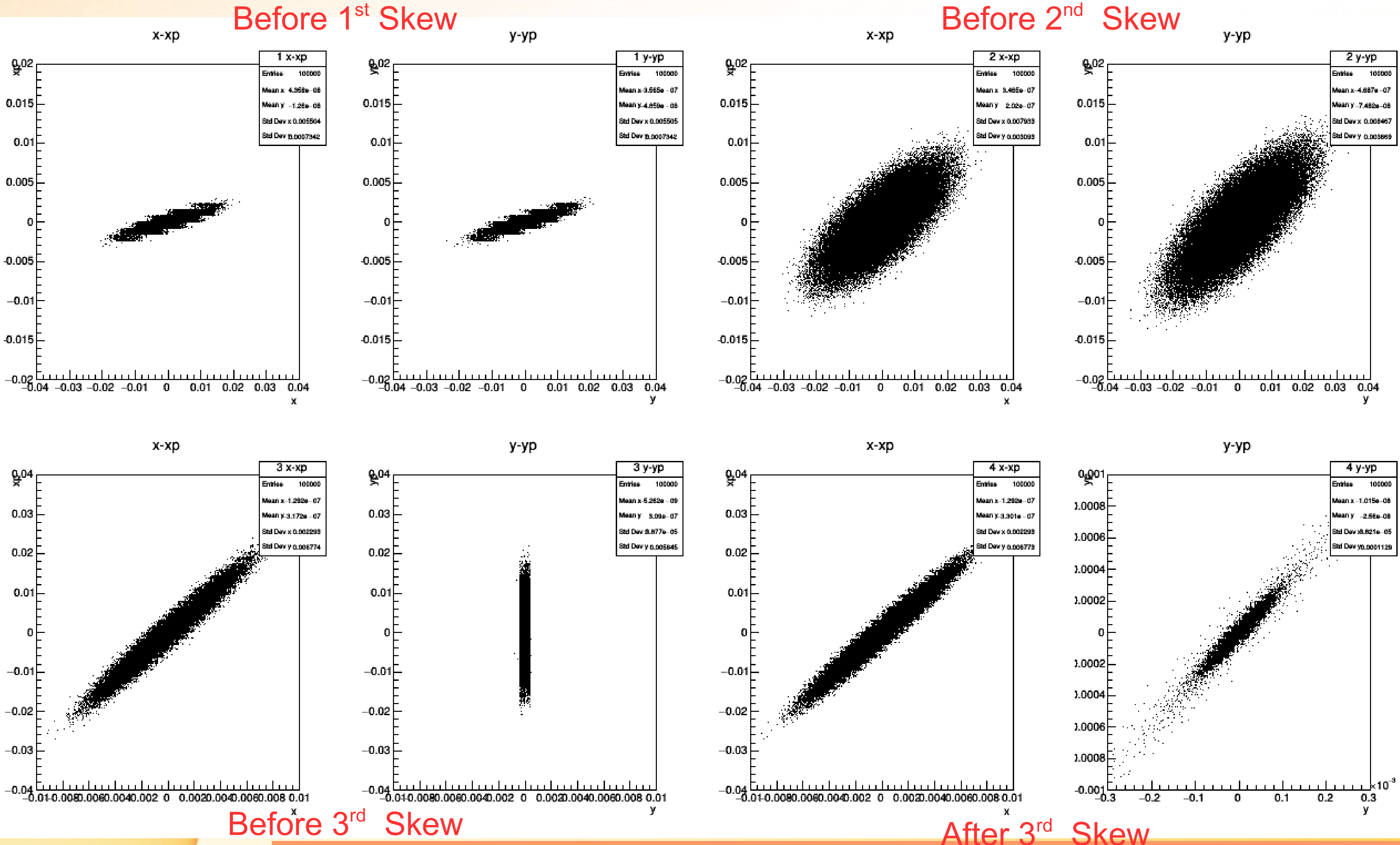


RFTB Section

- The beam is generated in 0.1 Tesla selenoid field.
- The canonical angular momentum is converted in the free-space.
- The beam is accelerated and the correlation is restored by skew-Q channel.



