Numerical Simulations for High Brightness Electron beams and Thomson/Compton Collisions

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Outline

- Introduction
  - The Brightness
  - An example of a Linac (photo injector) ad hoc for Thomson/Compton sources
  - RF-Gun introduction (physics and beam dynamics)
- Useful codes for space charge dominated beam simulations
  - Point to Point (P-P) 2D - 3D Codes
  - The Astra code
  - Examples of the Astra Use
- CAIN, a Montecarlo quantum code to simulate electron-photon interactions
  - Some examples of the CAIN use
- Useful references

❖ The Brightness – 1

Brightness

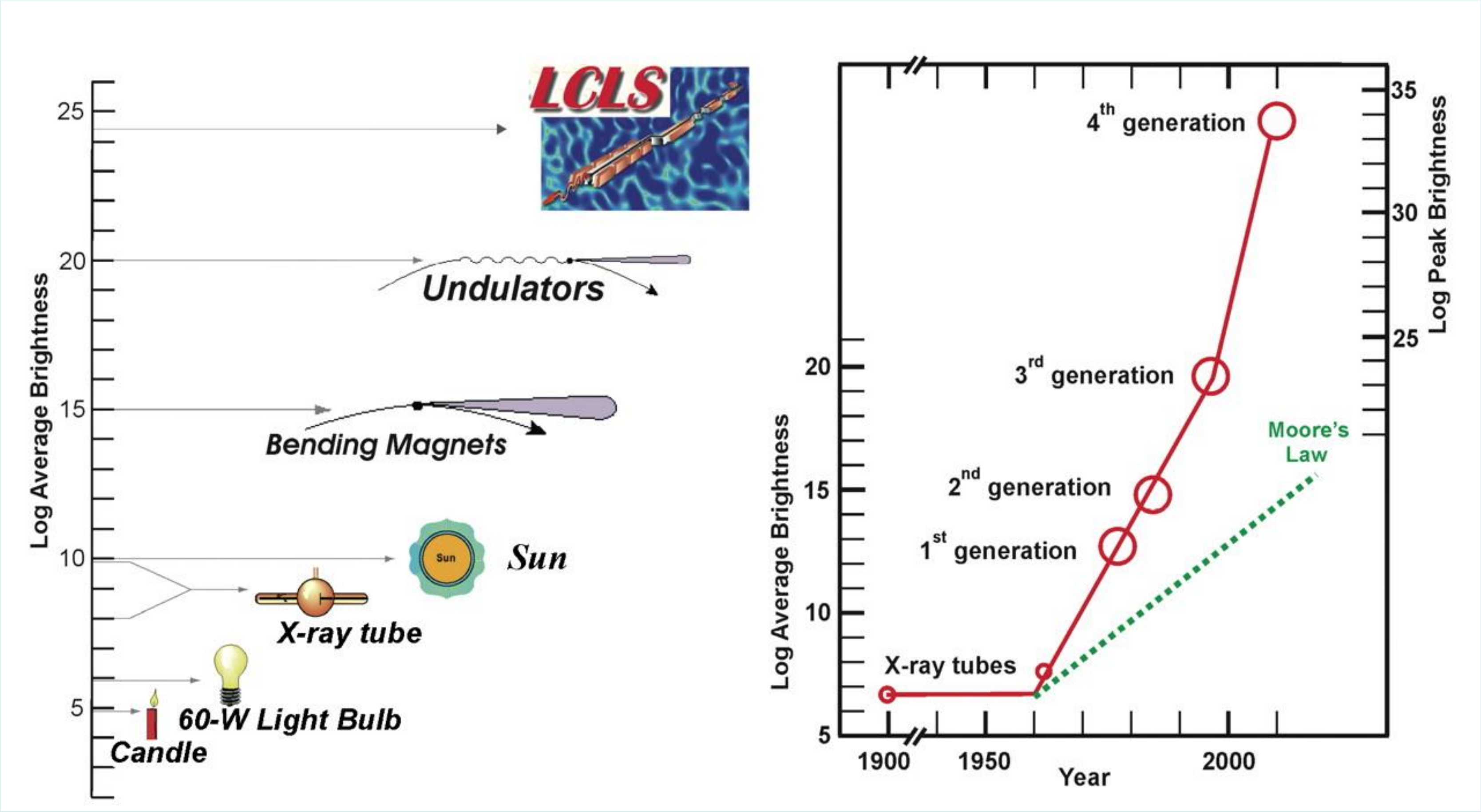
$$B = \frac{2I}{\pi^2 \varepsilon_{x,n} \varepsilon_{y,n}}$$

Current

$$I[A] = \frac{Q[C]c[m/\sec]}{\sigma_z[m]\sqrt{12}}$$

Emittance

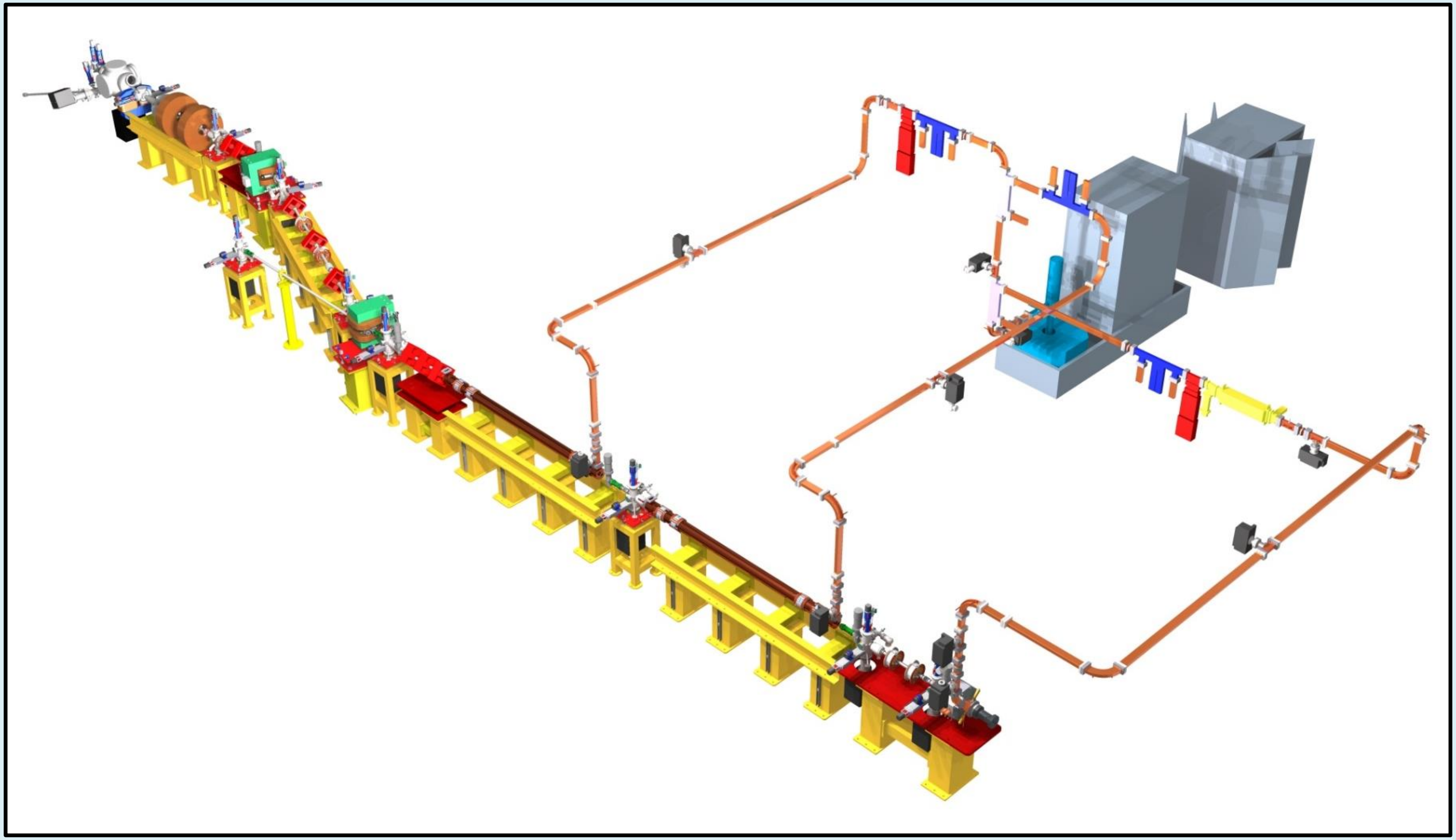
$$\varepsilon_{n,x} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\cdot x'\rangle^2}$$



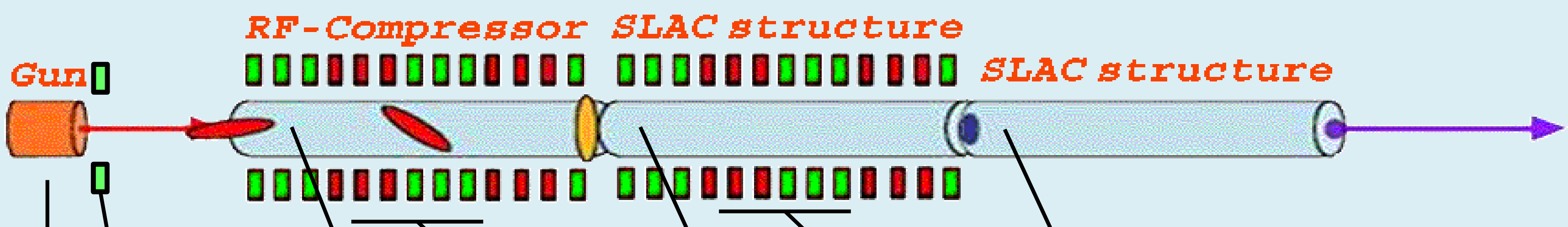
STAR project (at Univ. of Calabria campus)

Southern european Thomson source for Applied Research: monochromatic, tunable, ps-long, polarized X-ray beams, from 20 to 140 keV. Unical, CNISM, INFN and Sinc. Trieste Collaboration.

Experiments on matter science, cultural heritage, radiological imaging with micro-tomography capabilities are foreseen . Collision laser based on a Yb:Yag 100 Hz



A typical High Brigthness electron BeamLine



First Solen. array
- Position
- Intesity

Second Solen. array
- Position
- Intesity

Gun Solenoid:
- Position
- Intensity

First Acc. Cavity
- Position
- Inj.phase
- RF E_{peak}

Second Acc. Cavity
- Position
- Inj.phase
- RF E_{peak}

Third Acc. Cavity
- Position
- Inj.phase
- RF E_{peak}

The Gun:
- Laser Longitudinal profile
- Laser transverse dimension (relative uniformity)
- Inj. phase in RF Acc.Field
- RF E_{peak}

19 parameters, some strongly coupled (non linearly) to each other
In-blue harder parameters to be set (12/19)
In-black easier parameters to be set (7/19)

Radio-Frequency Photo-Injectors

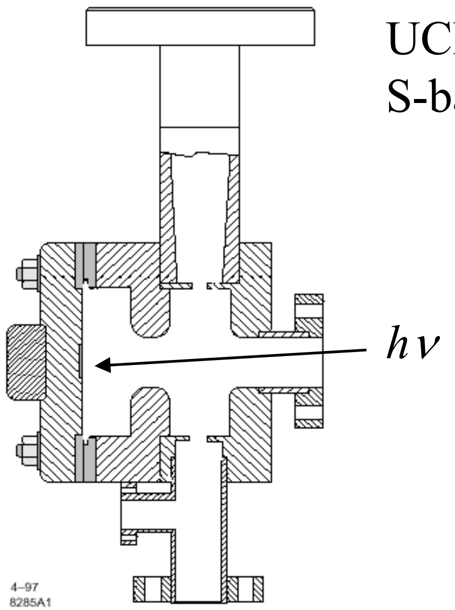
$$Q_{eff} = N_{electrons} / N_{laser-photons}$$

$$Q_{eff}\,(Cu \;\; photo-cathode) \cong 5 \cdot 10^{-5}$$

$$W_{Cu} = 4.2eV, \;\; h\nu = 4.6eV$$

$$Q = 1 \;\; nC \;\; needs \;\; U_{las} = \frac{h\nu \cdot Q_{bunch}}{Q_{eff}} = 92 \;\; \mu J$$

