An innovative low energy ERL merger

A. Bacci (INFN-Mi) on behalf of BriXSinO project team

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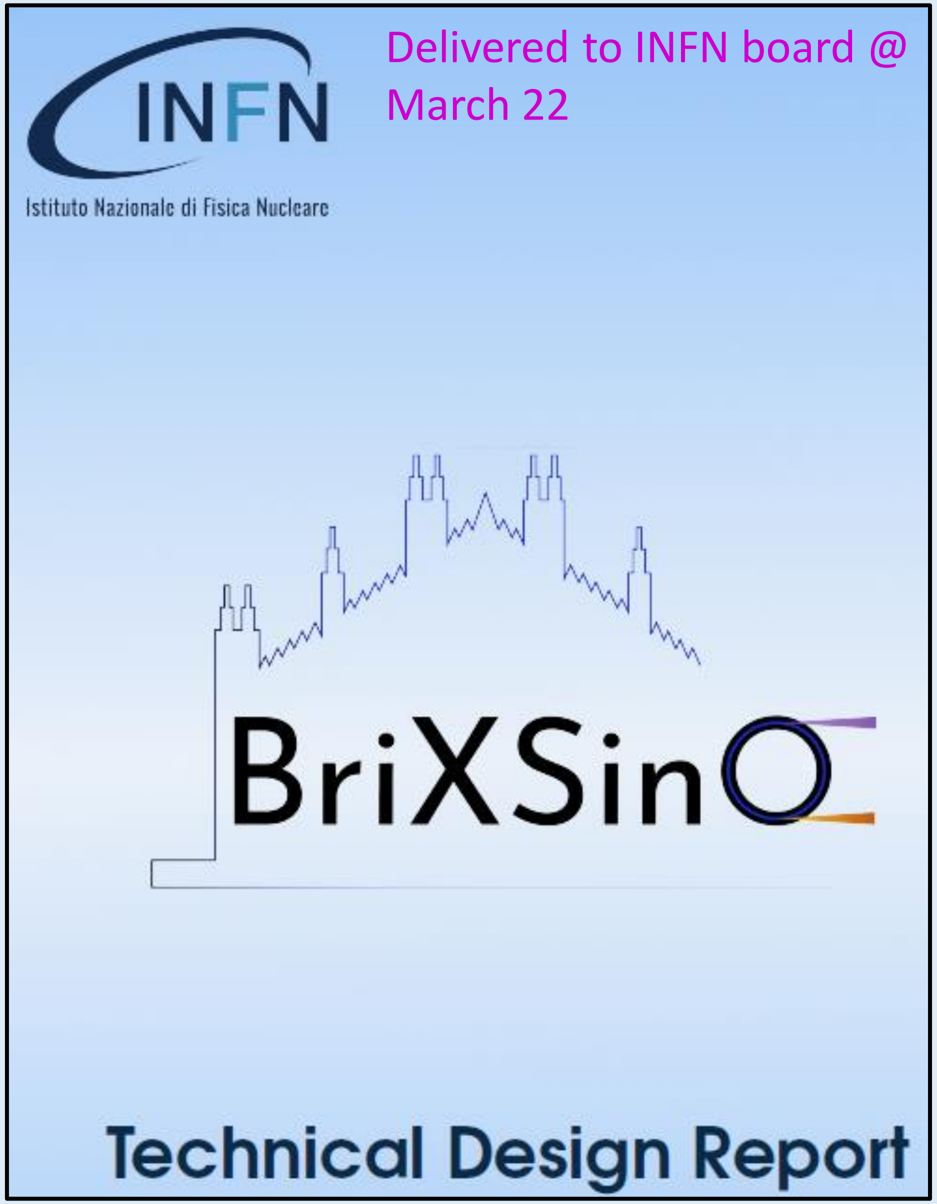
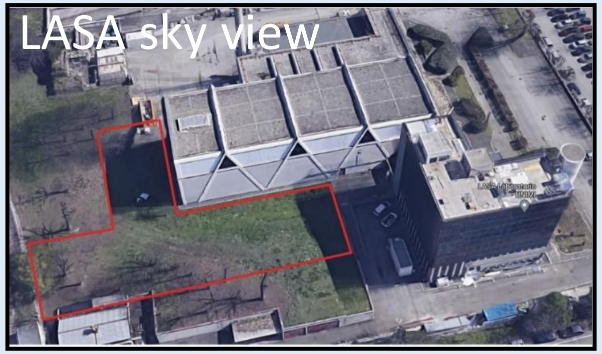
BriXSinO ERL project, the origin (1/2)



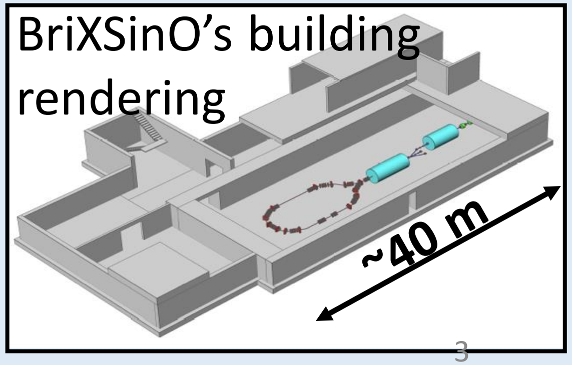
Delivered to INFN board @ March 22

L.A.S.A. - Laboratorio Acceleratori e Superconduttività Applicata
→ Accelerator Laboratory and Applied Superconductivities

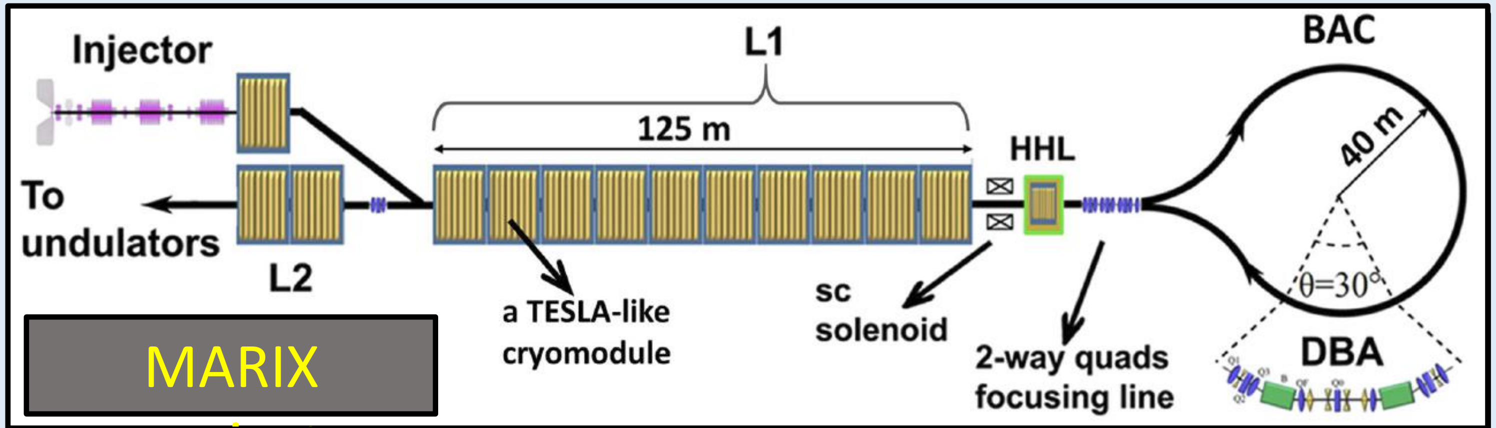
LASA sky view



BriXSinO's building rendering



BriXSinO ERL project, the origin (2/2)



A. Bacci, M. Rossetti Conti et al., PRAB 22, 111304 (2019)

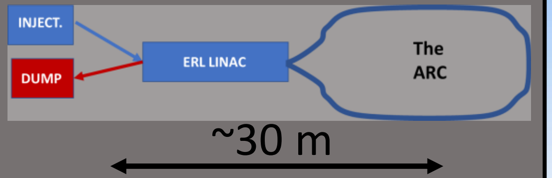
2020 ACTIS - INFN Grant awarded to Marcello Rossetti Conti

- ✓ **Arc Compressor Test In a Synchrotron @ Solaris (Poland, Krakow)**

ACTiS

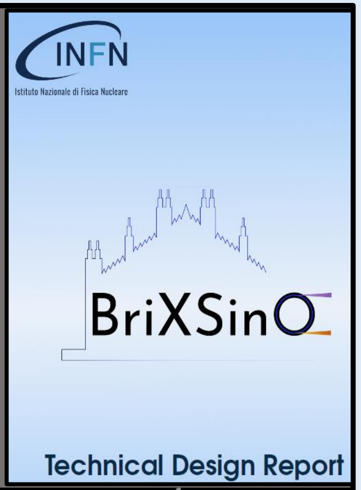
S. Di Mitri and M. Cornacchia, EPL 109, 62002 (2015)

2022 ERL BriXSinO ~ 10 M€



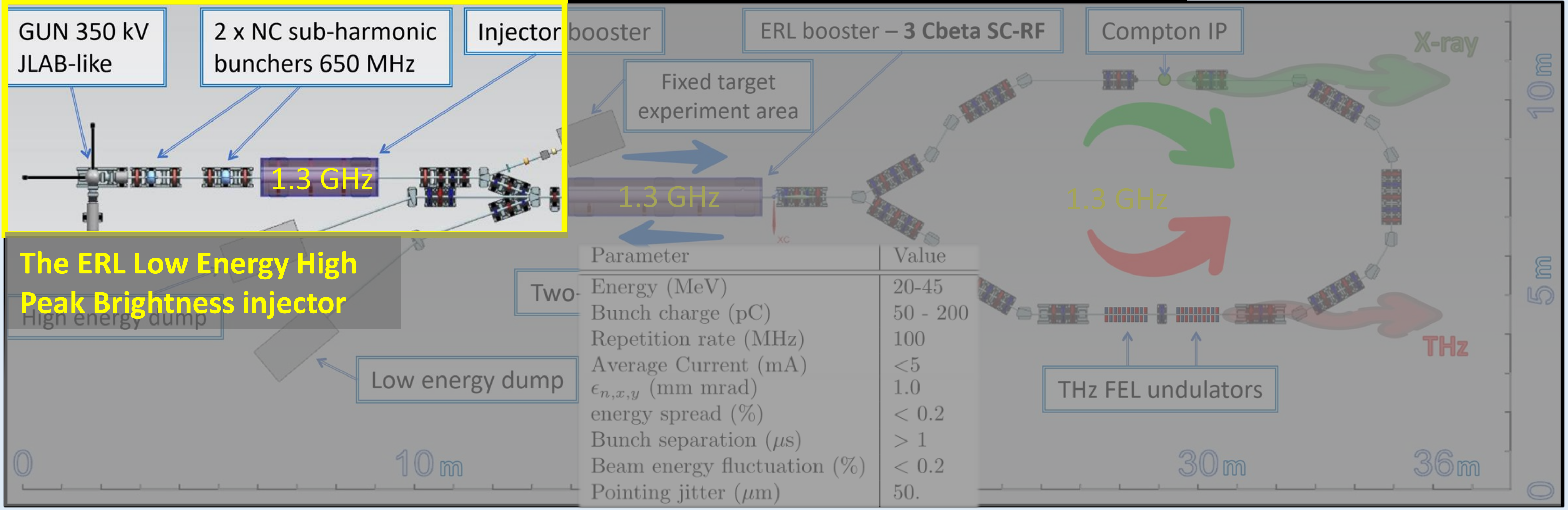
Test Facility for:

- ✓ **TPTW acc.**
- ✓ **Low Energy Arc Compression**
- ✓ **ERL TPTW high flux ICS & THz FEL**



The BriXSinO Layout

***Bri**lliant source of **X**-rays based on **S**ustainable and **in**n**O**vative accelerators*



Parameter	Value
Energy (MeV)	20-45
Bunch charge (pC)	50 - 200
Repetition rate (MHz)	100
Average Current (mA)	<5
$\epsilon_{n,x,y}$ (mm mrad)	1.0
energy spread (%)	< 0.2
Bunch separation (μs)	> 1
Beam energy fluctuation (%)	< 0.2
Pointing jitter (μm)	50.