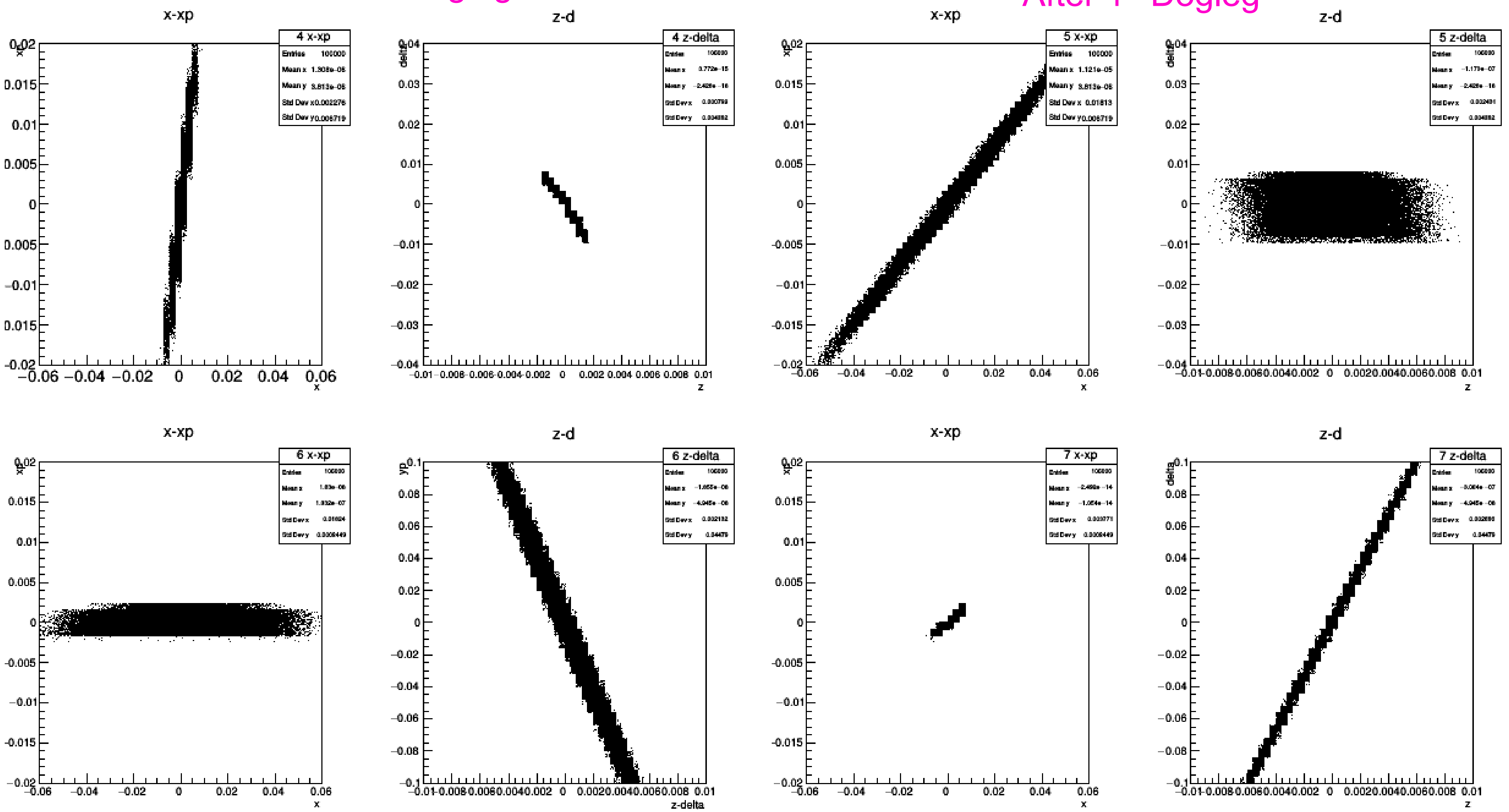
Phase-space in RFTB



Phase-space in TLEX

Before 1st Dogleg

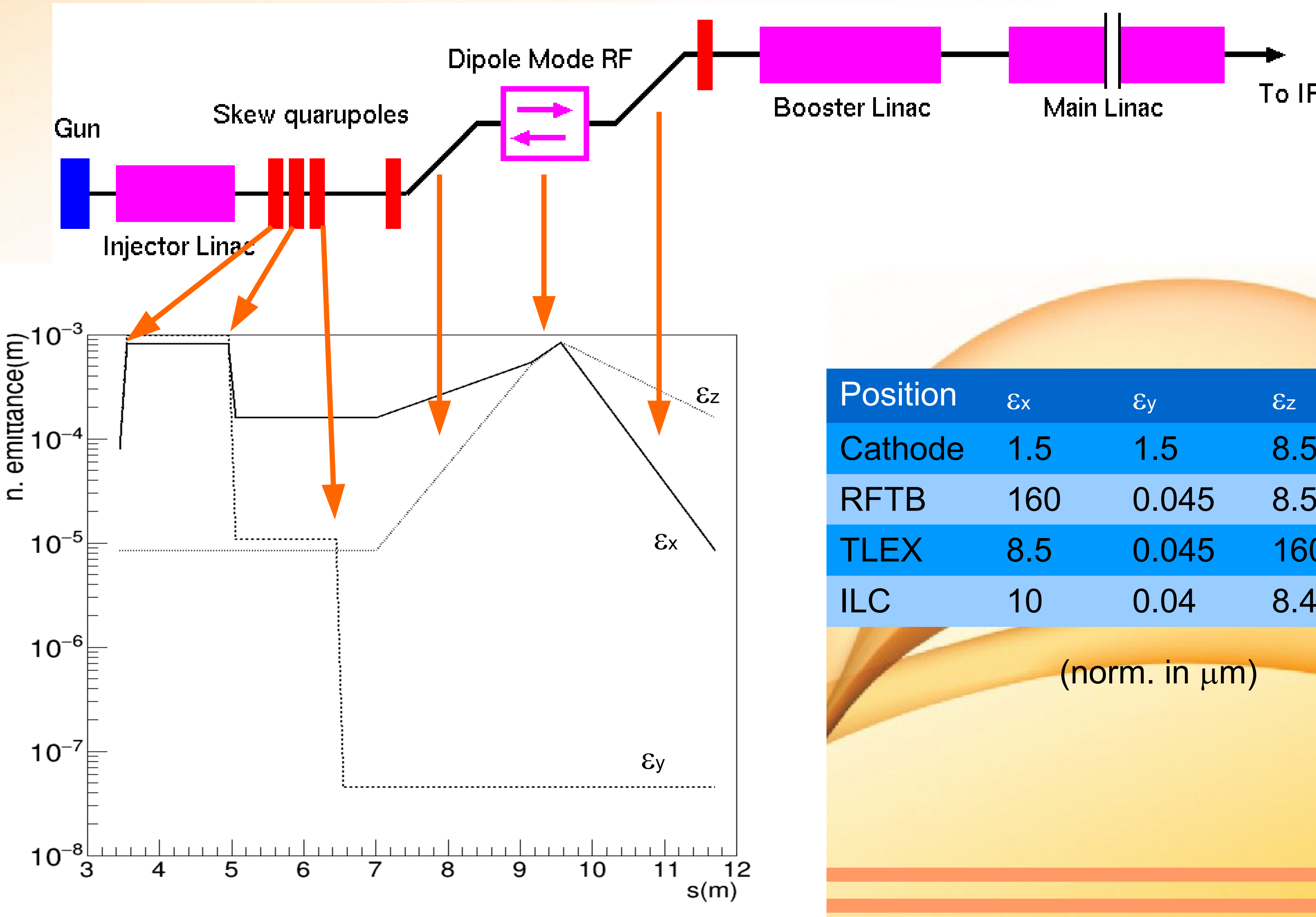
After 1st Dogleg



After dipole RF

After 2nd Dogleg

Emittance Evolution



Position	εx	εy	εz
Cathode	1.5	1.5	8.5
RFTB	160	0.045	8.5
TLEX	8.5	0.045	160
ILC	10	0.04	8.4e+5

(norm. in μm)

Parameters

Parameter	Value	Unit
Bsol	0.1	T
Initial emittance	1.5	mm.mrad
Bunch length	12	ps (full width)
Beam size	1.6	mm (rms)
Gamma after acc.	49	
g1	-0.503	T/m
g2	0.926	T/m
g3	2.058	T/m
alpha	0.3	rad
η (dispersion)	0.355	
ξ (mom. compaction)	0.106	
RF voltage	1.29	MV (at λ)

Flat Beam Generation at STF

- RFBT experiment will be carried at KEK-STF.
- TLEX experiment will be carried out at ANL WFA.
- The flat beam compatible to LC will be demonstrated in STF by introducing the TLEX beam line as a future proposal.