UCLA/SLAC/BNL
S-band next gen. RF Gun



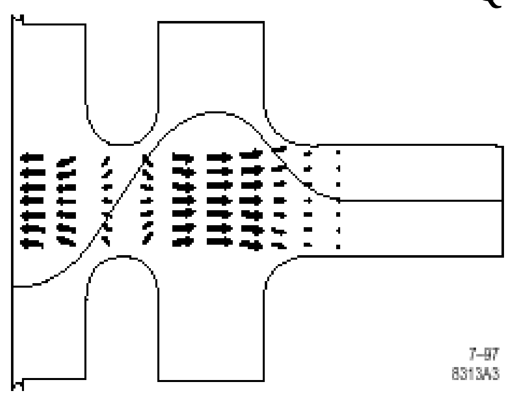
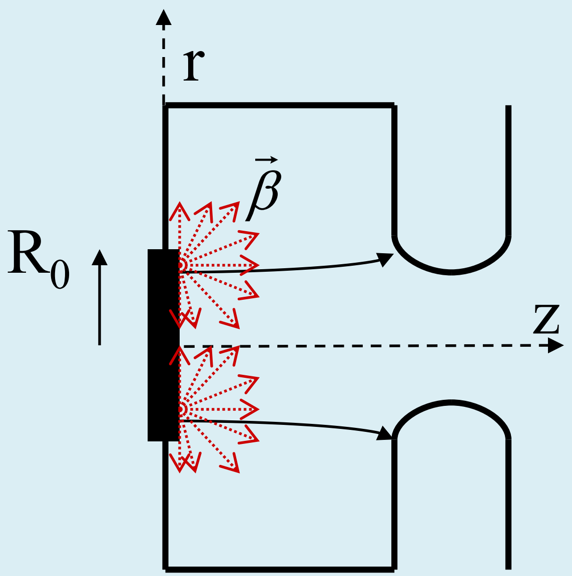


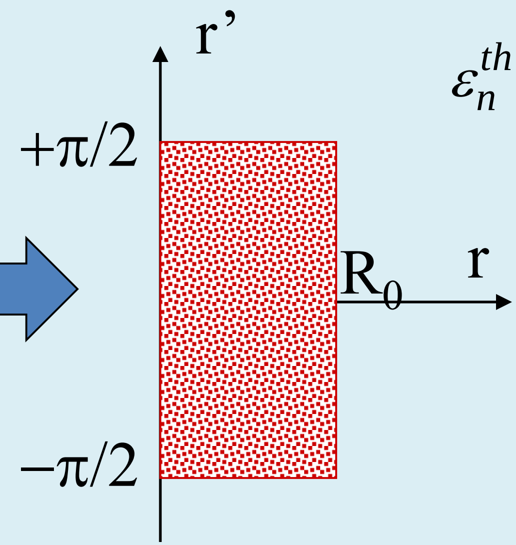
Photo-Cathode Emissivity **J < 10 kA/cm²**
(t)Prompt emission on a ps time scale

Thermoionic Injectors
Cathode Emissivity J < 20 A/cm2

Beam Dinamycs in Photo-Injectors

themperature emittance @ photo-cathode
(real liouvillian emittance)





$$\varepsilon_n^{th} = \frac{\langle \beta\gamma \rangle}{2} \sqrt{\langle r^2 \rangle \langle r'^2 \rangle - \langle r r' \rangle^2}$$

$$\langle r^2 \rangle \equiv \frac{\int_0^{R_0} r^3 dr}{\int_0^{R_0} r dr}$$

$$\langle x^2 \rangle = \frac{\langle r^2 \rangle}{2}$$

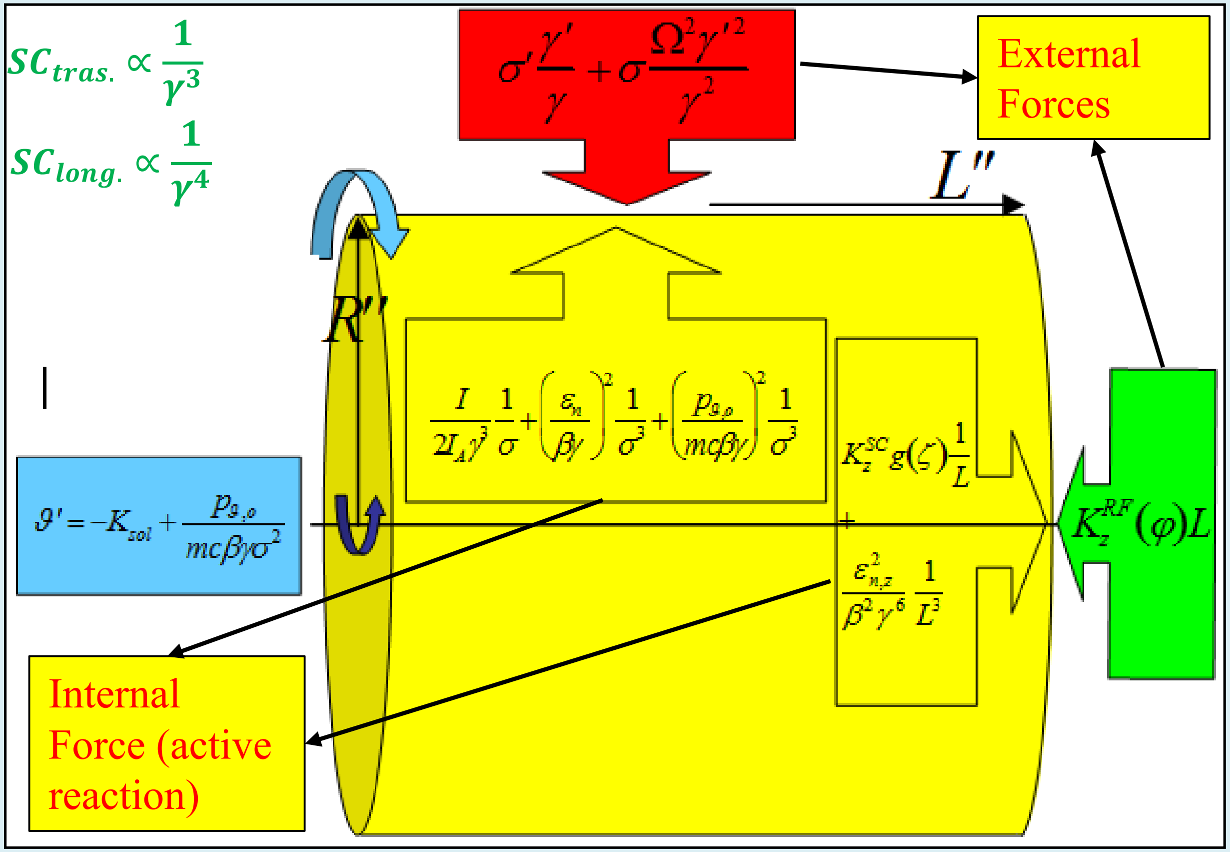
$$\langle \beta\gamma \rangle \cong \langle \beta \rangle \cong \sqrt{2T_e / m_e c^2} = 2 \cdot 10^{-3} \sqrt{T_e[eV]}$$

$$\varepsilon_n^{th} = \frac{\pi \langle \beta \rangle R_0}{4\sqrt{6}}$$

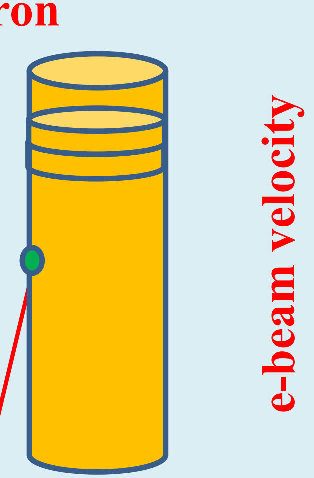
$$\varepsilon_n^{th}\ [mm \cdot mrad] = 0.64\ \ R_0[mm]\ \sqrt{T_e[eV]}$$

Optimize High Brigthness BeamLines is challenging – 1

The electron beam is an ‘reactive’ distribution:



A Traveling Electron beam



charged particle by Gauss-Amper *Fs*

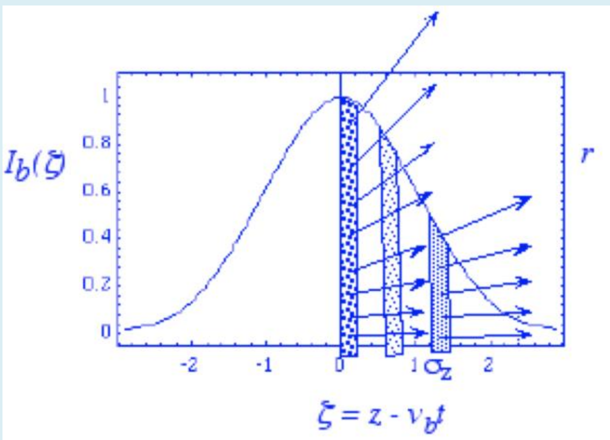
$$\frac{Coulomb\ rep.F}{Mag.attrac.\ F} = \left(\frac{c}{v}\right)^2 = \beta^2$$

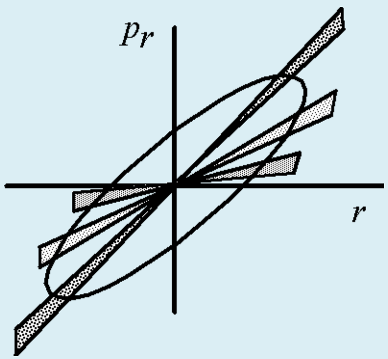
Space-Charge dominated bunches are hard to be tamed

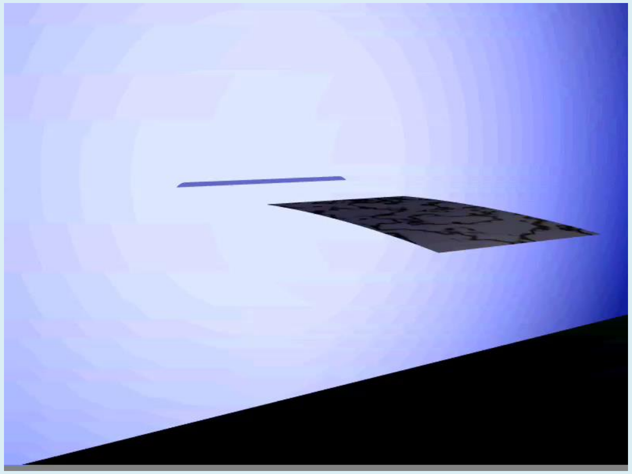
A. Bacci, A.R. Rossi / Nuclear Instruments and Methods in Physics Research A 740 (2014) 42–47 on sc and laminar beam

S.C.R.C.P. or
Laminar Plasma-Beam

- Plasma launched at relativistic velocities along the propagation axis with equivalent ionization = $1/\gamma^2$; plasma confinement provided by external focusing (solenoids, ponderomotive RF focusing, acceleration)
- Spread in plasma frequency along the bunch ⇒ strong time-dependent space charge effects ⇒ inter-slice dynamics







Projected emittance (shadow) >> slice emittance (foil thickness)

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$$\varepsilon_n \equiv \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2} \quad >> \quad \varepsilon_{nsl} \equiv \sqrt{\langle x^2 \rangle_\zeta \langle p_x^2 \rangle_\zeta - \langle x p_x \rangle_\zeta^2}$$

Liouvillian emittance = foil volume

Some of the more used Codes

A consistent simulatin of the SC must be done by using PIC or P-P codes

Parmela	**(Los Alamos National Lab. , L. Youg and J. Billen, PIC/P-P(?))**
Tstep	**(Parmela Clone, from a Private Company, PIC)**
Astra	**(Desy, Klaus Floettmann, Free Code, PIC/P-P), used at Flash-FEL**
GPT	**(Private company Pulsar Physics, Netherlands)**
IMPACT-T and IMPACT-Z	**(Berkeley Lab., Ji Qiang, Free Code)**

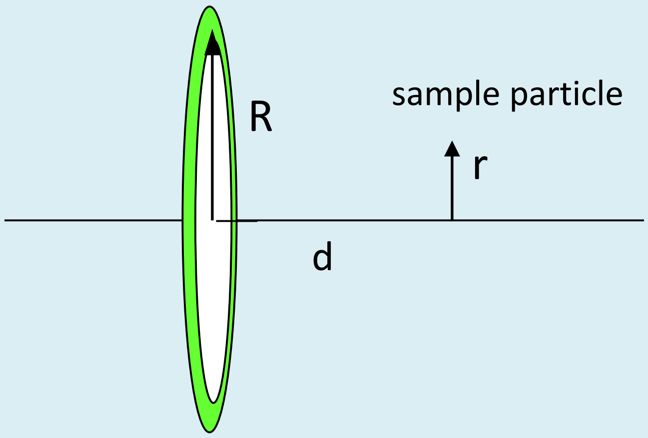
Usually the Space-Charge is a main issue for Linac injectors up to 100 MeV. Typical applications: FEL, Thomson/Compton sources or ultra short bunches for Plasma Wave Accelerators)

CODES Model (2D cylindrical symmetry or 3D p-p)

Space charge force computation: Lorentz-transforming the particles position and field maps into the average rest frame of the beam.

It then applies static forces to the various rings of the cylindrical map assuming a constant charge density inside a ring.

This algorithm requires to have some particles in each of the cell of the cylindrical grid.