Maximum Energies
- ✓ TPTW acceleration up to 80 MeV
- ✓ ERL WP up to 45 MeV

Why an ERL (1/2)

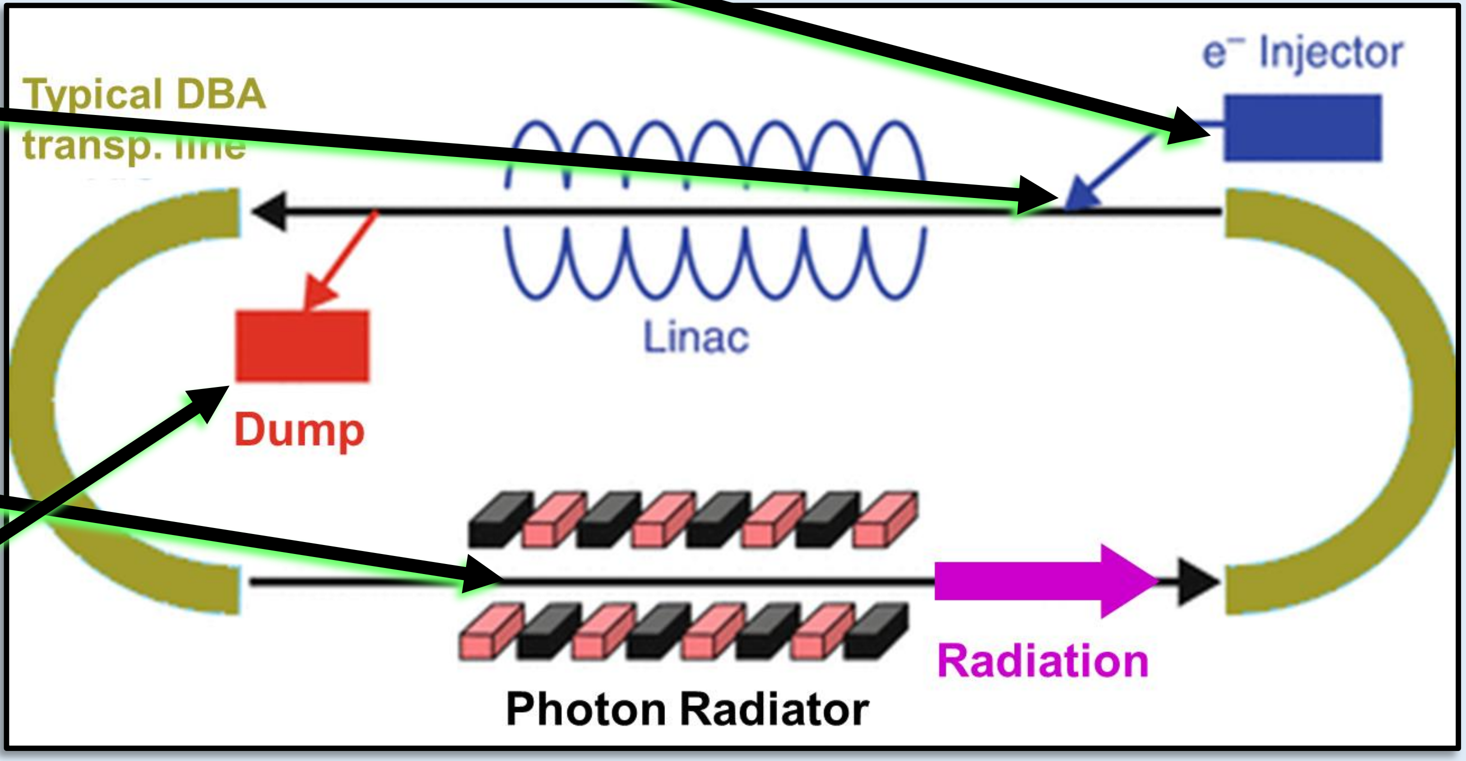
flow-chart & race-track ERL

Fresh electrons generated @ low energy → typically few MeV

Bunches are accelerated @ wanted energy by a LINAC → LINAC BD top quality.

Single use of the beam then decelerated to merger energy → during deceleration full energy recovering by SC high Q cavities

4 - The beam is dumped @ merger energy → typically, no neutron production, less radio protection issues, smaller dump devices →→ a very GREEN machine



Why an ERL (2/2) – Further considerations

Previous two decades WW Labs focused on **beam quality to prove the principia**

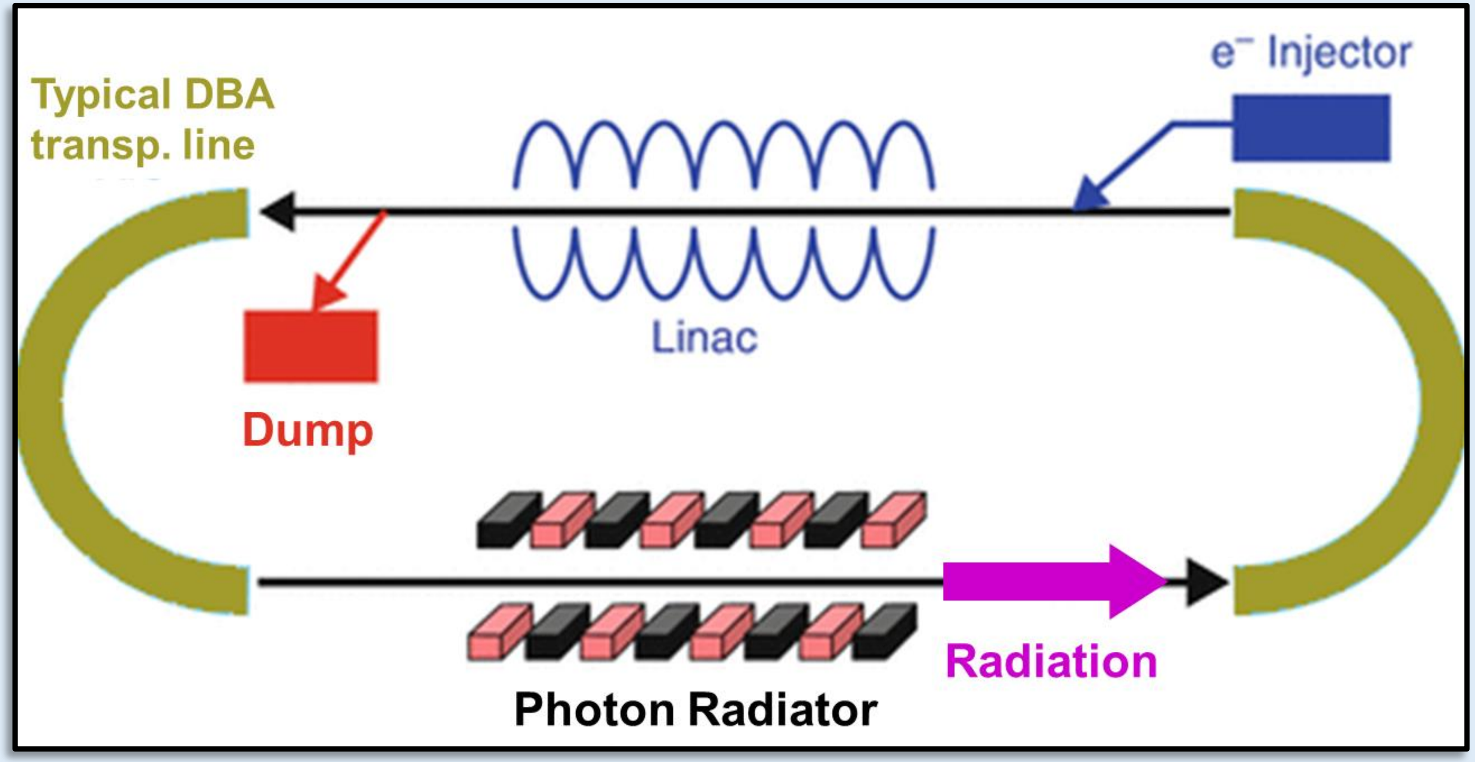
e. g. LCLS-I or Flash (DESY) - driven by photoinjector at 10 – 50 – 100 Hz
Nowadays, the request is the FLUX or Rep. Rate, in FEL, ICS, Colliders etc …

beam power request:

Infeasible: 100 Hz LINAC, 5 mA average beam current @ 150 MeV → 750 kW (~250 flats)

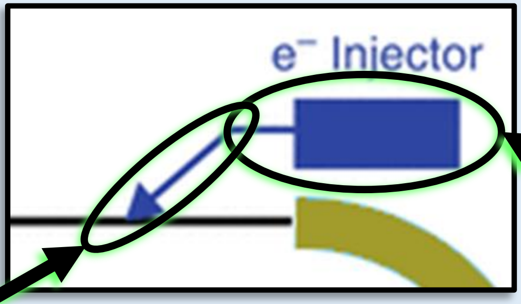
Real Case: STAR (@ UNICAL – Italy) Q_b= 2nC @ 100Hz (i.e., 200nA) @ 150 MeV → 30 W

ERL
BriXSinO: 5mA @ 4 MeV → 20kW (~ 7 flats)
- Energy Loss = Injector Energy.
- Max. energy NO power limitation
- SC technology NO thermal dissipation



Low energy injectors Critical aspects

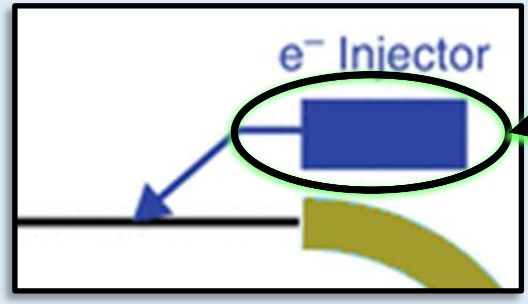
A MUST is
Push the beam brightness @ maximum values
AN INJECTOR GAME



A performing GUN Boosting @ few MeVs

Dipoles path
Preserving Beam Quality
Huge Peak Brightness
A Space-Charge S-C issue!