Summary

- Emittance exchange gives a freedom to optimize the emittance paritioning among degree of freedom.
- ILC compatible beam can be made with these techniques.
- A tiny ε_y can be made by RFTB with a mm size beam without strong space charge effect.
- ε_x after RFTB is too large. TLEX fix the problem by swap it to the small ε_z.
- Simulation with space charge, non-linarity, thick lens effects... are issues.
- Pilot experiments will be carried out at KEK-STF and ANL-WFA.
- It can be a proposal for a future plan of STF.

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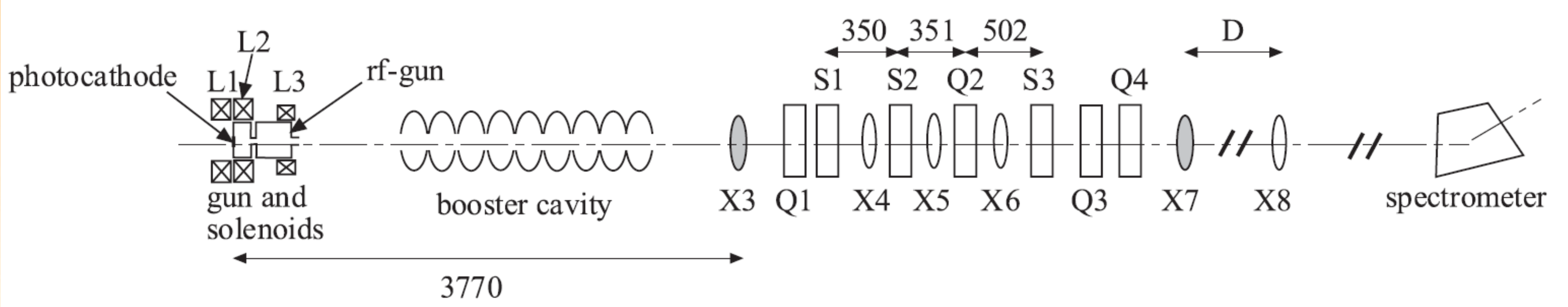
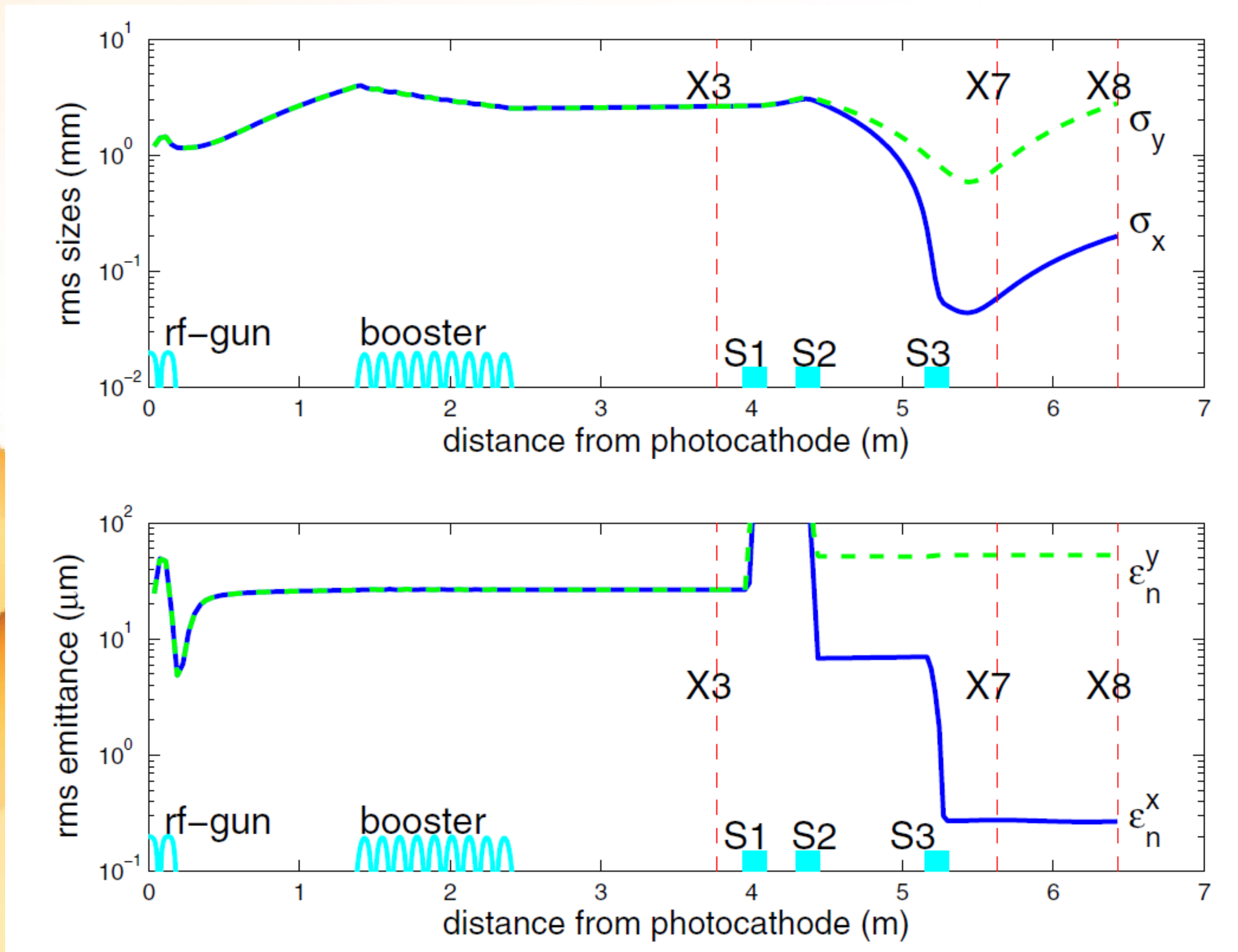
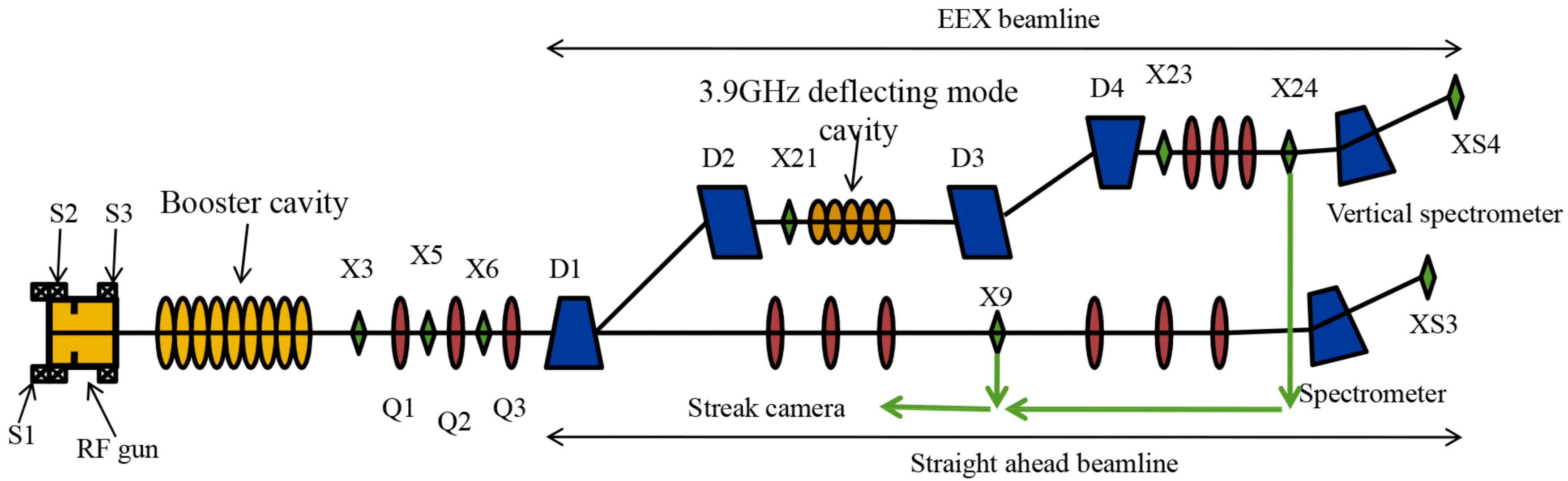