In the rest frame of the circle, there is only an electrostatic field[2]. This from the electrostatic potential (in polar coordinates):

$$V'_j(r,\theta) = \frac{\lambda_j R}{4\pi\varepsilon_0}\int_0^{2\pi}\frac{1}{\sqrt{R^2+r^2-2Rr\sin(\theta)\cos(\phi)}}\,d\phi = \frac{Q_j}{2\pi^2\varepsilon_0}\frac{\mathrm{K}\left(\frac{4Rr\sin(\theta)}{a^2+r^2+2Rr\sin(\theta)}\right)}{\sqrt{R^2+r^2+2Rr\sin(\theta)}}$$

in which $\mathrm{K}(k)$ is the elliptic integral[3]:

$$\mathrm{K}(k) = \int_0^{\pi/2}\frac{1}{\sqrt{1-k\sin(\theta)}}\,d\theta$$

$$E'_r = \frac{Q}{4\pi^2\varepsilon_0 r\sqrt{d^2+4Rr}}\left(K(\alpha) - \frac{R^2-r^2+z^2}{d^2}E(\alpha)\right)$$

$$E'_z = \frac{QzE(\alpha)}{2\pi^2\varepsilon_0 d^2\sqrt{d^2+4Rr}}$$

where

$$\mathrm{E}(k) = \int_0^{\pi/2}\sqrt{1-k\sin(\theta)}\,d\theta,\quad d^2 = (R-r)^2+z^2 \text{ and } \alpha = 4Rr/(d^2+4Rr)$$

Let us introduce:

ASTRA

A Space Charge Tracking Algorithm

Version 3.0

October 2011

(Update April 2014)

Astra input files and free parameters

Let see the STAR project input files

All 3D (or 2D) pic tracking code have two main algorithms: 1) e-bunch extraction from cathode or particles generation), 2) e-bunch tracking into the beam-line.

Input for e-bunch extraction:

generator-start1.in + (C:\Doc_Lavoro\lectu...nda\Finale\ex_1_Bunch_

File Modifica Strumenti Sintassi Buffer Finestra Aiuto

```
&INPUT
 FNAME = 'rfgunxx.ini '
 IPart=2000                    !usually in this machines are suggested 10000 macro particles
 Species='electrons'           !different kind can be simulated
 Probe=.F.                     !to track marked particles in the bunch
 Noise_reduc=.T.               !Hammersley sequence (quasi-random distribution)
 Cathode=.T.                   !temporal distribution with Z=0, and flag ad hoc
 Q_total=   0.500              !Bunch charge in nC
 Ref_zpos=0.0E0
 Ref_clock=0.00E0
 Ref_Ekin=1.0E-6
 !Dist_z='p',
 !Lt=0.0160
 !rt=0.001
 Dist_z='g'                    !Gaussian longitudinal distribution
 sig_clock=3.4E-3
 LE=1.1037E-03                 !Energy of photo-electron for isotropic distribution
 Dist_pz='i'                   !isotropic distribution
 sig_Ekin=0.0E0
 Dist_x='radial'               !transversal uniformity (if only x, cylindrical symmetry is assumed)
 sig_x=    0.338               ! sig_x=R_max/2
 Dist_px='r'
```

main parameters to work on Laser pulse shaping

Astra input files and free parameters

pls-start.in (C:\...Linac_0_8.8m) - GVIM

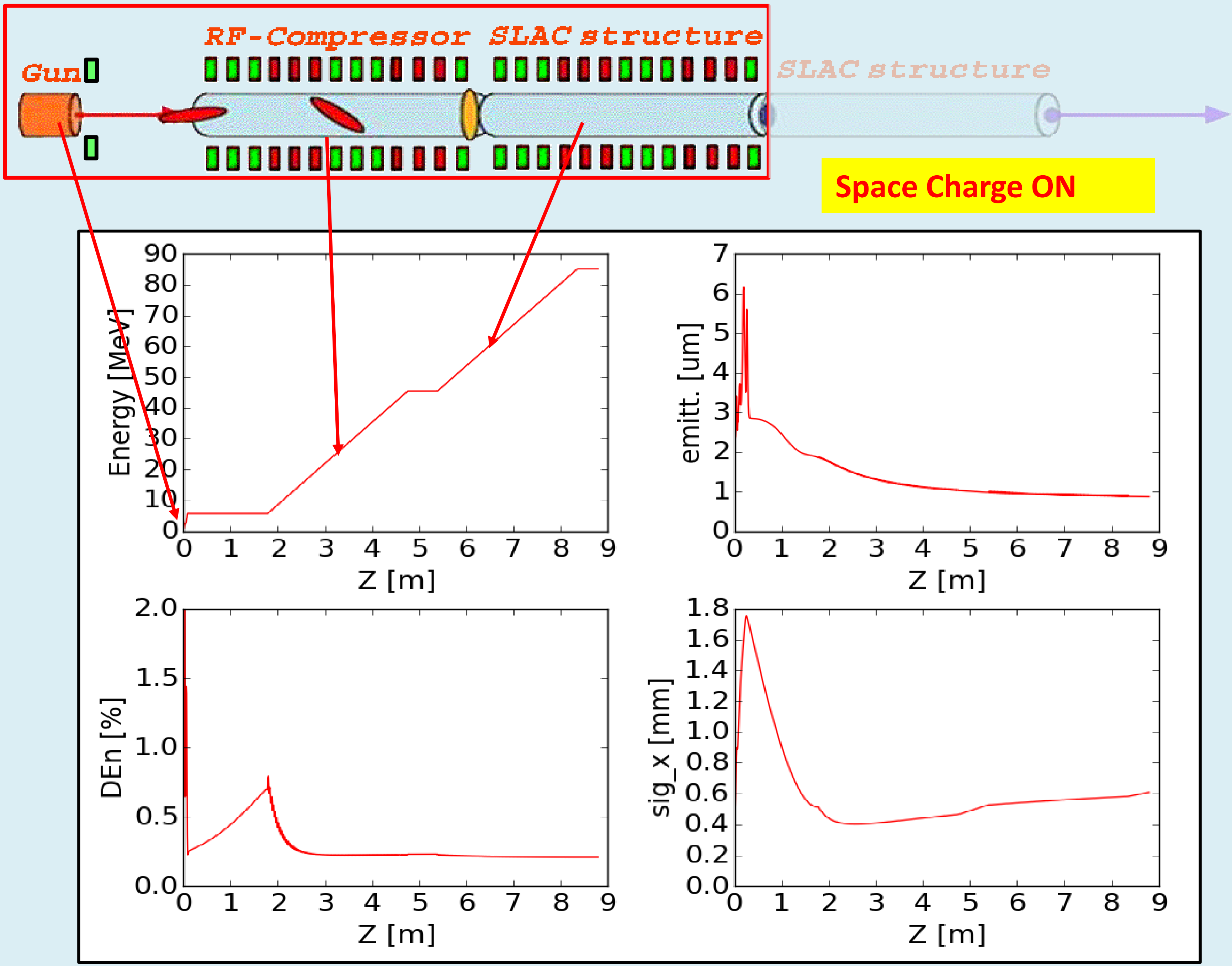
File Modifica Strumenti Sintassi Buffer Finestra Aiuto

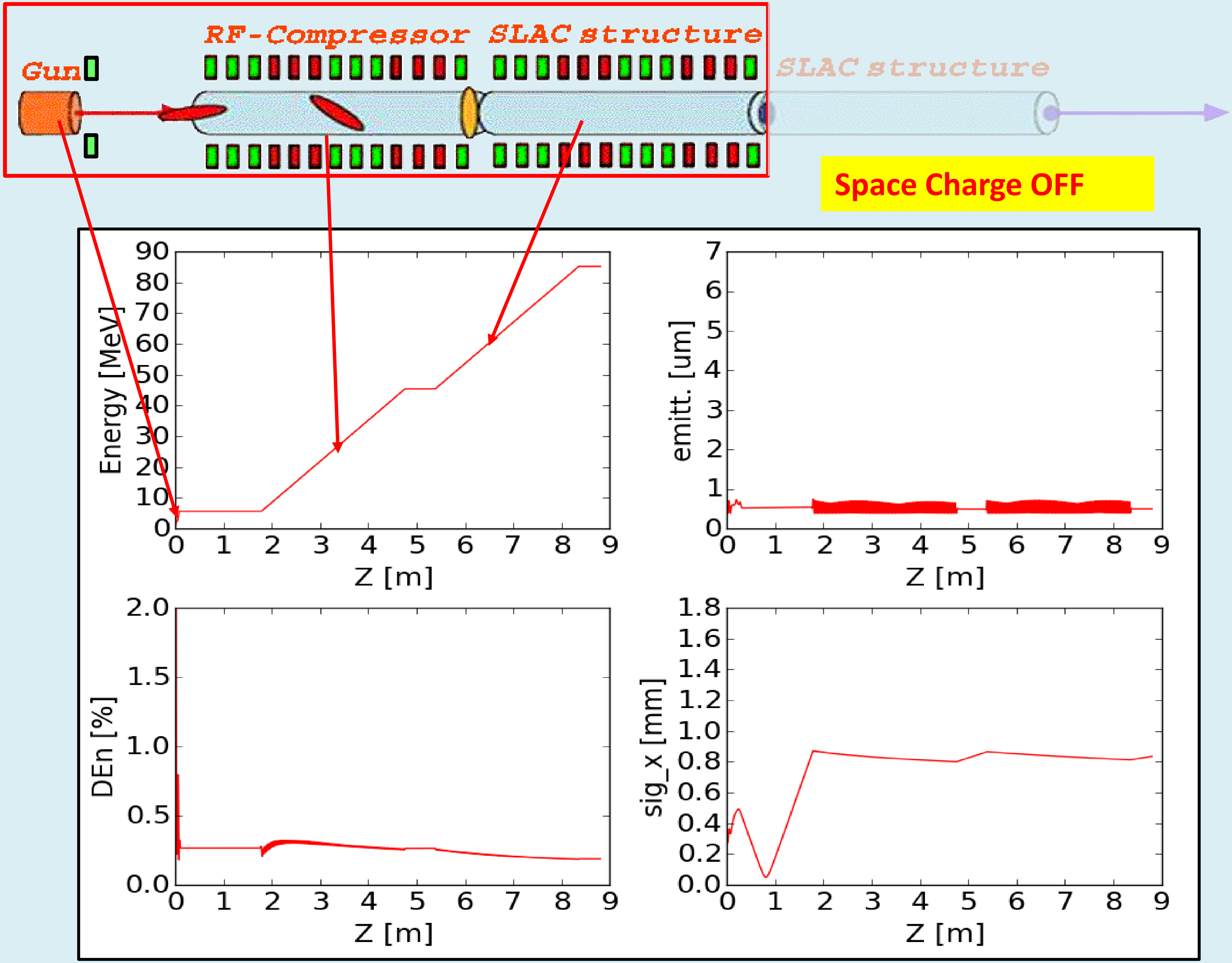
```
 &NEWRUN
 Head='Gun120MV/m, 0.5nC, START_60MeV case'
 RUN= 2 ,
 Loop=F, Nloop=2
 Distribution = 'rfgunxx.ini '
 Xoff=0.0E0, Yoff=0.0E0
 Lmagnetized=F
 EmitS=T
 PhaseS=T
 TrackS=T
 RefS=T
 TcheckS=T
 CathodeS=T
 TRACK_ALL=T,  PHASE_SCAN=F,   AUTO_PHASE=T
 check_ref_part=F,
 ZSTART=0.0,   ZSTOP=8.8
 Zemit=2050
 Zphase=2
 Max_step=200000
 H_max=0.0005
 H_min=0.0000
/

&OUTPUT
/

&SCAN
 LScan=F,
 Scan_para='Phi(1)'
 S_min=102 ,   S_max=118 ,   S_numb=9
 FOM(1)='bunch charge'
 FOM(2)='hor emit'
 FOM(3)='bunch length'
 FOM(4)='hor spot size'
 FOM(5)='phi end'
/
                          24,5          Cim
```

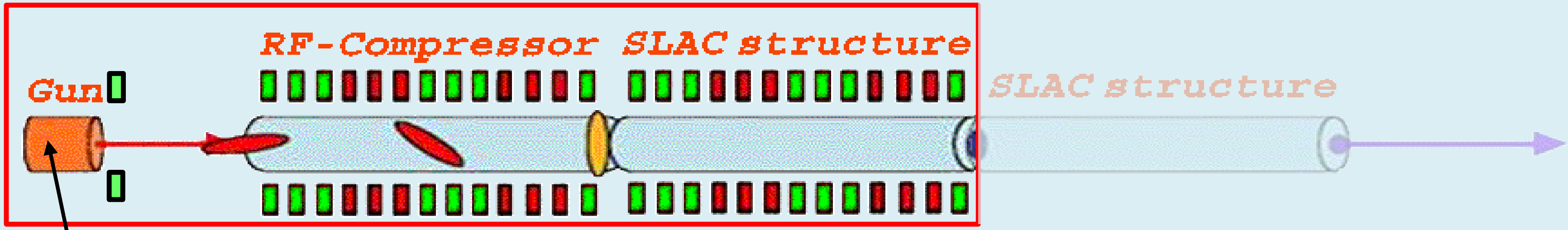
```
 &CHARGE
 Loop=F
 LSPCH=T
 !Nrad=15, Nlong_in=60
 Nrad=15, Nlong_in=25
 Cell_var=2.0
 min_grid=0.0
 Max_scale=0.1
 Max_count=100
 Lmirror=T
 Linert=T
 /

 &Aperture
 /
 &FEM
 /

&CAVITY
 Loop=F,
 LEFieLD=T
 FILE_EFieLD(1) = 'new45.dat'
 Nue(1)=2.856, MaxE(1)=120.0,Phi(1)=-3.741 ,c_pos(1)=0.0
 FILE_EFieLD(2) ='TWS_sparc.dat'
 Nue(2)=2.856, MaxE(2)=24.1, Phi(2)=-1.339 ,c_pos(2)=1.75
 c_numb(2)=84
 /

 &SOLENOID
 Loop=F
 LBFieLD=T,
 FILE_BFieLD(1)='GUNSOL_SPARC_++--.poi'
 MaxB(1)=0.310647,S_pos(1)=0.19575
 FILE_BFieLD(2)='SOL1.txt', MaxB(2)=0.493 ,S_pos(2)=9.35
 FILE_BFieLD(3)='SOL1.txt', MaxB(3)=-0.769,S_pos(3)=10.0
 /

 &QUADRUPOLE
Questa è già l'ultima modifica              60,31        9
```