BriXSinO Low energy injectors (1/2)

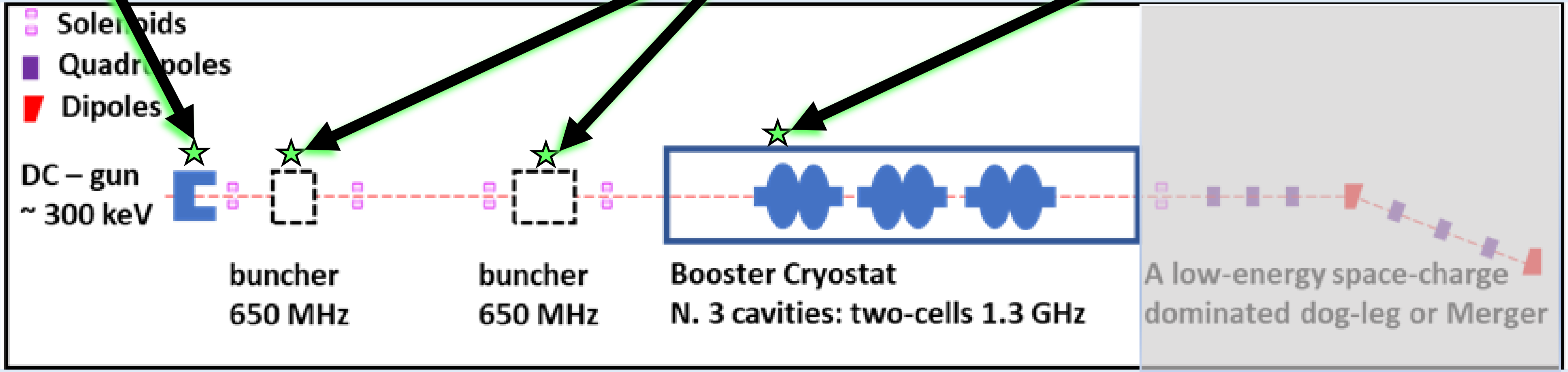


A performing GUN Boosting few MeVs

250 – 350 KeV DC-gun
- no edge performances
- reliable & cheep

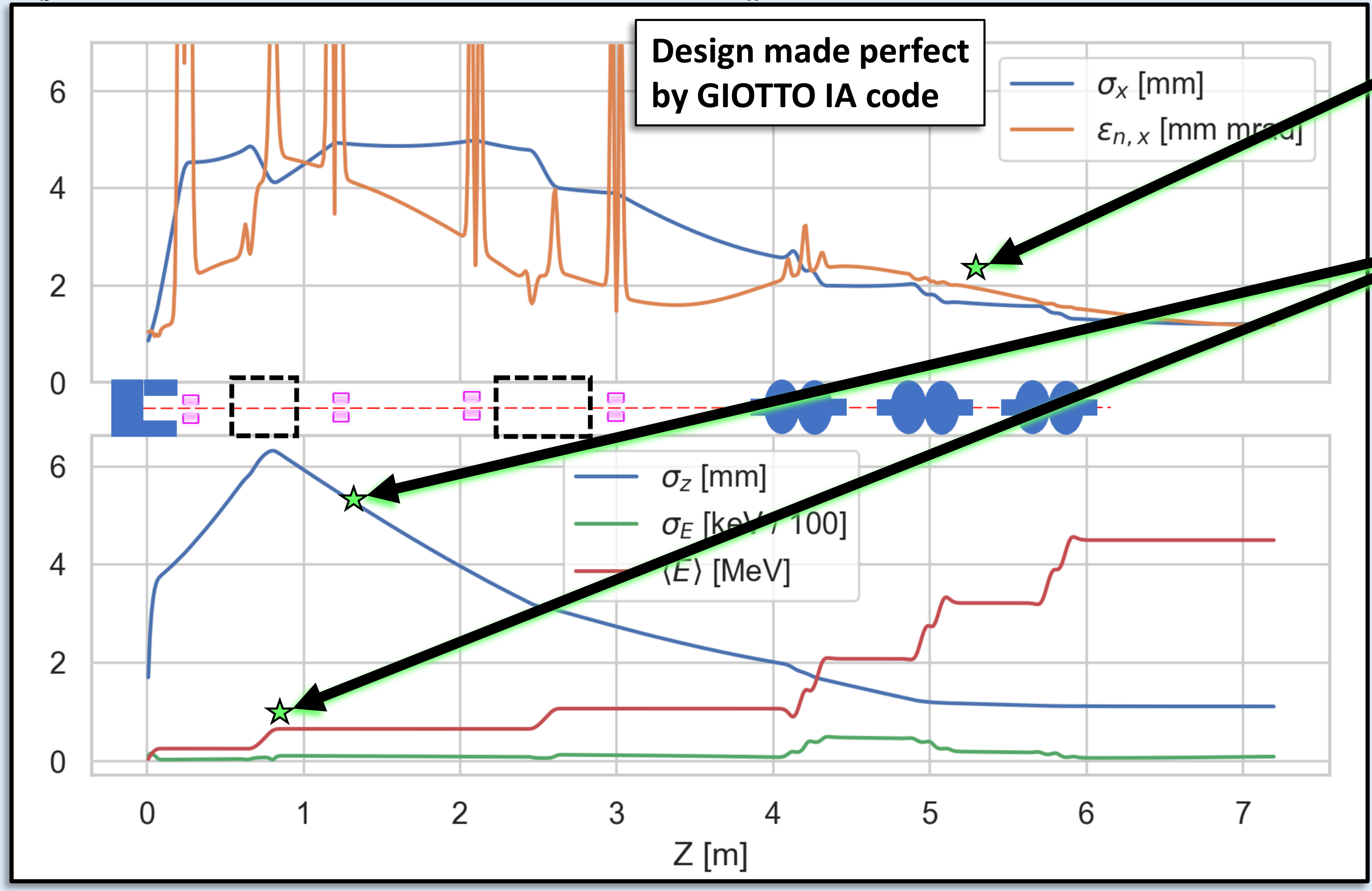
Two sub-harmonic bunchers 650 MHz (booster & main LINAC @ 1.3GHz)
- V_{ph} → β=0.740 & β = 0.906
- acceleration & compression
- low σ_E by RF curvature
- longer λ → Longer bunches
- Cigar-like distrib. → low emittances

3 two-cells SC cavity:
- boost @ 4.5MeV (10 MeV capability for others) .
- Different RF injection phases
- Velocity bunching



BriXSinO Low energy injectors (2/2)

Q_b = 100 *pC*, Laser_t=22 *ps*, rise_t=1 *ps*, Laser_σ_x=700 *um* *(Rep.rate 50 MHz)*



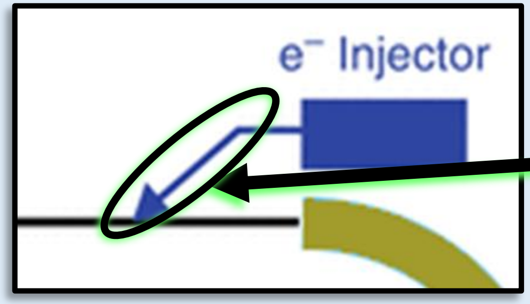
emit-compensation
in S-C regime
well tuned

Bunchers
both comp. & acc.

BD @ injector exit
env. = 1 mm env.
σ_Z = 1 mm
ε_n = 1um
very very low σ_E

Very good enters the Disp.Path

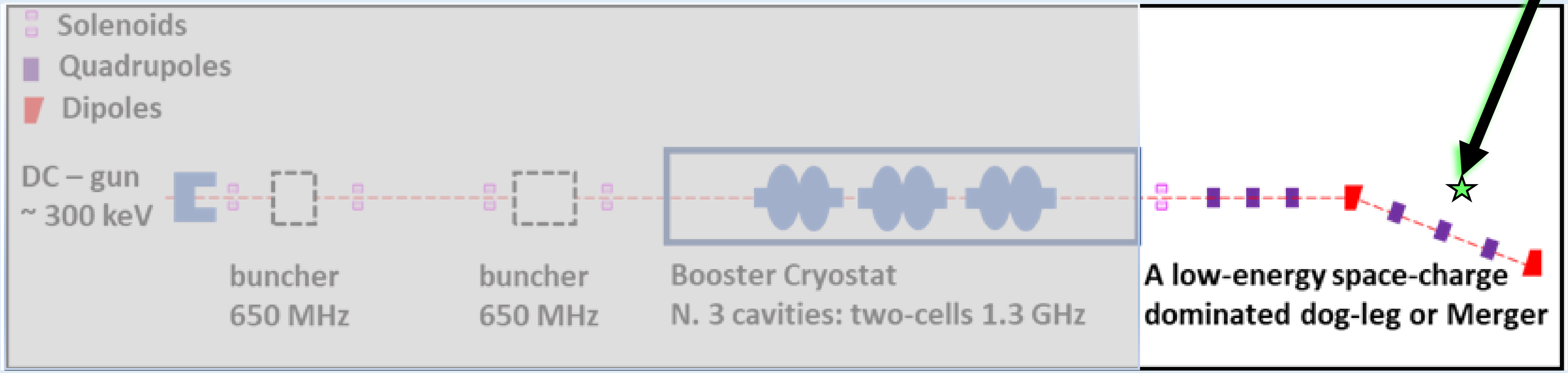
BriXSinO Dispersive path design with GIOTTO AI code (1/4)



To design a Dipoles path
Preserving Beam Quality
Huge Peak Brightness
A Space-Charge S-C issue!

IF no S-C regime
it is linear geometry; achromatic lattice design
MATRIX CODES: Trace-3D, Elegant, MAD, etc. …

high brightness @ Low energy
↓
S-C regime + Dipoles i.e. Dispersion
↓
NON Linear Correlated BD
We use a genetic IA code



Literature works on S-C Dispersive paths (1/3)

Problem addressed in a few papers, one of the most interesting: NIM- A 557 (2006) 165-175

Merger designs for ERLs☆

Vladimir N. Litvinenko[a,*], Ryoichi Hajima[b], Dmitry Kayran[a]