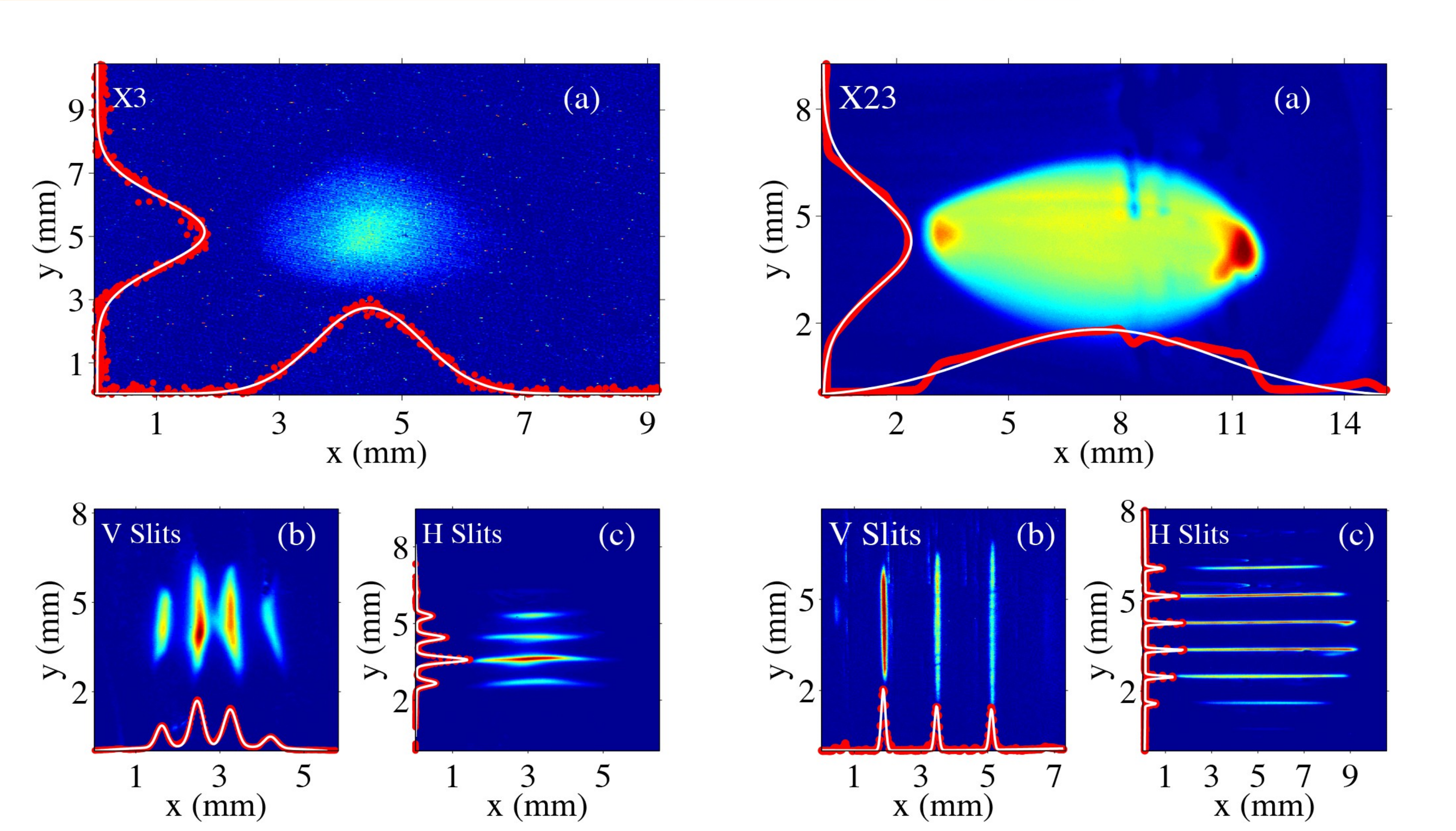
P.Piot, Y.-E Sun, K.-J. Kim
PRSTAB(9)031001(2006)

Emittance Ratio 100 was achieved.

1^{st} observation of TLEX



J. Ruan., *et al.* "First observation of the exchange of transverse and longitudinal emittances." FERMILAB-PUB-10-468-AD *(2011).*


X3
(a)
y (mm)
x (mm)
V Slits
(b)
H Slits
(c)
X23
(a)
V Slits
(b)
H Slits
(c)