Astra main output files

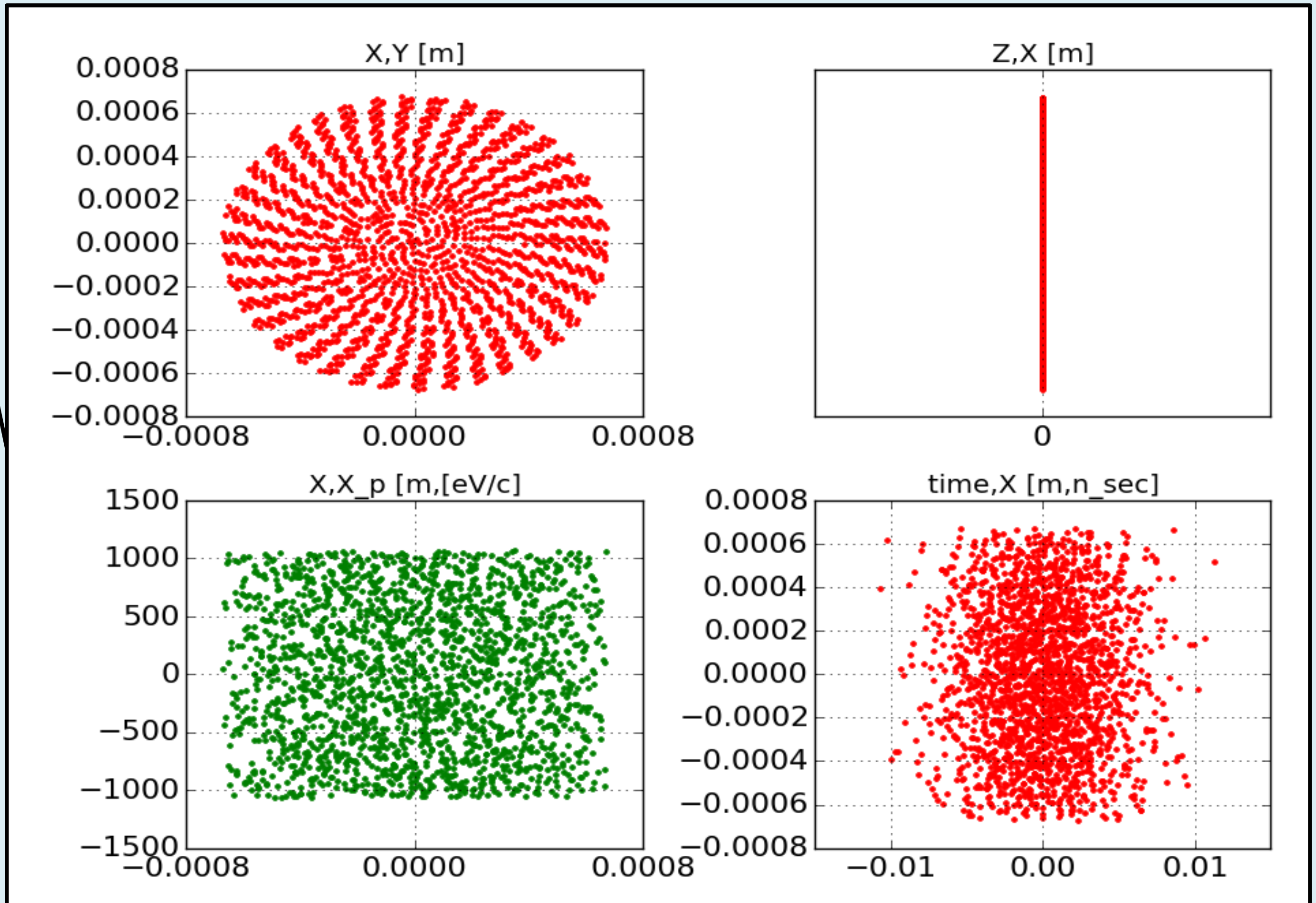
Name	1	2	3	4	5	6	7	8	9	Format
ref	z m	t ns	pz MeV/c	dE/dz MeV/m	Larmor angle rad	x_{off} mm	y_{off} mm	px eV/c	py eV/c	1P,9E12.4 1P,9E20.12
track	seq. numb	stat. flag	z m	x mm	y mm	Ez V/m	Er, or Ex V/m	0.0, or Ey V/m		2I5,1P,6E12.4
Cathode	z m	t ns	long. sp. ch. field on cathode V/m	acc. field on cathode V/m	charge nC	min. grid position m	max grid position m	emission flag		1P,7E12.4,L3
Fields	z m	t ns	Cavity gradient (i) (i = 1…number of cavities N_C) MV/m							1P,N_CE12.4
tcheck	z m	t ns	$\frac{\sigma_{r0}}{\sigma_r}^{nr(r)}$	$\frac{\sigma_{z0}}{\sigma_z}^{nr(z)}$	$\frac{\gamma}{\gamma_0}^{nr(\gamma)}$	$\frac{\sigma_{r0}}{\sigma_r}^{nz(r)}$	$\frac{\sigma_{z0}\cdot\gamma_0}{\sigma_z\cdot\gamma}^{nz(\gamma)}$	scaling counter		1P,7E12.4,I10
Xemit	z m	t ns	x_{avr} mm	x_{rms} mm	x'_{rms} mrad	$\varepsilon_{x,norm}$ π mrad mm	$x\cdot x'_{avr}$ mrad			1P,7E12.4
Yemit	z m	t ns	y_{avr} mm	y_{rms} mm	y'_{rms} mrad	$\varepsilon_{y,norm}$ π mrad mm	$y\cdot y'_{avr}$ mrad			1P,7E12.4
Zemit	z m	t ns	E_{kin} Mev	z_{rms} mm	ΔE_{rms} kev	$\varepsilon_{z,norm}$ π keV mm	$z\cdot E'_{avr}$ keV			1P,7E12.4

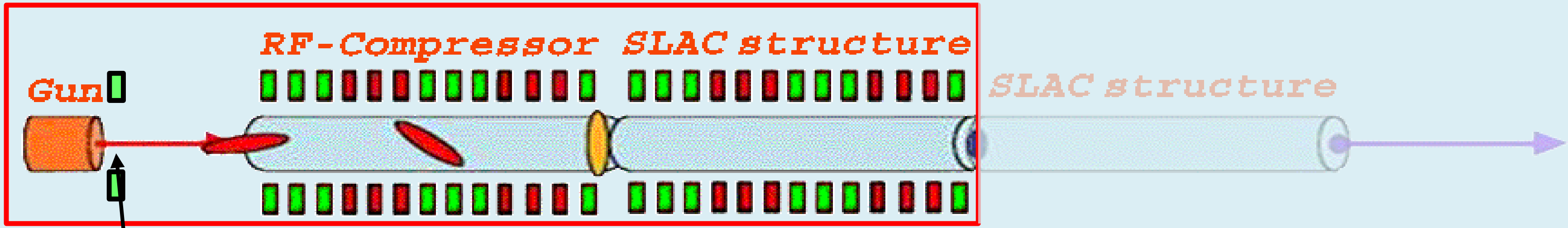

Gun
RF-Compressor
SLAC structure
SLAC structure
Space Charge ON
Energy [MeV]
Z [m]
emitt. [um]
Z [m]
DEn [%]
Z [m]
sig_x [mm]
Z [m]


RF-Compressor
SLAC structure
Gun
SLAC structure
Space Charge OFF
Energy [MeV]
emitt. [um]
DEn [%]
sig_x [mm]
Z [m]