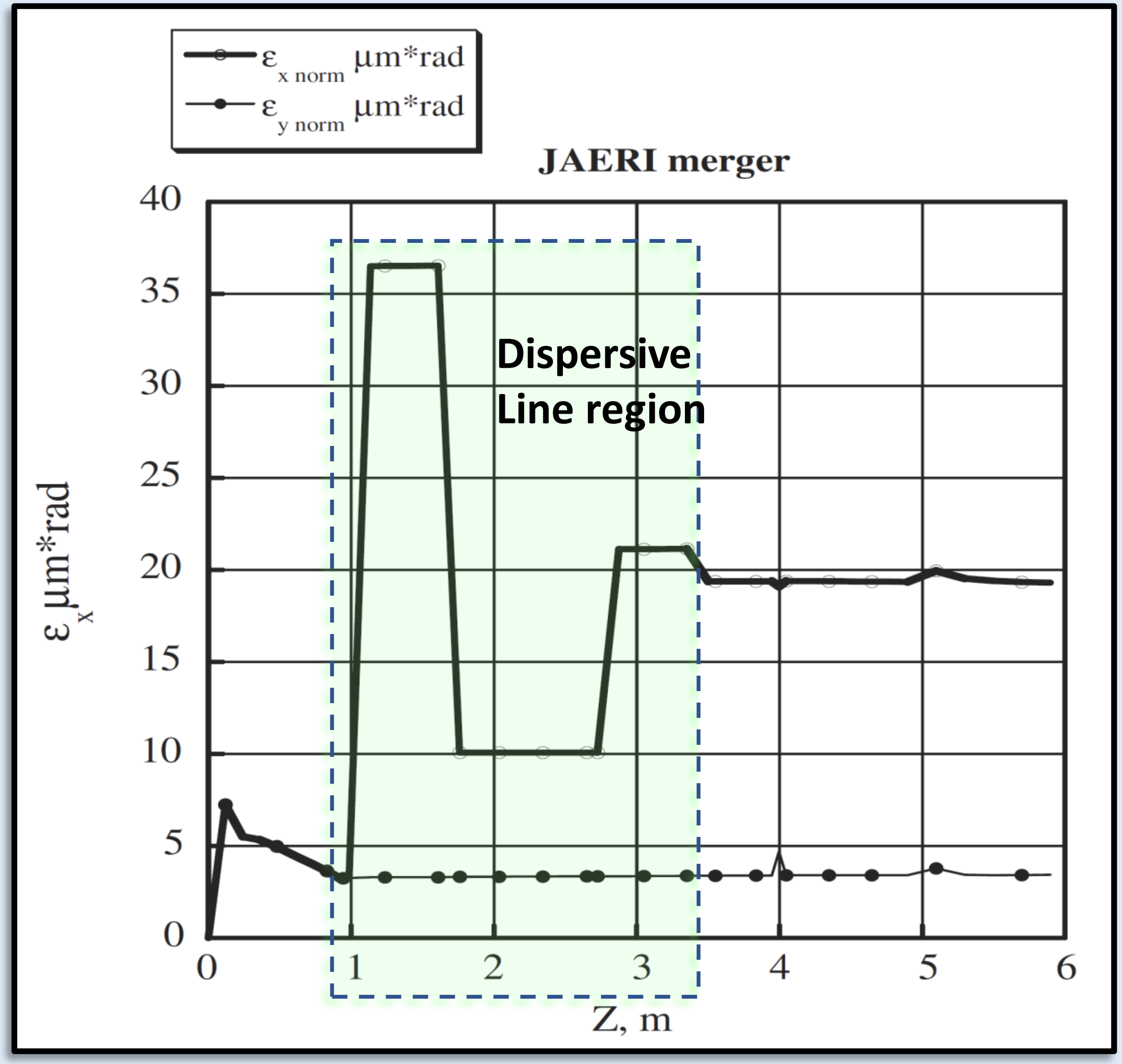
[a]Brookhaven National Laboratory, Upton, NY 11973, USA
[b]Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki 319-1195, Japan

Available online 16 November 2005

The paper considers the effects of:

Transvers S-C Fources TSCF
Longitud. S-C Fources LSCF

consider some ERL machines:
TJNAF Jefferson Lab,
BINP Novosivirsk,
Particularly JAERI Japan Atomic Energy Institute



Literature works on S-C Dispersive paths (2/3)

"NIM- A 557 (2006) 165-175, analytical study
- TSCF emit increases treated as in rf Photoinjecto [1]
- LSCF emit increases same physics of CSR induced emittance, papers [2] & [3]; violation of achromatic condition due to electron-energy redistribution

The authors give a GOLDEN role:

↓

"Dispersive path with weakly focusing elements"

↓

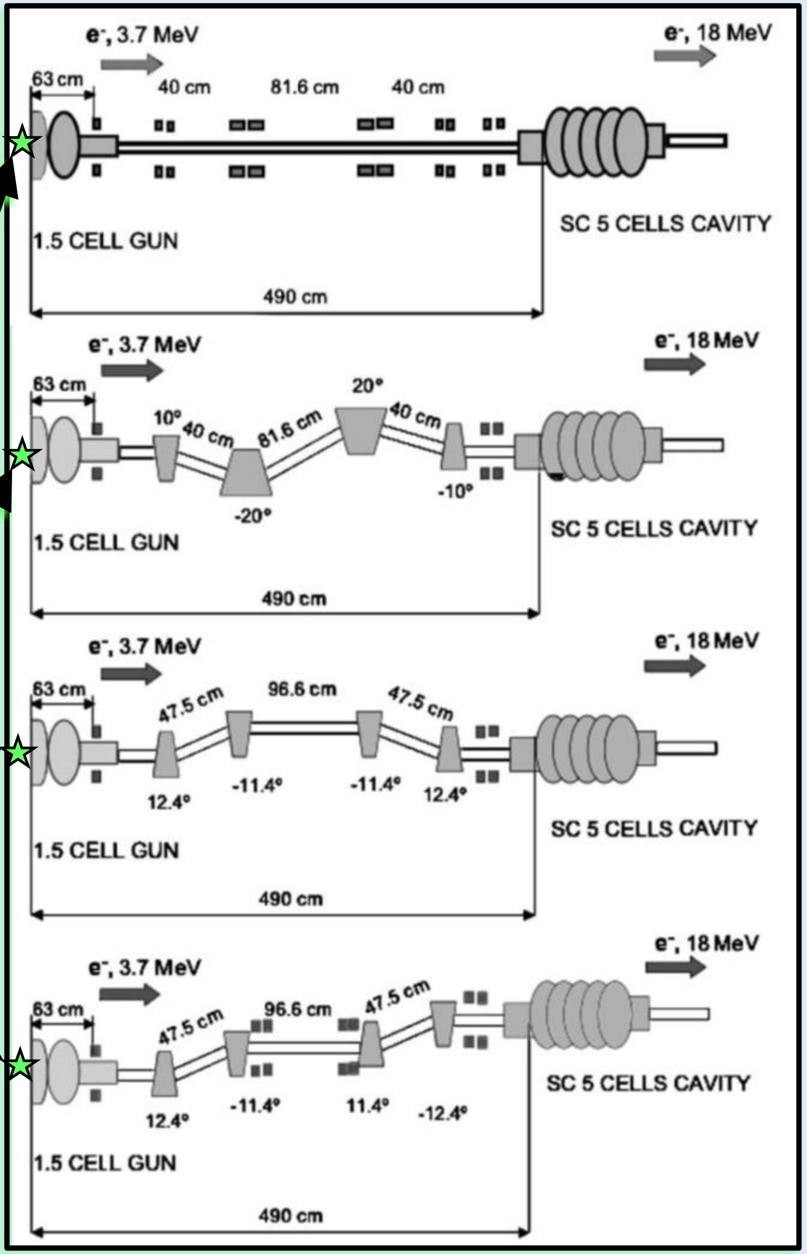
$f \geq L_{\text{Disp-path}}$

↓

ZIG-ZAG beam line

Four different Dispersive paths simulated with Parmela 3D code

1. Straight
2. ZIG-ZAG
3. Chicane
4. DogLeg

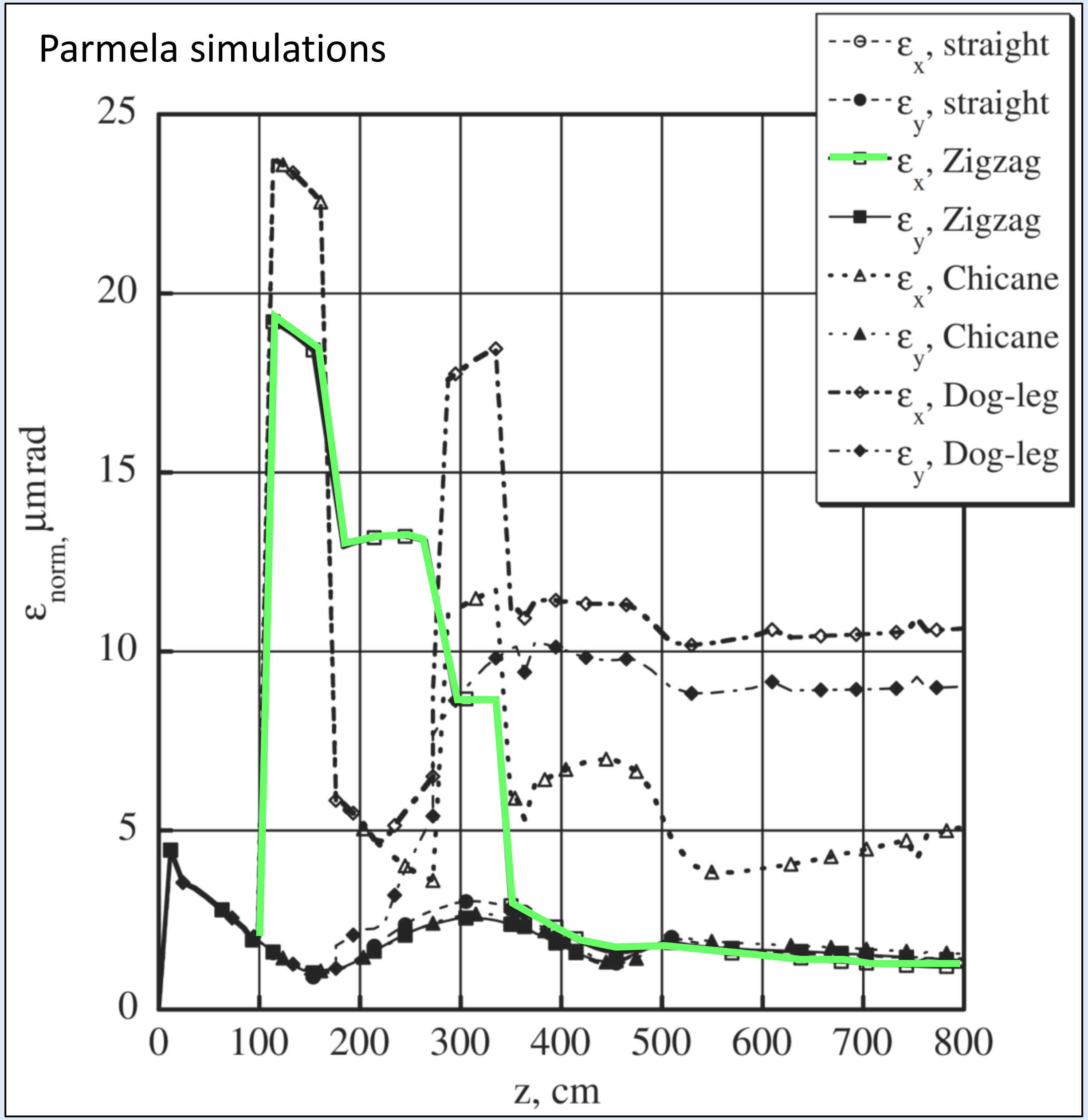


[1] *J.B. Rosenzweig, L. Serafini, PRE 49 (1994) 1599*

[2] *R. Hajima, jpn JAP 42 (2003) L974*

[3] *Y.S. Derbenev, et al., TESLA-95-05, 1995; B.E. Carsten, PRE 54 (1996) 838*

Literature works on S-C Dispersive paths (3/3)