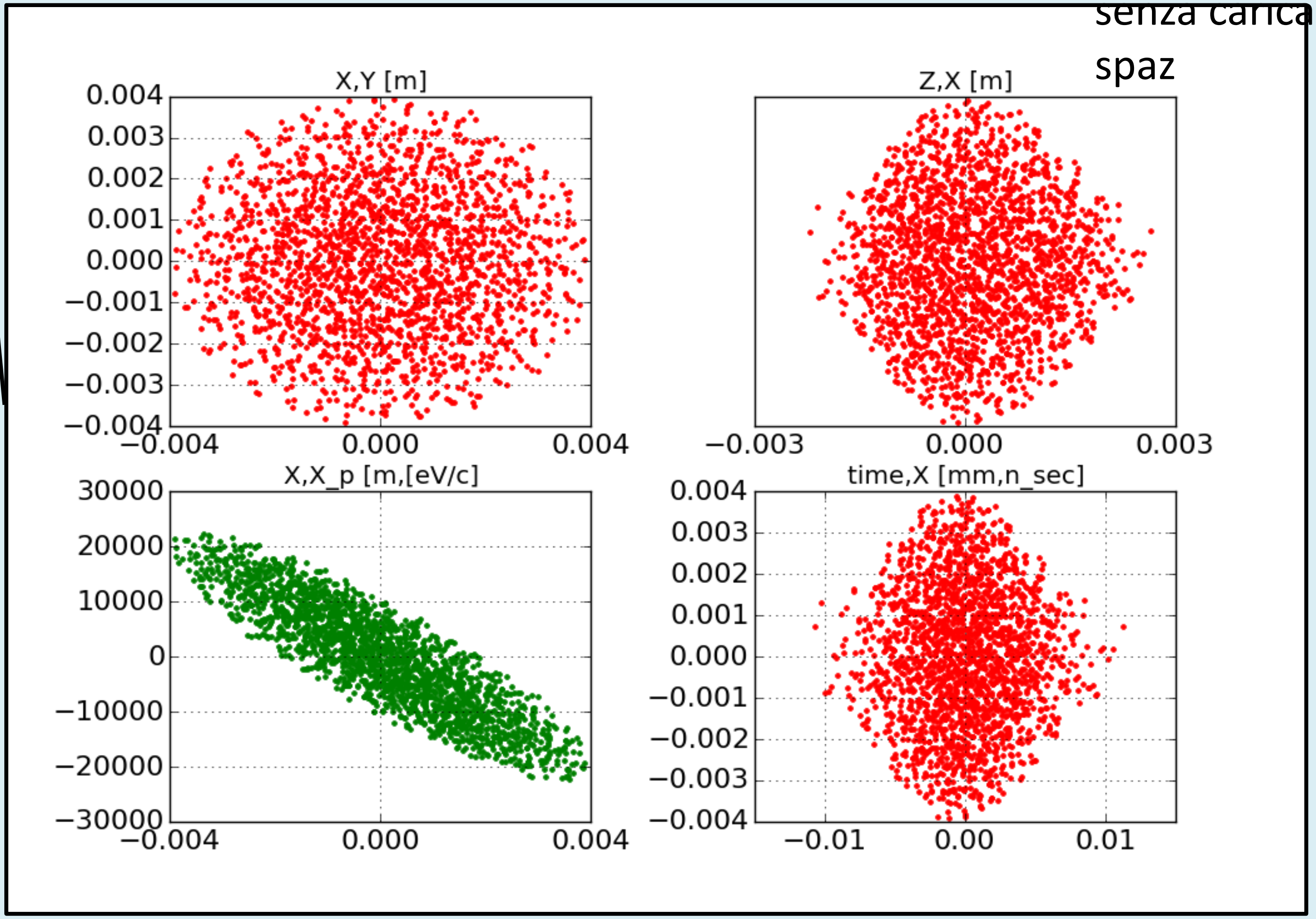
On the cathode

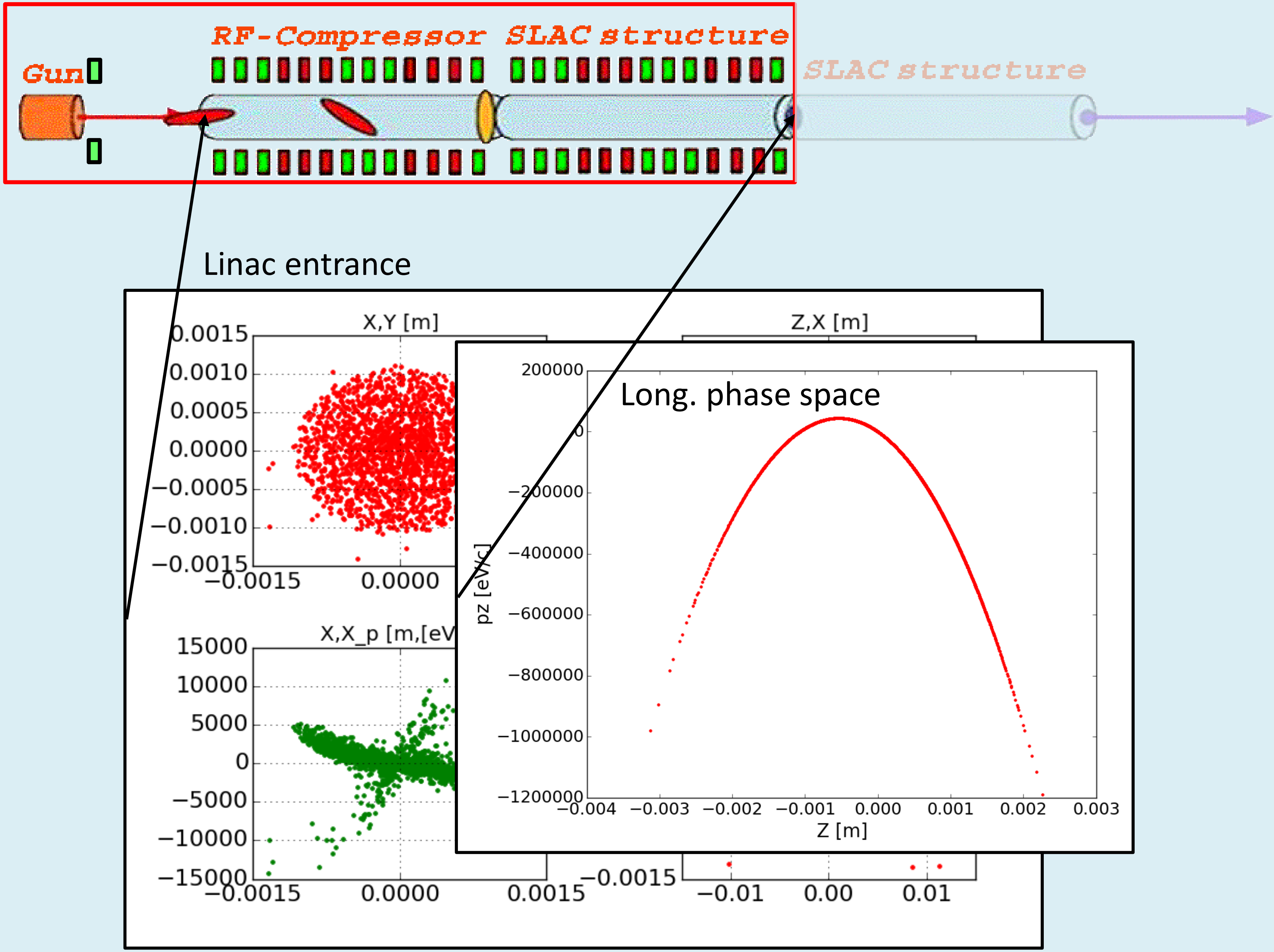




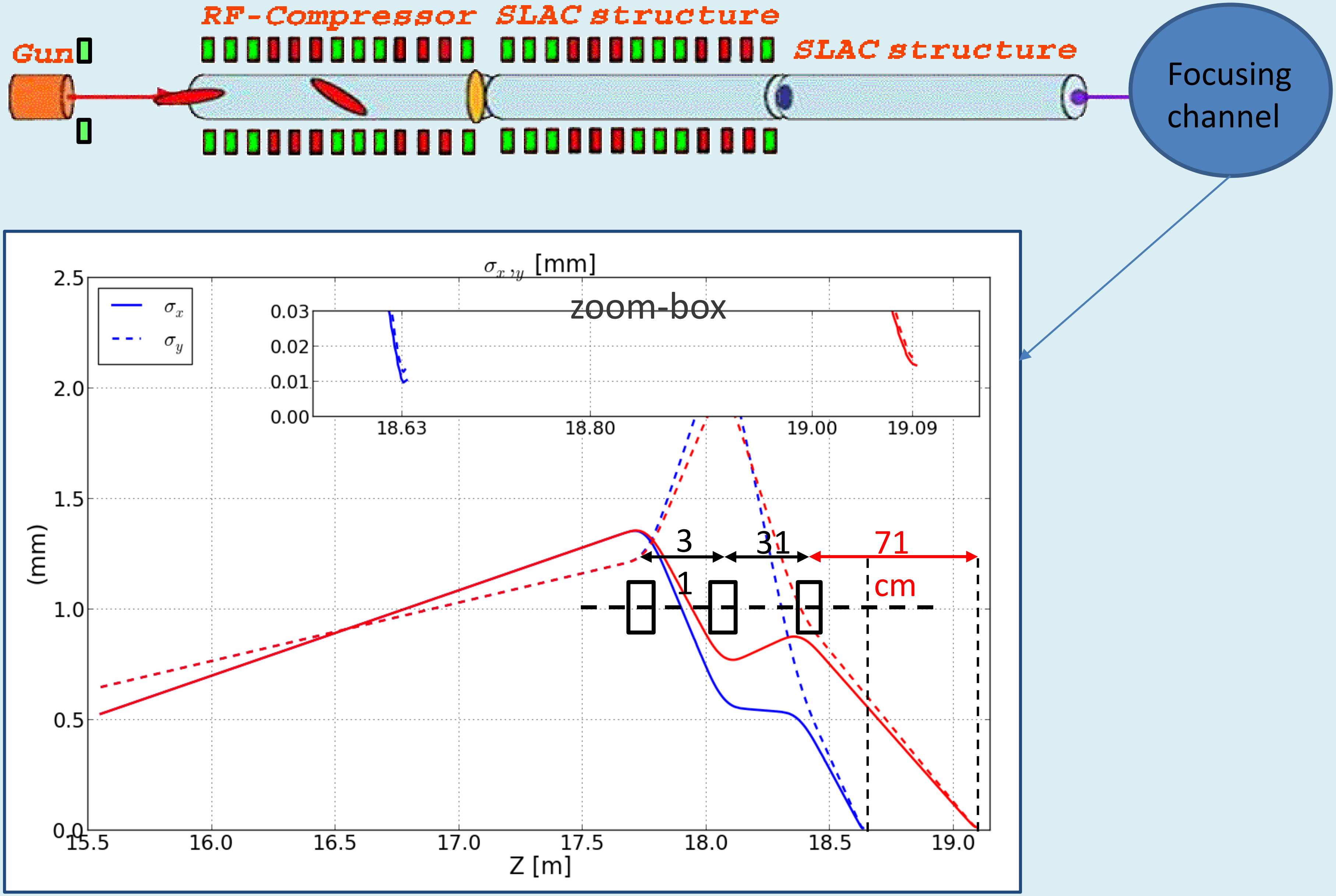
Gun Exit

Aggiungere senza carica spaz

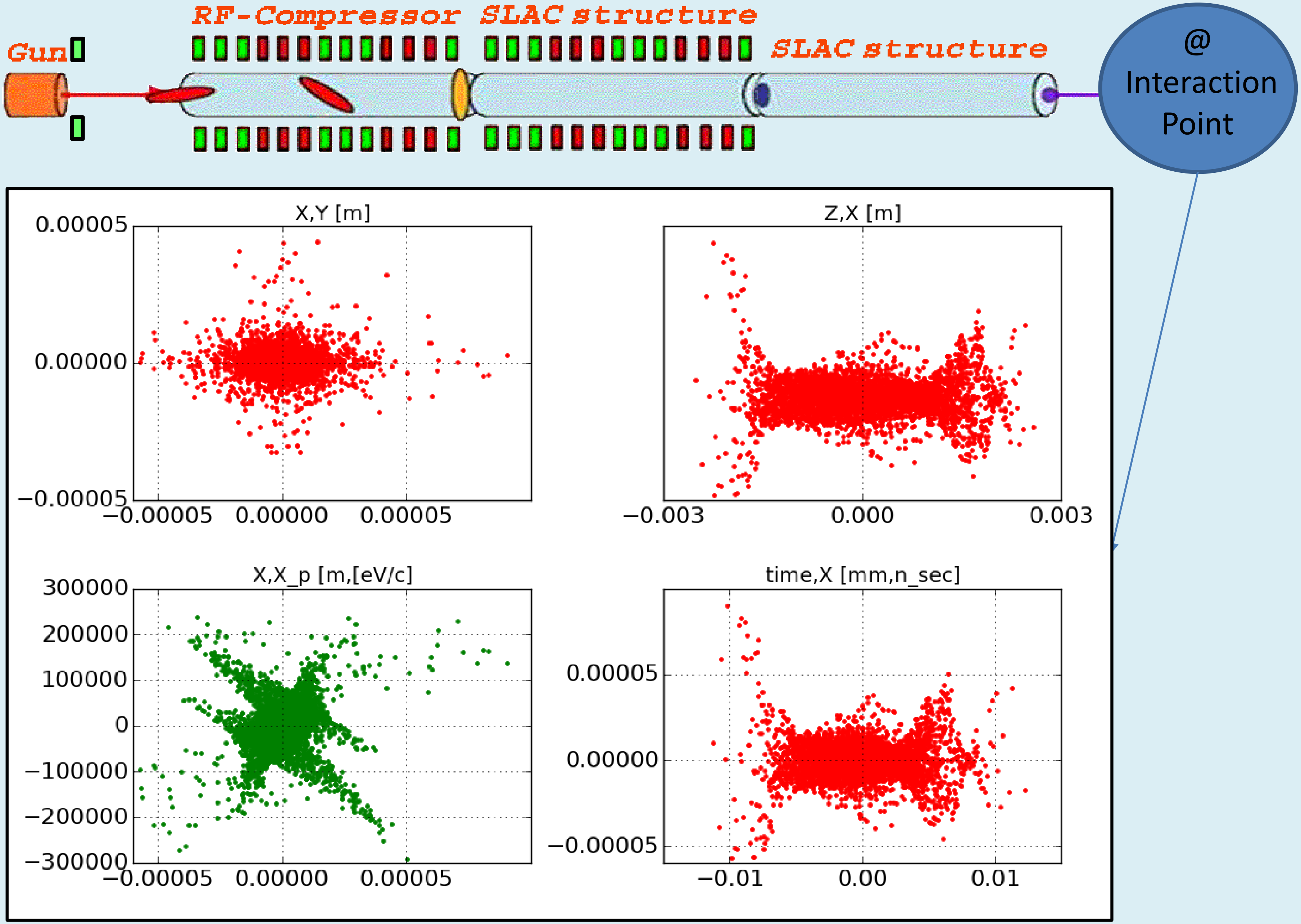




RF-Compressor
SLAC structure
Gun
SLAC structure
Linac entrance
X,Y [m]
Z,X [m]
X,X_p [m,[eV
Long. phase space
pz [eV/c]
Z [m]



Gun
RF-Compressor
SLAC structure
SLAC structure
Focusing channel
σx,y [mm]
zoom-box
σx
σy
(mm)
Z [m]
3
31
71
cm
1



Gun
RF-Compressor
SLAC structure
SLAC structure
@
Interaction
Point
X,Y [m]
Z,X [m]
X,X_p [m,[eV/c]
time,X [mm,n_sec]

A Quantum Code, To simulate the Electron-Phothon Bunches schattering

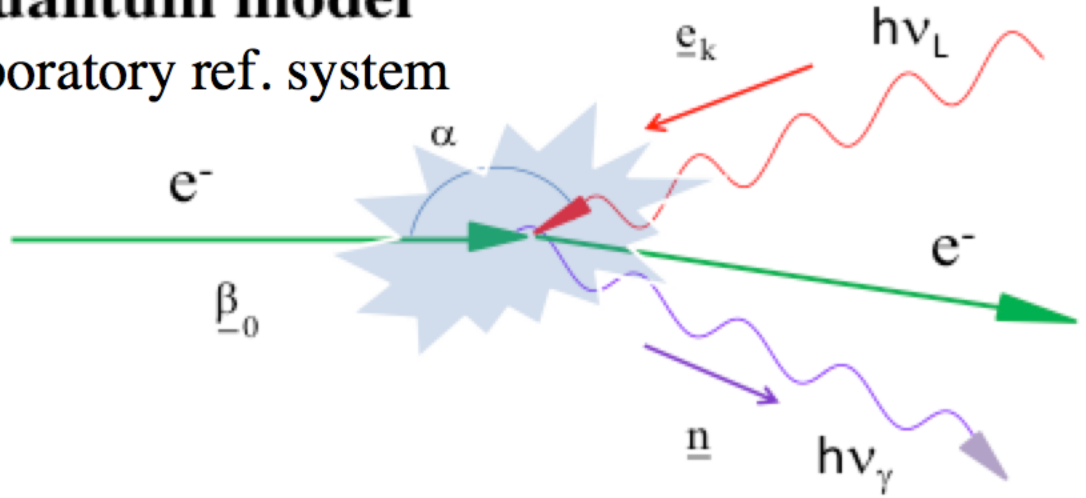
CAIN SIMULATION CODE

GAMMA BEAM

CAIN code
developed by K. Yokoya
Monte Carlo code
based on QED
Landau-Lifshitz approach

Quantum model

Laboratory ref. system



3 regimes: a) Elastic, Thomson b) Quasi-Elastic, Compton with Thomson cross-section c) Inelastic, Compton, recoil dominated

$$\nu = \nu_L \frac{1 - \underline{e}_k \cdot \underline{\beta}_0}{1 - \underline{n} \cdot \underline{\beta}_0 + \frac{h\nu_L}{mc^2\gamma_0}(1 - \underline{e}_k \cdot \underline{n})}$$

$$\lambda = \lambda_L \frac{1 - \underline{n} \cdot \underline{\beta}_0}{1 - \underline{e}_k \cdot \underline{\beta}_0} + \frac{h}{mc\gamma_0} \frac{1 - \underline{e}_k \cdot \underline{n}}{1 - \underline{e}_k \cdot \underline{\beta}_0}$$

Petrillo V. and al., NIM A **693** (2012)
Sun C. and Wu Y. K., PRSTAB **14** (2011) 044701

Cain Input file

```
ALLOCATE  MP=50000;

SET   photon=1, electron=2, positron=3, mm=1D-3, micron=1D-6,
       nm=1D-9, mu0=4*Pi*1D-7,psec=1e-12*Cvel,

 sigz=0.000281,
 ntcut=5,
 laserwl=515.000000*nm,
 pulseE=0.400000,
 sigLr=14.000000*micron,
 w0=2*sigLr,
 rayl=Pi*w0^2/laserwl,
 sigt=1.500000*psec,
 angle=0.130900,
 tdl=1.0,
 powerd=(2*pulseE*Cvel)/[Pi*sigt*Sqrt(2*Pi)*w0^2],
```

laser parameters

```
SET MsgLevel=1;

SET Rand=5*40003.000000;

BEAM FILE='exp.dat';
```

incoming electron beam

```
LASER LEFT, WAVEL=laserwl, POWERD=powerd,

      TXYS=(0.000000, 0.000000, 0.000000, 0.000000),
      E3=(-Sin(angle),0.0,-Cos(angle)), E1=(0,1,0),
      RAYLEIGH=(rayl,rayl), SIGT=sigt, GCUTT=ntcut,
      STOKES=(0.000000, 0.000000, 1.000000),
      TDL=(tdl,tdl) ;
```

laser reference frame and polarization

```
LASERQED  COMPTON, NPH=0;
```

linear compton scattering

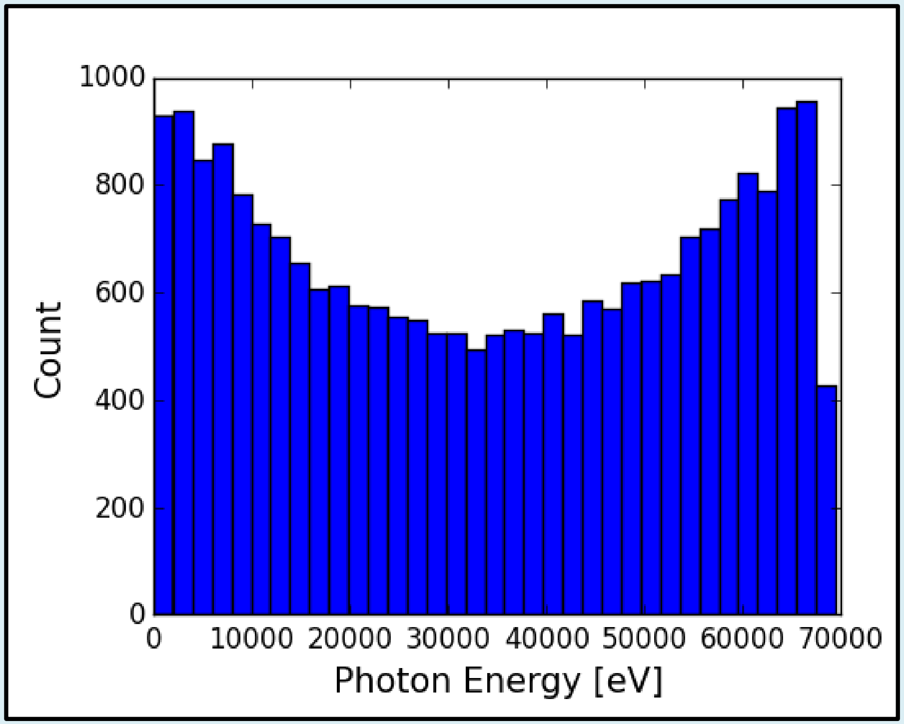
```
SET MsgLevel=0;  FLAG OFF ECHO;
SET Smesh=sigt/3;
SET  it=0;

PUSH  Time=(-ntcut*(sigt+sigz),ntcut*(sigt+sigz),250);
      IF Mod(it,20)=0;
       PRINT it, FORMAT=(F6.0,'-th time step');
       PRINT STAT, SHORT;
      ENDIF;
     SET it=it+1;
ENDPUSH;
```

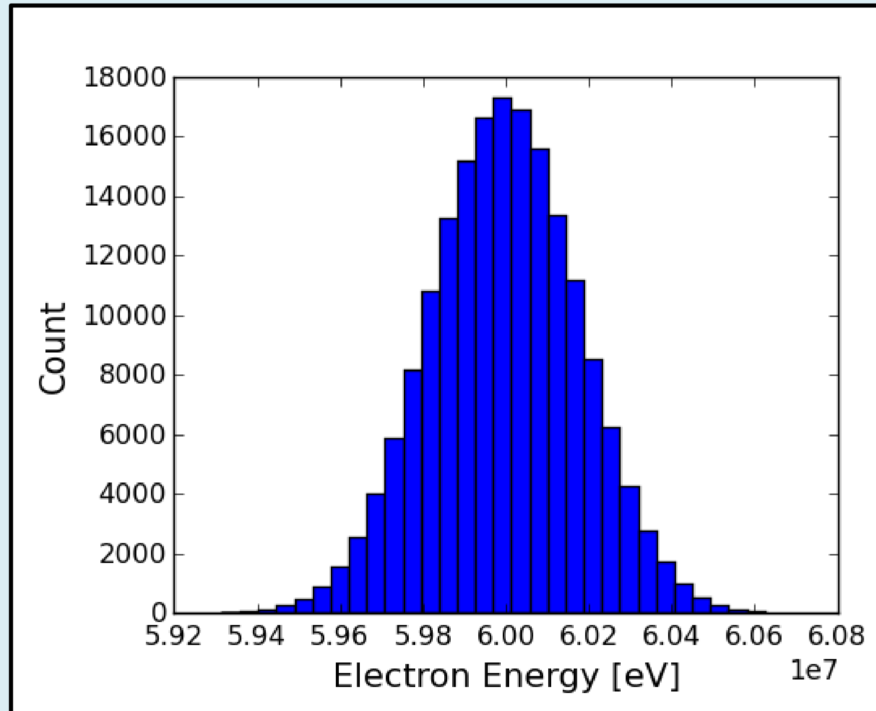
time evolution

```
DRIFT T=0;

WRITE BEAM, KIND=(electron), FILE='cain_output_electrons.dat';

WRITE BEAM, KIND=(photon), FILE='cain_output_photons_20000.dat';
```

STAR Linac,
X-ray source @ 60 MeV –recoil << initial Δγ/γ

Let consider an electron-bunch with an Δγ/γ of 0.003 , scattering λ=1um, 0.4 J, W0=20um laser





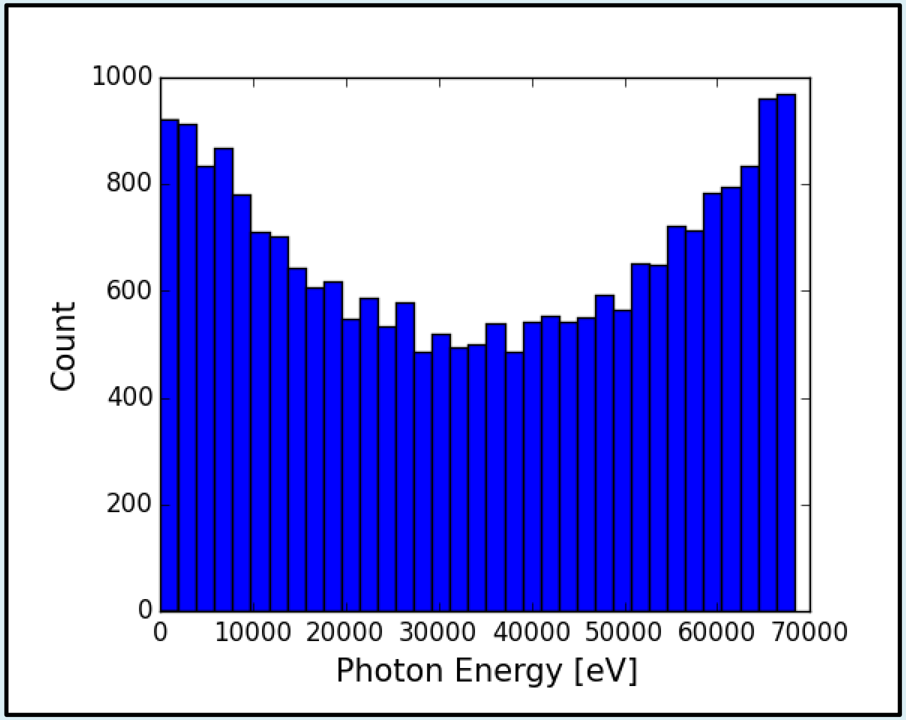
$$Emax = \frac{4\gamma^2 h\upsilon}{1+\Delta}, \quad \Delta = \frac{4\gamma h\upsilon}{511keV}$$

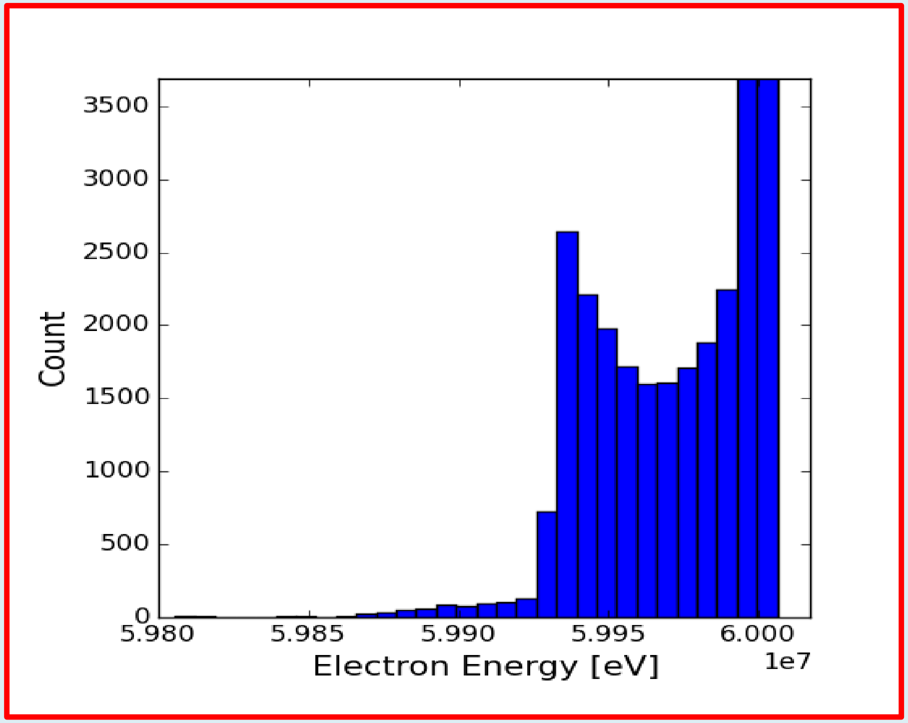
$$E_{ph}\ (\lambda_{laser} = 1\ um) = 1.24\ eV$$

$Emax = 71.340keV,$ Δ=0.00116 (recoil)

STAR Linac,
X-ray source @ 60 MeV – recoil small but > initial Δγ/γ

Let consider an electron-bunch with ultra low Δγ/γ of 0.00003 and same condition as before