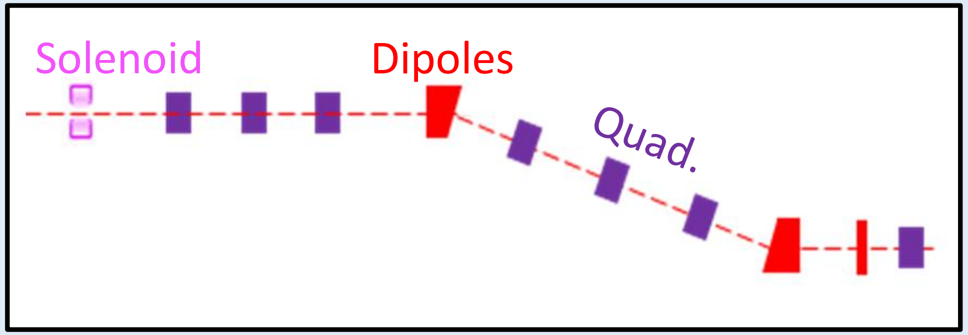


BriXSinO Dispersive path design with GIOTTO AI code (1/5)

We decided to go straight by using OUR IA Optimization code GIOTTO
We modify bit GIOTTO & Developed a new code capable to use ASTRA to design dispersive paths

The recipe for solving numerically the problem is:

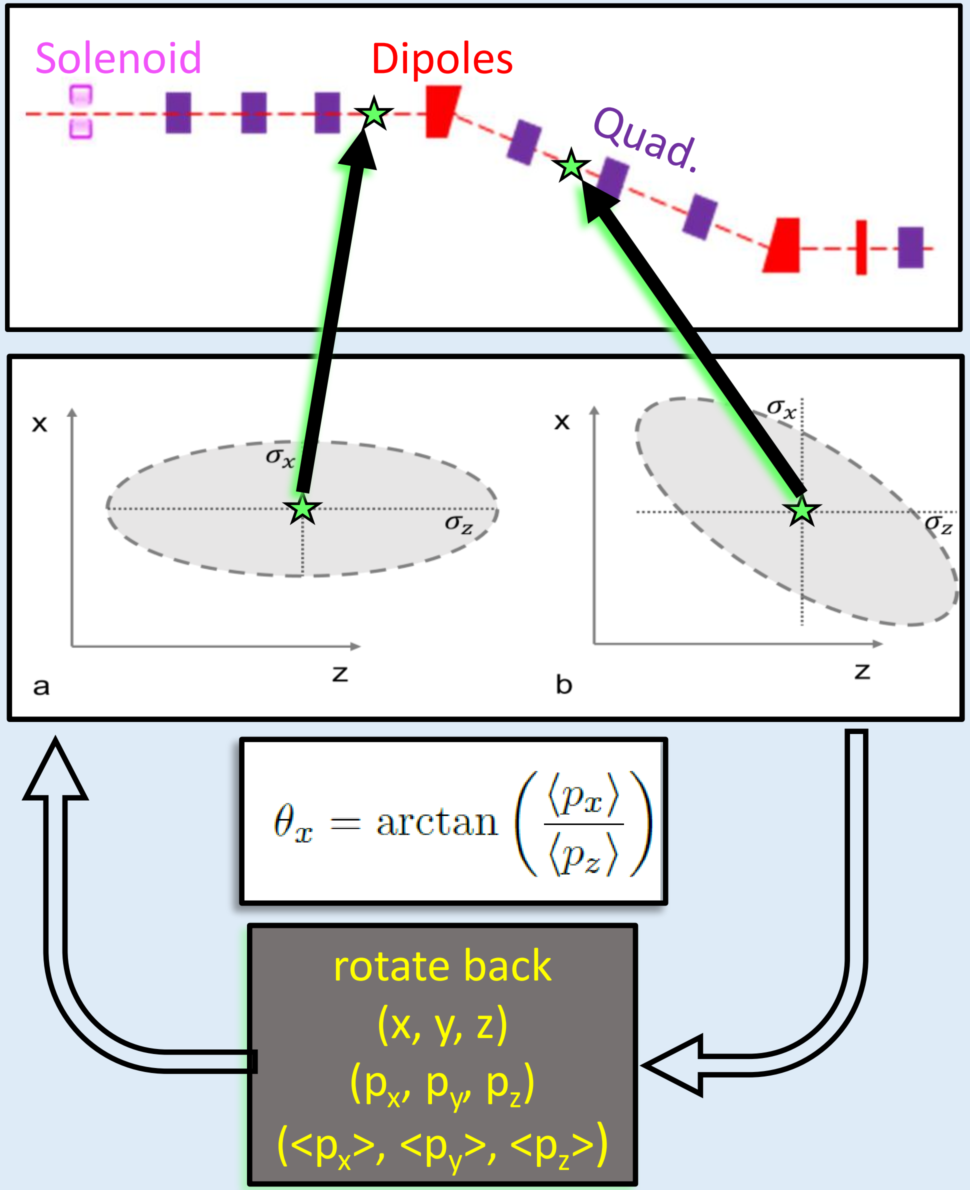
1) A full 3D tracking code for a S-C BD; ASTRA code [1] is the perfect!
2) An algorithm to cope with NON-Linear problems; USING ASTRA as SOLVER. GIOTTO [2] is perfect!
3) Add to ASTRA the capability to design Dispersive Paths:
   We developed a post processor the uncorrelated (un-rotate) astra-beams traveling in slope direction and that computing η and η', as all the others main parameters, RotnSlice code.



[1] K. Floettmann, A Space charge TRacking Algorithm, https://www.desy.de/~mpyflo/
[2] A. Bacci, M. Rossetti Conti, at al. Giotto: A genetic code for demanding beam-dynamics optimizations

RotnSlice post-pro (1/2)

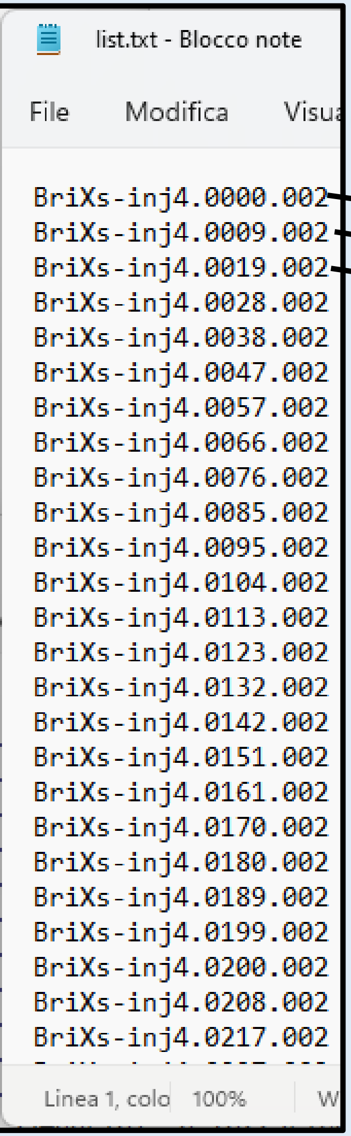
In Astra after a dipole: bunch rotation; not the CoSyS



$$\theta_x = \arctan\left(\frac{\langle p_x \rangle}{\langle p_z \rangle}\right)$$

```
**************************  INSTRUCTIONS  ***************************************
- Computes eta_x, etaP_x, eta_y, etaP_y and other beam paramiters.
- Straightens tilted bunches (e.g. passed throught dipole fields).
- Rotates bunches by given angles.
- Performs bunch slice analysis or to compute Trace3D code inputs.
- Performs single-bunch analysis in comb trains.

Angles are computed by <Px>/<Pz> and <Py>/<Pz> OR imposed by the User

This Code is useful to compute fitness functions, based on eta parameters,
in the GIOTTO software (e.g. dispersion closure after dispersive paths).
Also enables GIOTTO to optimize comb beam dynamics

Different WORKING MODES:
** 1 ** Bunch slice analysis:
/>RotnSlice_05 <astra_file> [N_slclice]

 -Generates <an_out_xx.txt> beam parameters file with eta, eta_prime
  xx is the astra run index
 -If N_slclice = 1 it returns values for the whole bunch and
  also values in Trace3D  format
 -If N_slclice is not specified it means N_slclice=1
 -If N_slclice > 1 the slice analysis is performed

** 2 ** Elaborate a list of Astra's bunch distributions:
/>RotnSlice_05 <List_of_file.txt>

 -Generates <an_out_xx.txt> for every file into the list

** 3 ** Bunch rotation by an User defined angle:
/>RotnSlice_05 <astra_file> <output_file> <(theta_x,theta_y)>

 -Generates <output_file>, an Astra distribution that propagate in the
  direction (theta_x,theta_y) [rad]. It is a fortran complex format
  theta_x>0 means z_versor rotating versus x-axis
  theta_y>0 means z_versor rotating versus y-axis

** FURTHER CAPABILITIES **:
Optional input file <RnS_Opt_in.txt> to be added in working folders
 -Contains the NAMELIST "&optional_par" to change following variables

VARIABLE        |type       |default      |meaning
freq [MHz]       real        2856.0d6      RF for long-emit [rad-keV] (Trace3D format)
rotate           logical     TRUE          rotates the bunches
```

RotnSlice post-pro (2/2)