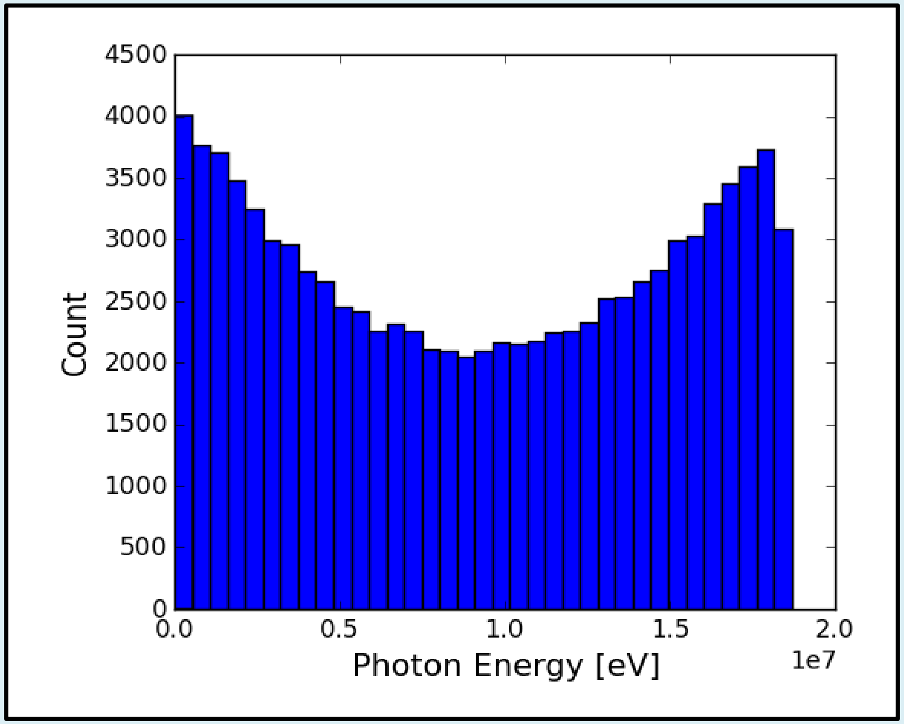


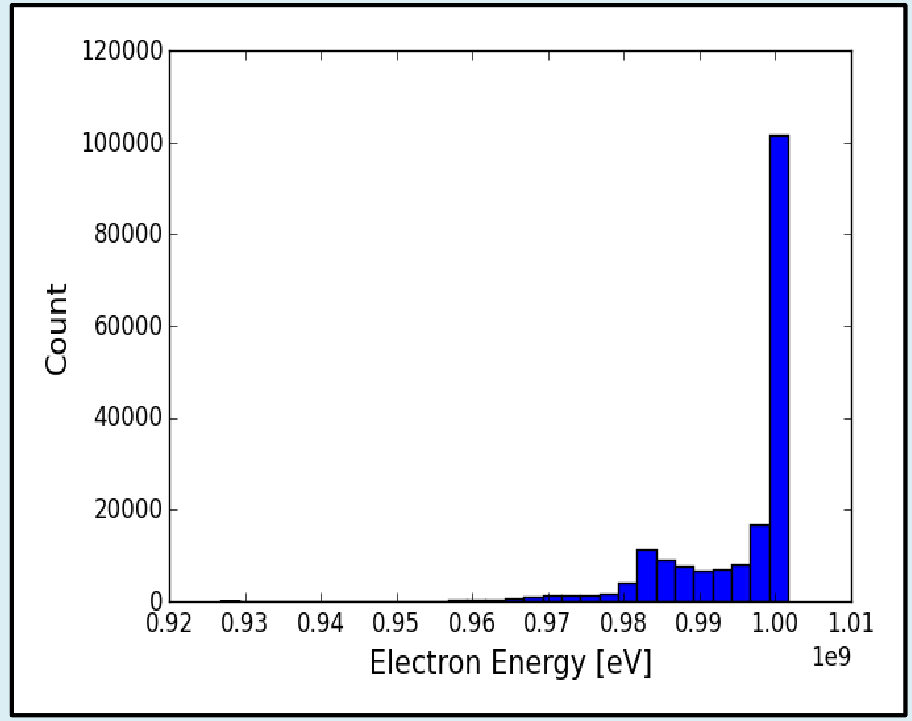


$Emax = 71.340 keV,$ Δ=0.00116

STAR Linac,
X-ray source @ 1 GeV –not negligible recoil

Let consider an electron-bunch with an $\Delta\gamma/\gamma$ of 0.0005, scattering λ=1um, 1 J, W0=20um laser





$$Emax = \frac{4\gamma^2 h\nu}{1+\Delta}, \quad \Delta = \frac{4\gamma h\nu}{511keV}$$

$$N_{photons} = \frac{8.4E8 \cdot Laser_{Energy}[J] \cdot Q_{bunch}[pC]}{Photon_{Energy}\,[eV] \cdot (\sigma_x^2\,[\mu m] + 0.25 \cdot W_0[\mu m])}$$

$Emax = 19.46 MeV$, Δ=0.019

$$E_{ph}\,(\lambda_{laser} = 1\,\mu m) = 1.24\,eV$$

$$W_0 = \sqrt{R_L \cdot \lambda_L / \pi}$$

Suggested readings

J.S. Fraser et al., IEEE Trans. Nucl. Sci. NS-32 (1985), p.1791

R.L. Sheffield et al., Proc. 1988 Linear Accelerator Conf., Williamsburg, VA, Oct. 1988, CEBAF rep. 89-001 (1989), p.520

C. Travier, Particle Accelerators 36 (1991), p.33

K.J. Kim, NIM A275 (1989), p.201

B.E. Carlsten, IEEE Catalog no. 89CH2669-0 (1989) p.313

B.E. Carlsten et al., Proc. 1988 Linear Accelerator Conf., Williamsburg, VA, Oct. 1988, CEBAF rep. 89-001 (1989), p.365

L. Serafini, AIP Conf. Proc. 279 (1993), p.645 *and* L.Serafini, NIM A340 (1994), p.40

J.B.Rosenzweig and L.Serafini, Phys. Rev. E-**49** (1994), p.1599

S.C. Hartman and J.B.Rosenzweig, Phys. Rev. E-**47** (1993), p.2031

W.K.H. Panofsky and W.A. Wenzel, Rev. Sci. Instr. 27 (1956), p.967

More suggested readings

J.B. Rosenzweig and E. Colby, AIP CP 335 (1995), p.724

L.Serafini, Particle Accelerators 49 (1995), p.253

L. Serafini et al., NIM A387 (1997), p.305

L.Serafini and J.B.Rosenzweig, Phys. Rev. E-**55** (1997), p.7565

Proceedings of the ICFA 1999 Workshop on *The Physics of High Brightness Beams*, Los Angeles, 1999, Published on World Sci. ISBN 981-02-4422-3, June 2000

Proceedings of the ICFA 2002 Workshop on *Physics and Applications of High Brightness Beams*, Chia Laguna, Italy, 2002, in publication, see www.physics.ucla.edu/AABD

S. G. Anderson and J. B. Rosenzweig, PRSTAB **3** (2000), p. 094201-1

F. Zhou et al., PRSTAB **5** (2002), p.094203-1

INFN-SPARC Project Web Site http://pcfasci.fisica.unimi.it/Homepage.html

end

GIOTTO – Genetic Interface for OpTimising Tracking with Optics

From 2007 up to day, the code is grew in power and versatility

What makes the difference:

Nowadays "**quasi-classic**" optimization techniques >> elitism; advanced mutation operators; hill climbing; regeneration from best solutions; parallelization *(Open-MPI, MS-mpi)*

fitness function freely defined by the user, by using all the tracking code's outputs (Astra) or by a dedicated **post processor** for the Lcomb configuration:
PosZ, time, En, Den, SigZ, Xemit, sigX, divergX, Yemit, SigY, divergY, emitY ….
Multi bunches Post_Pro:SCurrent(NSpike), SemitX(Nspike), SemitY, Sdist(Nspike) ….

Constraints freely defined by the user

NameList (nml) can be imported into a DB and each nml variables can be used as a Giotto variable to be optimized (genes) (ex. Phi(1)…Phi(50),maxe(1),maxb(1), sig_x,sig_clock --- No limit in the number)

switches from Genetic Optimizations to Statistical Analysis. Each variable can be analyzed. The **sampling interval** can be sampled in **uniform** or **Gaussion** way – very fast stat. analysis.

GIOTTO repository: http://pcfasci.fisica.unimi.it/Pagine/GIOTTO/GIOTTO.htm
or write to alberto.bacci@mi.infn.it

The Brightness – 2

geometrical emittance

normalized rms-emittance

$$\varepsilon_{n,x} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'\rangle - \langle x\cdot x'\rangle^2}$$

Ellipse equation (The Area is επ)

must be normalized because: $x' = \frac{p_{x,j}}{p_{z,j}},\ y' = \frac{p_{y,j}}{p_{y,j}}$

Martin Reiser – Theory and Design of Charged Particle Beams

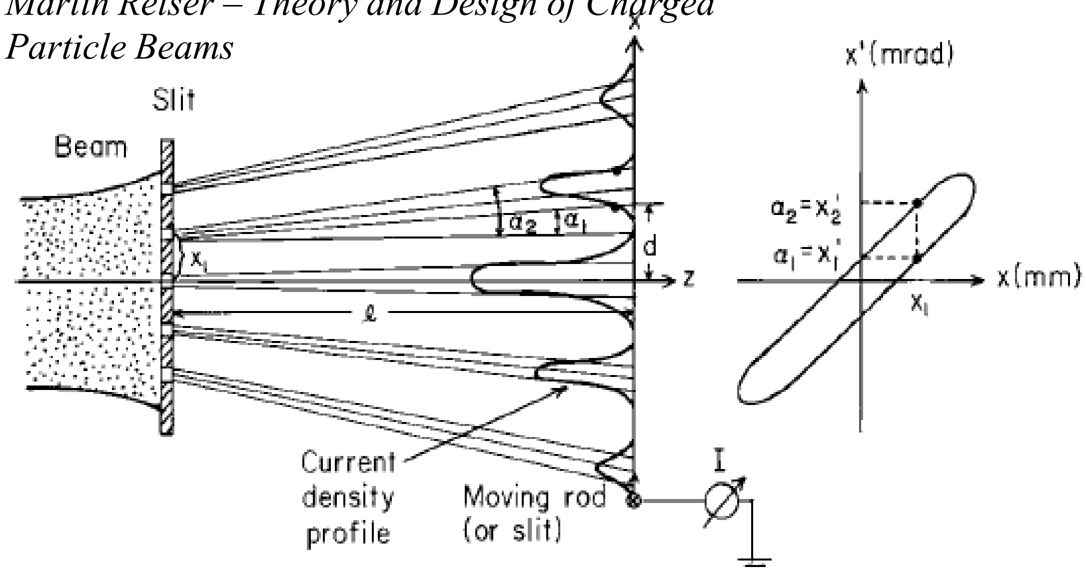


Fig. 3.1 Method of measuring the trace-space distribution of a beam.

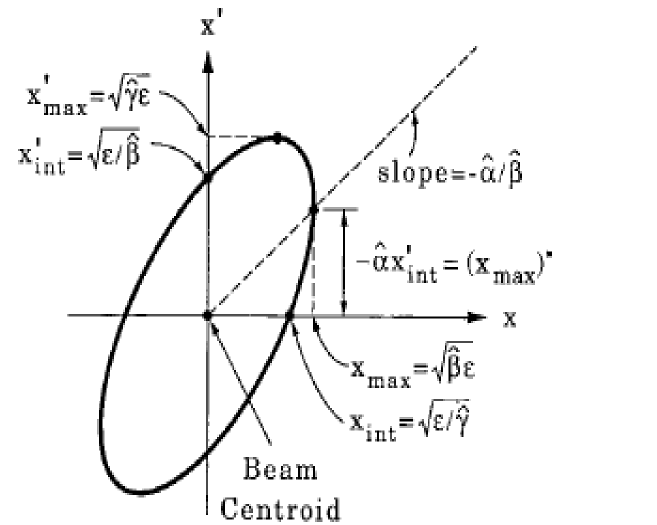


Fig. 3.26 Trace-space ellipse described by equation $\hat{\gamma}x^2 + 2\hat{\alpha}xx' + \hat{\beta}x'^2$ and relations for several important points on the circumference of the ellipse.

Courant-Snyder or Twiss parameters:

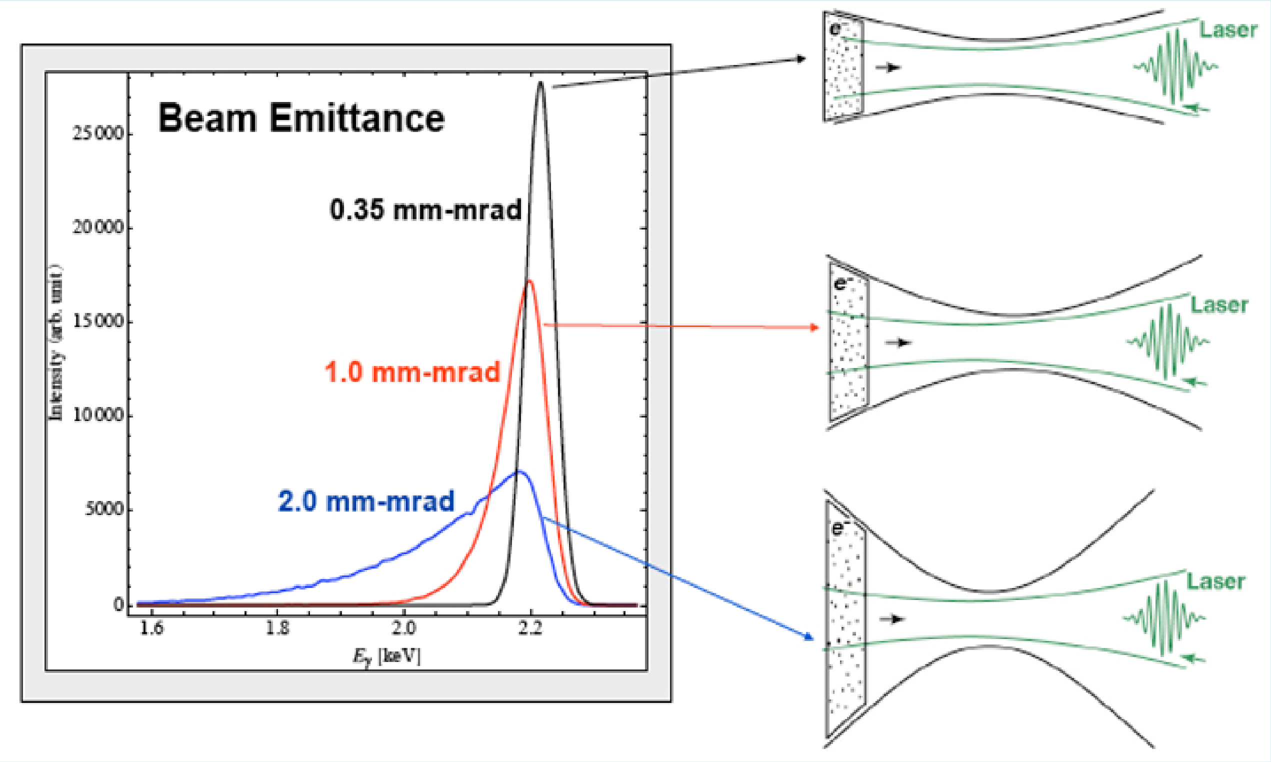
$$\beta_x = \frac{\langle x^2\rangle}{\varepsilon_x} \quad \gamma_x = \frac{\langle x'^2\rangle}{\varepsilon_x} \quad \alpha_x = -\frac{\langle xx'\rangle}{\varepsilon_x} \quad \beta_x\gamma_x - \alpha_x^2 = 1$$

Why High Brightness

- **In Free Electron Lasers:**

  the condition to start micro-bunchign instabilities $\varepsilon_{n,x} \leq \frac{\lambda_r}{4\pi}\gamma$

- **In Thomson/compton source – To drammatically improve the Spectral Density**



❖ Very useful codes (particles tracking and beam line Optimization)

Codes that work on Twinss Parameters and by using transport matrices
Non for low energy:

MAD (Methodical Accelerator Design, FREE ,first ed.‘70) – MADX (ed. 2012,) (CERN: http://mad.web.cern.ch/mad/). Exist many Clones or Similar Codes like MaryLIE (first ed. ’70):

> **Can use Lie Algebra which works on symplectic vectorial space (energy conservation) good for high order optics and rings (e.g. Runge Kutta RK methods show energy drift), noway can also track particles.**

Trace3D (first ed. 87-3th ed. 1997, Los Alamos National Lab., FREE):

> **It works only with distribution. It is very light, easy and fast. Thurther can be used also for photons ($\varepsilon=\lambda/4\pi$)**

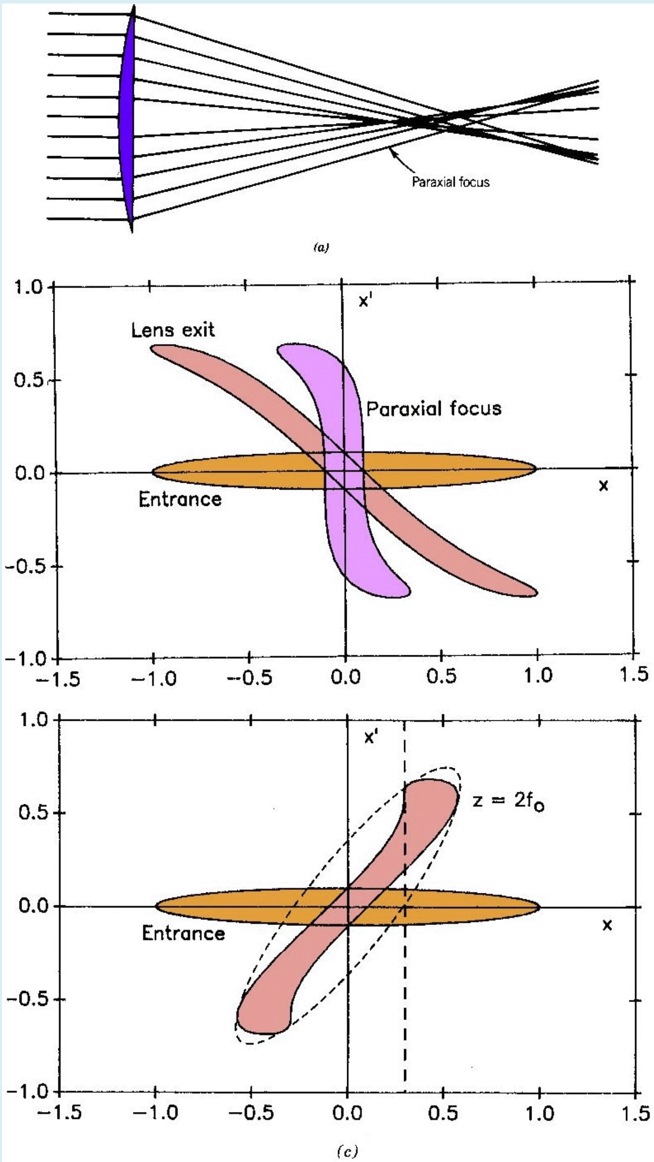
Elegant (‘88, ELEctron Generation AN Tracking, M. Borland, Argonne National Lab. FREE):

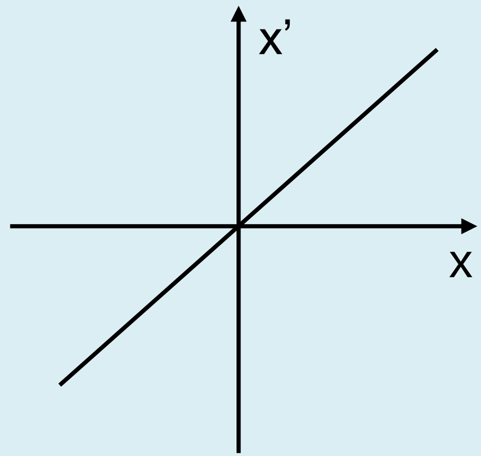
> **First gol was the tracking with 2nd matrices and time-dependent elements (Acc. Cavities). One of the first code considering CSR and WakeFields effects. It can track milions of particles permitting to see microbunching by CSR in the bends.**

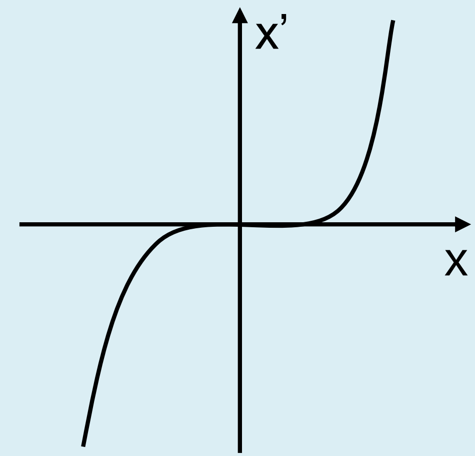
Benefits: extremely fast and useful to beam line optimizzation
Drawbacks: Usually don’t consider the Spce-Charge or have an analitical aproximations (usually linear for water bag distributions)

Brightness or Emittance Degradation

A focusing channel







Considering that for any position x the divergece of the particle is $x' = C\,x^n$

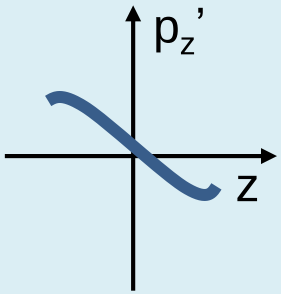
$$\varepsilon_x^2 = \overline{x^2 x'^2} - \overline{xx'}^2 = C^2\left(\overline{x^2 x^{2n}} - \overline{xx^{n+1}}^2\right)$$

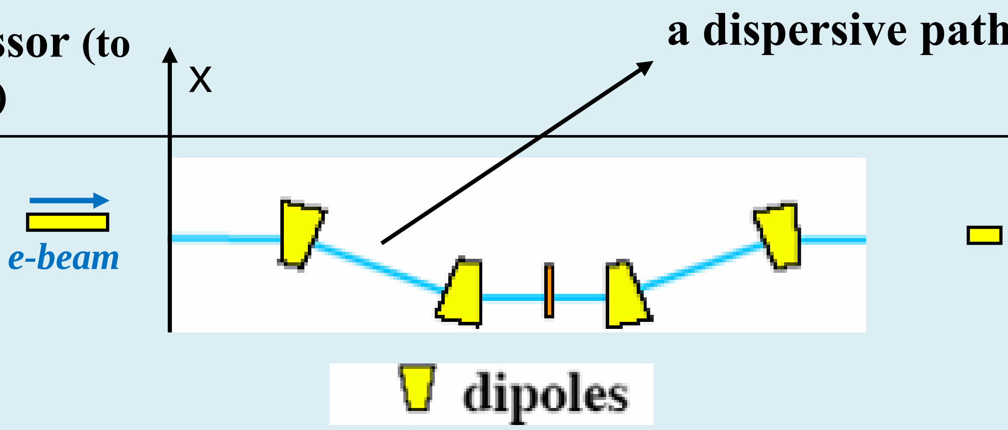
with n=1 the staight line gives rms emittance equal 0. For n≠1 the emittance is not 0, also if the two distribution area are 0

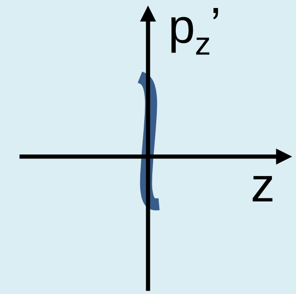
The Brightness – Emittance Degradation – 2

An important example:

Magnetic compressor (to increase the current)







Longitudinal phase space, pre tuned (or chirped) to couple correctly energy and position

- **When a charged particle is accelerated it emits radiation. In bending magnets, of the dispersive path (chicane), the transverse acceleration is a source of Coherent Synchrotron Radiation (CSR), which generates a non linear energy modulation (in the horizontal plane, $X' = p_x/p_z$), which degrade the emittance**
- **The same effect for Dog-Legs**
- **A strong degradation can be given by space charge which is not linear**

❖ Beamlines Optimizzation by Genetic Algorithms (GA's)

The specific name of genetic algorithm refers to a work led by John Holland and the student K. DeJong in 1975

K. DeJong: "An analysis of the behaviour of a class of adaptive systems". Phd dissertation. Department of Computer and Communication Sciences, University of Michigan, Ann Arbor.

The main strength of this optimization technique is given by:

1) A strong ability to solve multidimensional problems with strong correlation

2) Strongly parallelizable

looking for **"genetic" in to the Jacow** repository (CERN):

from **1975 up to 2007**: four proceedings and **only two** discuss Beam-lines optimization:

2006: *"ELECTRON TRANSPORT LINE OPTIMIZATION USING NEURAL NETWORKS AND GENETIC ALGORITHMS"*, D. Schirmer EPAC : Optimization from booster BoDo to the storage ring DELTA (Dortmund)

Reported for completenes, but not cope with high brightness electron beam optimization.

2007: *"OPTIMIZATION OF THE BEAM LINE CHARACTERISTICS BY MEANS OF A GENETIC ALGORITHM",* A. Bacci, V. Petrillo, A. R. Rossi, L. Serafini, EPAC

2008: ***"****OPTIMIZATION OF THE MAGNETIC LATTICE USING GENETIC ALGORITHMS"*, L. Yang, et al, LBNL, EPAC

2010: *"LOW EMITTANCE LATTICE OPTIMIZATION USING MOGA",* Weiwei Gao, et al, Heifei Light Source (P. R. China)

2011: *" COMBINED OPTIMIZATION OF A LINAC-BASED FEL LIGHT SOURCE USING A* ***MOGA****",* Christos F. Papadopoulos, et al, LBNL, FEL

2012: 3 works, 1) Lattice optimization of ANKA (synchrotron light source of Karlsruhe Institute of Technology), 2)**MOGA** of Linac beam line optimization for a seeded fel (Diamond), 3)**MOGA** for linac lattice of PAL XFEL (Republic of Korea)