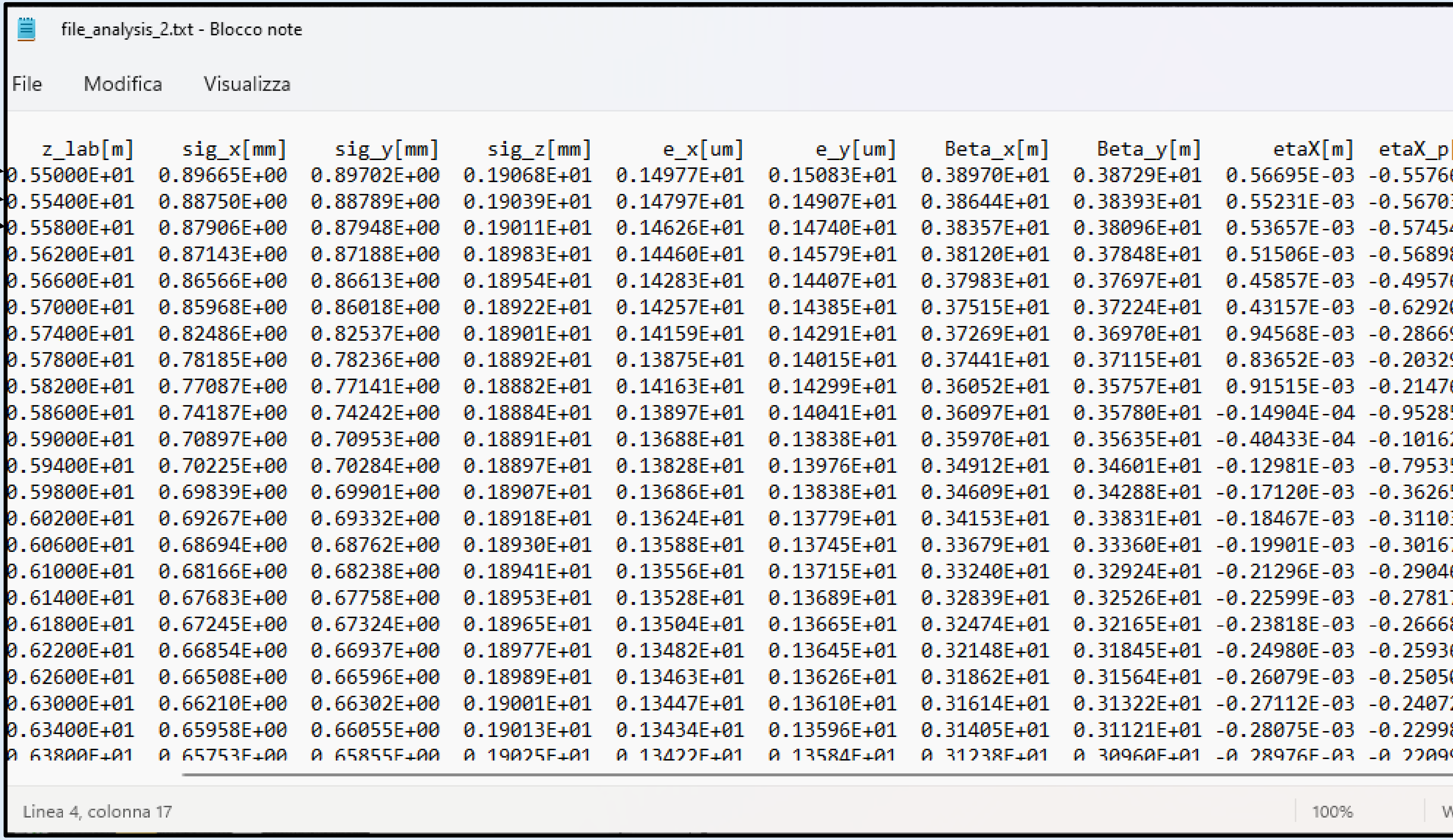
list.txt - Blocco note

File Modifica Visua

```
BriXs-inj4.0000.002
BriXs-inj4.0009.002
BriXs-inj4.0019.002
BriXs-inj4.0028.002
BriXs-inj4.0038.002
BriXs-inj4.0047.002
BriXs-inj4.0057.002
BriXs-inj4.0066.002
BriXs-inj4.0076.002
BriXs-inj4.0085.002
BriXs-inj4.0095.002
BriXs-inj4.0104.002
BriXs-inj4.0113.002
BriXs-inj4.0123.002
BriXs-inj4.0132.002
BriXs-inj4.0142.002
BriXs-inj4.0151.002
BriXs-inj4.0161.002
BriXs-inj4.0170.002
BriXs-inj4.0180.002
BriXs-inj4.0189.002
BriXs-inj4.0199.002
BriXs-inj4.0200.002
BriXs-inj4.0208.002
BriXs-inj4.0217.002
```

Linea 1, colo 100% W

RotnSlice



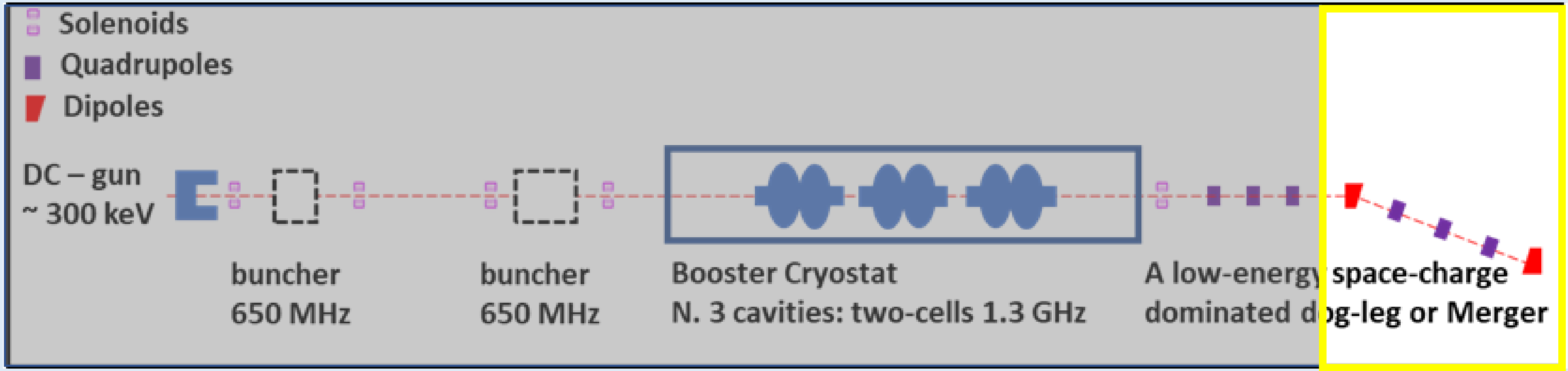
file_analysis_2.txt - Blocco note

File Modifica Visualizza

z_lab[m]	sig_x[mm]	sig_y[mm]	sig_z[mm]	e_x[um]	e_y[um]	Beta_x[m]	Beta_y[m]	etaX[m]	etaX_p
0.55000E+01	0.89665E+00	0.89702E+00	0.19068E+01	0.14977E+01	0.15083E+01	0.38970E+01	0.38729E+01	0.56695E-03	-0.5576
0.55400E+01	0.88750E+00	0.88789E+00	0.19039E+01	0.14797E+01	0.14907E+01	0.38644E+01	0.38393E+01	0.55231E-03	-0.5670
0.55800E+01	0.87906E+00	0.87948E+00	0.19011E+01	0.14626E+01	0.14740E+01	0.38357E+01	0.38096E+01	0.53657E-03	-0.5745
0.56200E+01	0.87143E+00	0.87188E+00	0.18983E+01	0.14460E+01	0.14579E+01	0.38120E+01	0.37848E+01	0.51506E-03	-0.5689
0.56600E+01	0.86566E+00	0.86613E+00	0.18954E+01	0.14283E+01	0.14407E+01	0.37983E+01	0.37697E+01	0.45857E-03	-0.4957
0.57000E+01	0.85968E+00	0.86018E+00	0.18922E+01	0.14257E+01	0.14385E+01	0.37515E+01	0.37224E+01	0.43157E-03	-0.6292
0.57400E+01	0.82486E+00	0.82537E+00	0.18901E+01	0.14159E+01	0.14291E+01	0.37269E+01	0.36970E+01	0.94568E-03	-0.2866
0.57800E+01	0.78185E+00	0.78236E+00	0.18892E+01	0.13875E+01	0.14015E+01	0.37441E+01	0.37115E+01	0.83652E-03	-0.2032
0.58200E+01	0.77087E+00	0.77141E+00	0.18882E+01	0.14163E+01	0.14299E+01	0.36052E+01	0.35757E+01	0.91515E-03	-0.2147
0.58600E+01	0.74187E+00	0.74242E+00	0.18884E+01	0.13897E+01	0.14041E+01	0.36097E+01	0.35780E+01	-0.14904E-04	-0.9528
0.59000E+01	0.70897E+00	0.70953E+00	0.18891E+01	0.13688E+01	0.13838E+01	0.35970E+01	0.35635E+01	-0.40433E-04	-0.1016
0.59400E+01	0.70225E+00	0.70284E+00	0.18897E+01	0.13828E+01	0.13976E+01	0.34912E+01	0.34601E+01	-0.12981E-03	-0.7953
0.59800E+01	0.69839E+00	0.69901E+00	0.18907E+01	0.13686E+01	0.13838E+01	0.34609E+01	0.34288E+01	-0.17120E-03	-0.3626
0.60200E+01	0.69267E+00	0.69332E+00	0.18918E+01	0.13624E+01	0.13779E+01	0.34153E+01	0.33831E+01	-0.18467E-03	-0.3110
0.60600E+01	0.68694E+00	0.68762E+00	0.18930E+01	0.13588E+01	0.13745E+01	0.33679E+01	0.33360E+01	-0.19901E-03	-0.3016
0.61000E+01	0.68166E+00	0.68238E+00	0.18941E+01	0.13556E+01	0.13715E+01	0.33240E+01	0.32924E+01	-0.21296E-03	-0.2904
0.61400E+01	0.67683E+00	0.67758E+00	0.18953E+01	0.13528E+01	0.13689E+01	0.32839E+01	0.32526E+01	-0.22599E-03	-0.2781
0.61800E+01	0.67245E+00	0.67324E+00	0.18965E+01	0.13504E+01	0.13665E+01	0.32474E+01	0.32165E+01	-0.23818E-03	-0.2666
0.62200E+01	0.66854E+00	0.66937E+00	0.18977E+01	0.13482E+01	0.13645E+01	0.32148E+01	0.31845E+01	-0.24980E-03	-0.2593
0.62600E+01	0.66508E+00	0.66596E+00	0.18989E+01	0.13463E+01	0.13626E+01	0.31862E+01	0.31564E+01	-0.26079E-03	-0.2505
0.63000E+01	0.66210E+00	0.66302E+00	0.19001E+01	0.13447E+01	0.13610E+01	0.31614E+01	0.31322E+01	-0.27112E-03	-0.2407
0.63400E+01	0.65958E+00	0.66055E+00	0.19013E+01	0.13434E+01	0.13596E+01	0.31405E+01	0.31121E+01	-0.28075E-03	-0.2299
0.63800E+01	0.65753E+00	0.65855E+00	0.19025E+01	0.13422E+01	0.13584E+01	0.31238E+01	0.30960E+01	-0.28976E-03	-0.2209

Linea 4, colonna 17 100% W

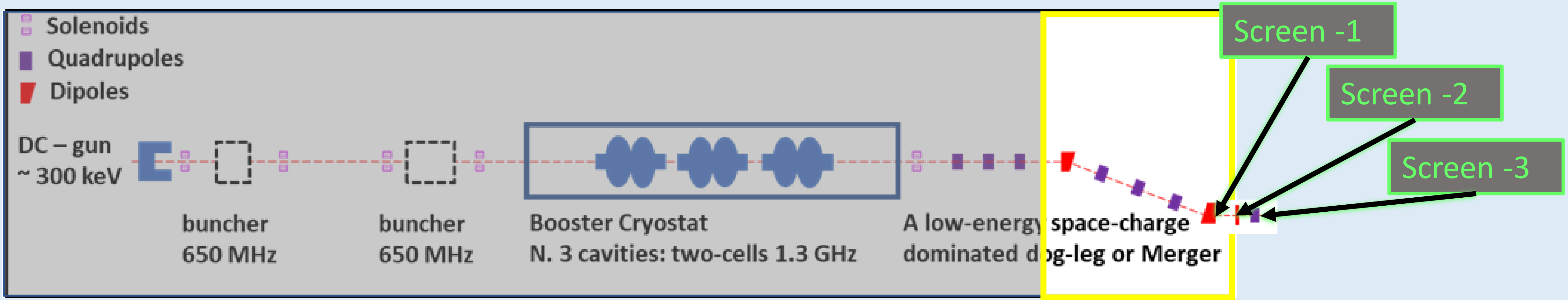
BriXSinO Dispersive path design with GIOTTO AI code (2/4)



GIOTTO with the Genetic approach used 15 GENES or knobs to solve the dispersive path:

Quad:	1-2-3-4-5-6
Cavity inj. Phases:	1-2-3-4-5
Solenoid fields:	2-3-4-5

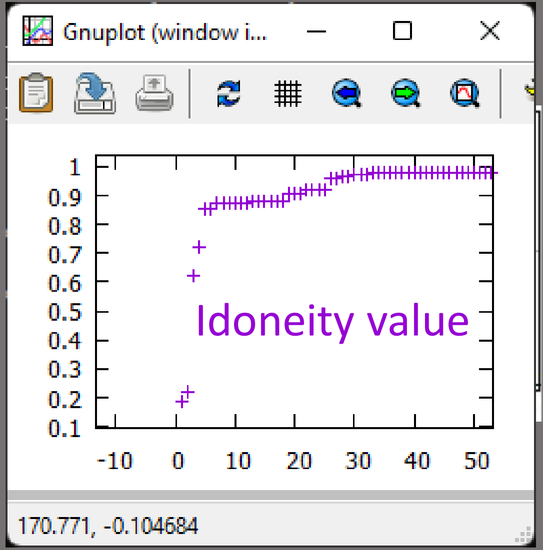
BriXSinO Dispersive path design with GIOTTO AI code (3/5)



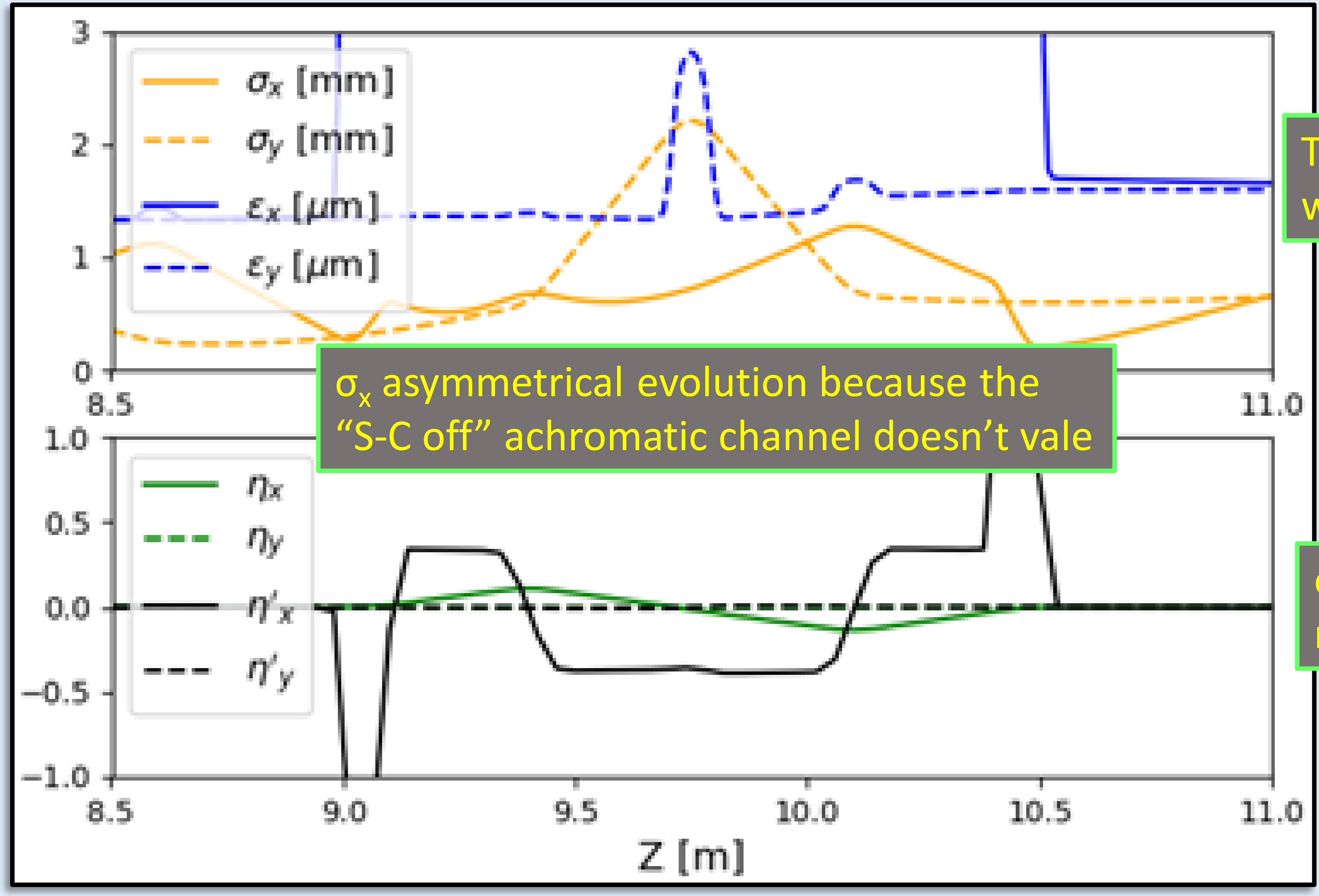
Idoneity Function (It is the sum of Lorentian curves)

$$\sum_{i=1}^{n} \frac{\sigma_i^2}{\sigma_i^2 + (Par_i - Taget_i)^2} \cdot A_i$$

Par_i	$Target_i$	σ_i	screen
ε_x	0.0	6	3
ε_y	0.0	6	3
η, η'	0.0	0.01	3
η, η'	0.0	0.01	2
η, η'	0.0	0.01	1



BriXSinO Dispersive path design with GIOTTO AI code (4/4)



σ_x asymmetrical evolution because the "S-C off" achromatic channel doesn't vale

The emittances are well conserved

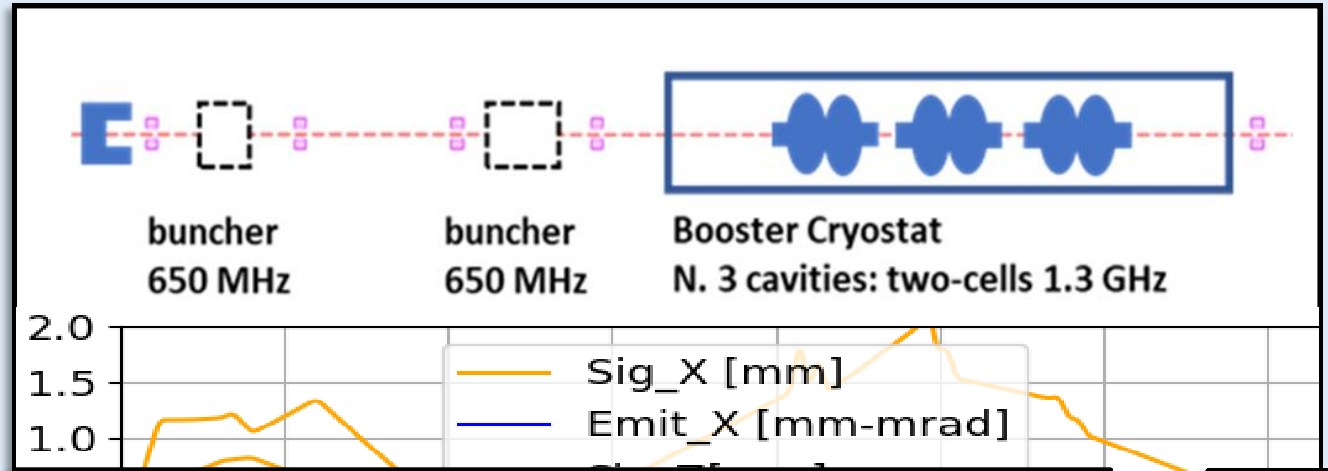
eta & eta' are reset to zero

Some main ERL WW projects Table of comparison

	Inj. Energy [MeV]	Qb [pC]	Injector emit.	<I> mA	Gun
Perle (Orsay, France)	7	500	6	20	CD gun 350 KeV
bERLinPro (Berlin, Germani)	7	77	<1	4/100	SRF photoinjector 2.3 MeV
C-beta (USA-Cornell)	7-8	77	0.7 – 1	Up to 100	DC gun 350 KeV
BriXSinO	**4.5**	**100**	**~1**	**Up to 5**	**DC gun** **250 keV**

BriXSinO ultra short ultra narrow bunches

BriXSinO ultra short ultra narrow bunch



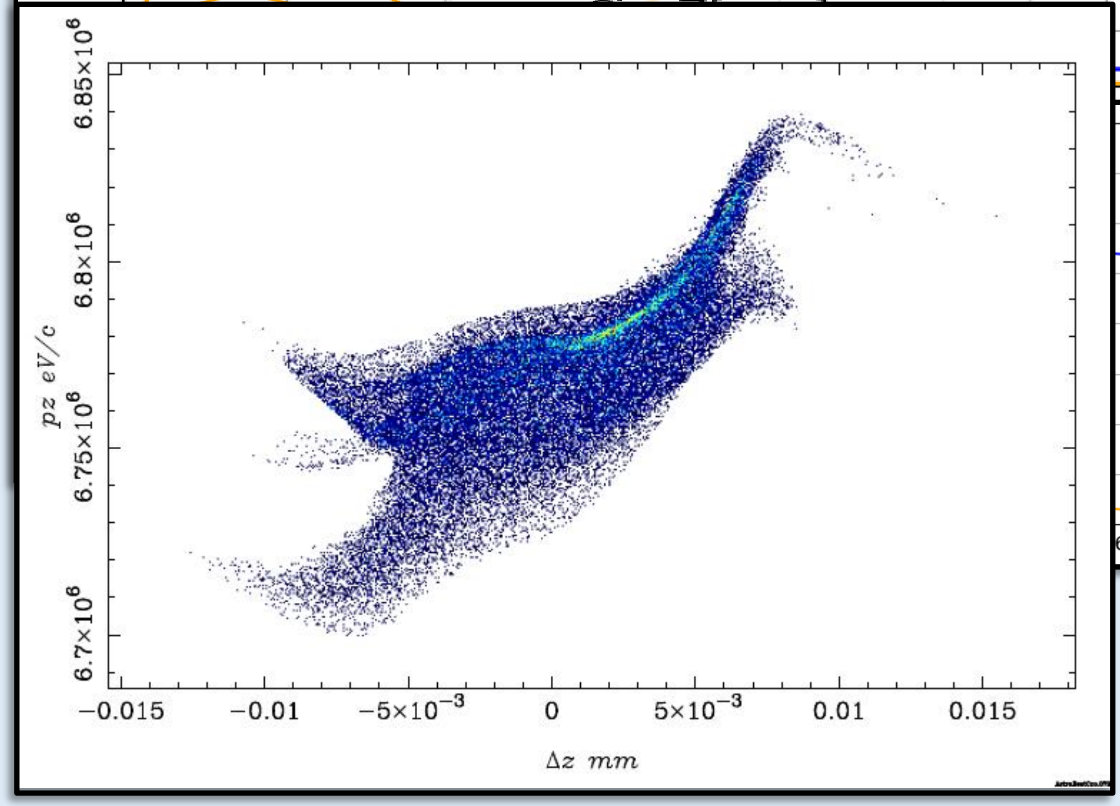
Bunch data @ Cathode:

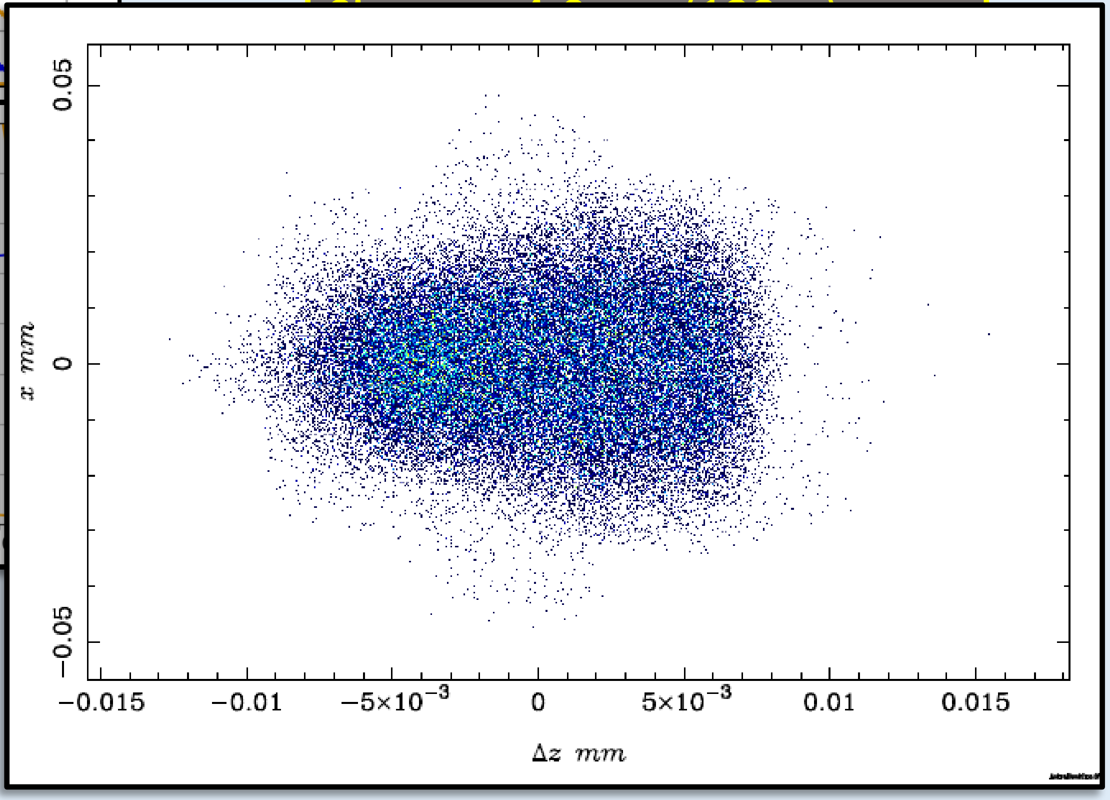
Q_b= 400 fC

Sig_t= 250 fs

Sig_x= 90 um

Bunch data @ LineEND





CO_2-Laser-Driven Dielectric Laser Accelerator

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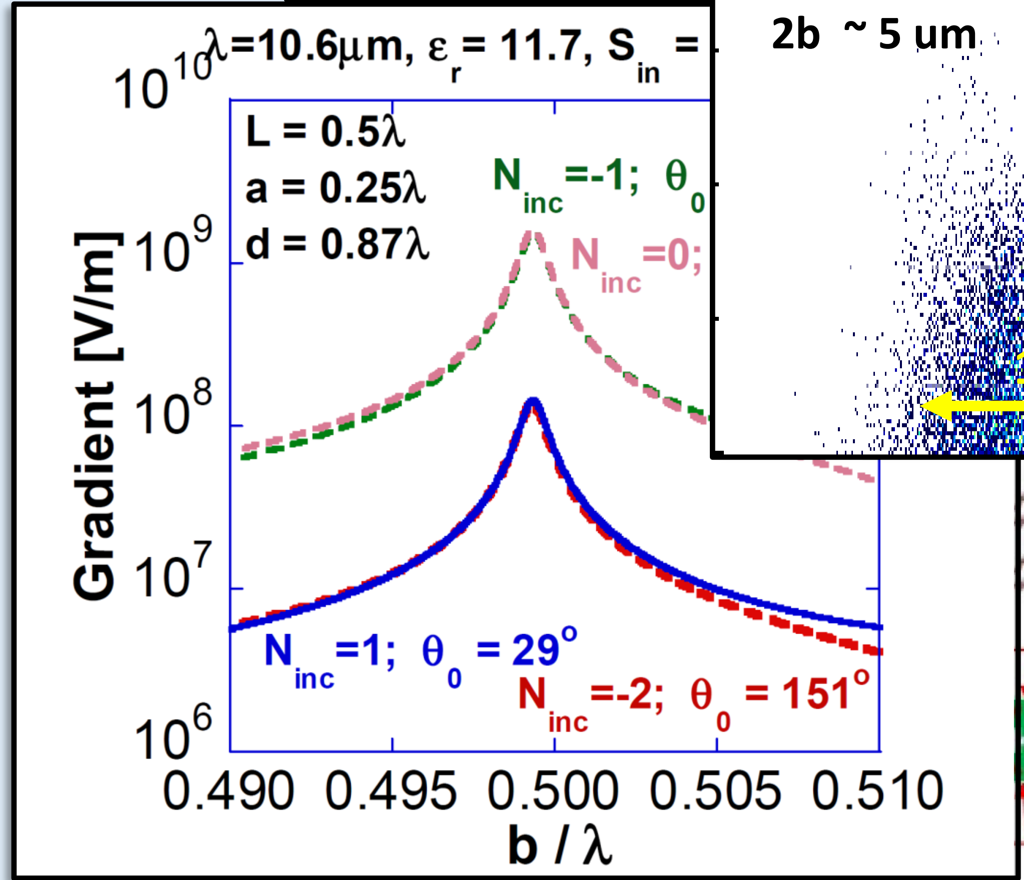

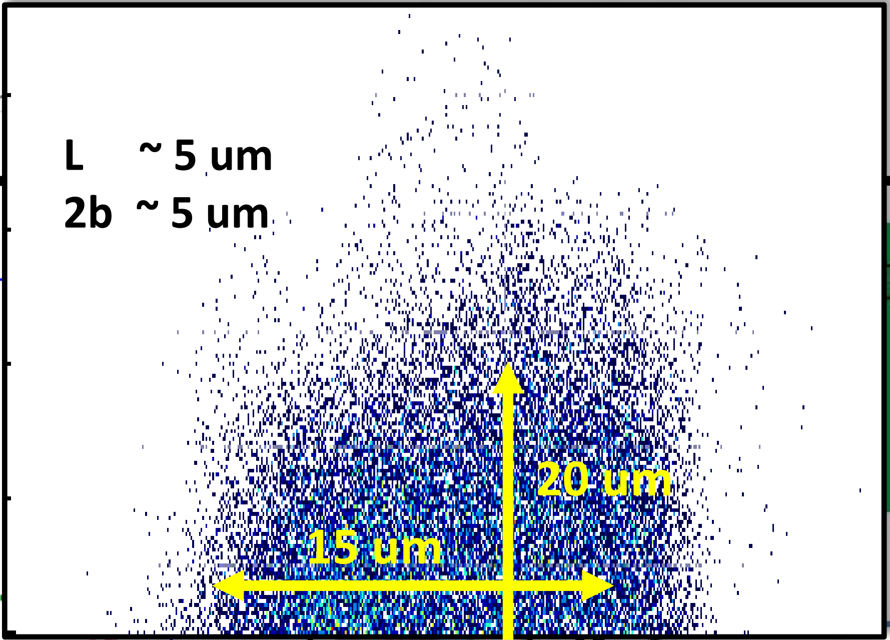

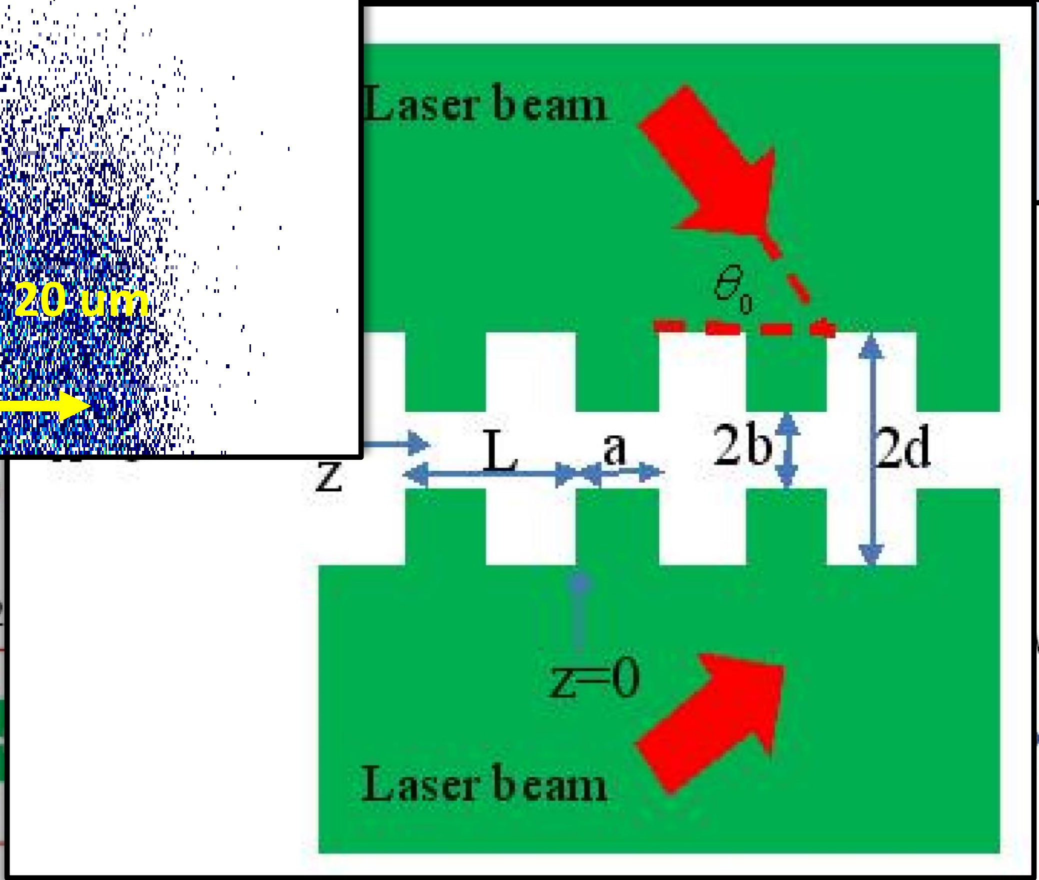

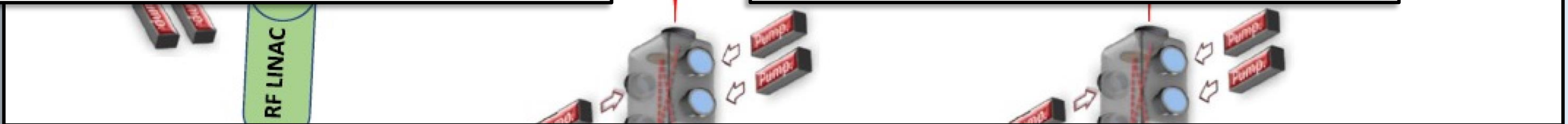

Conclusions

- We studied & proven a very low energy ERL injector/merger new layout
  - Energy quasi two times lower than C-beta & bERLinPro
  - A very good emittance considering the 250 keV gun
- RotnSlice tool for ASTRA+GIOTTO dispersive paths design
- Ultra short ultra narrow bunches production (still ongoing)

Thanks for your attention!