INFN MILANO
Istituto Nazionale di Fisica Nucleare

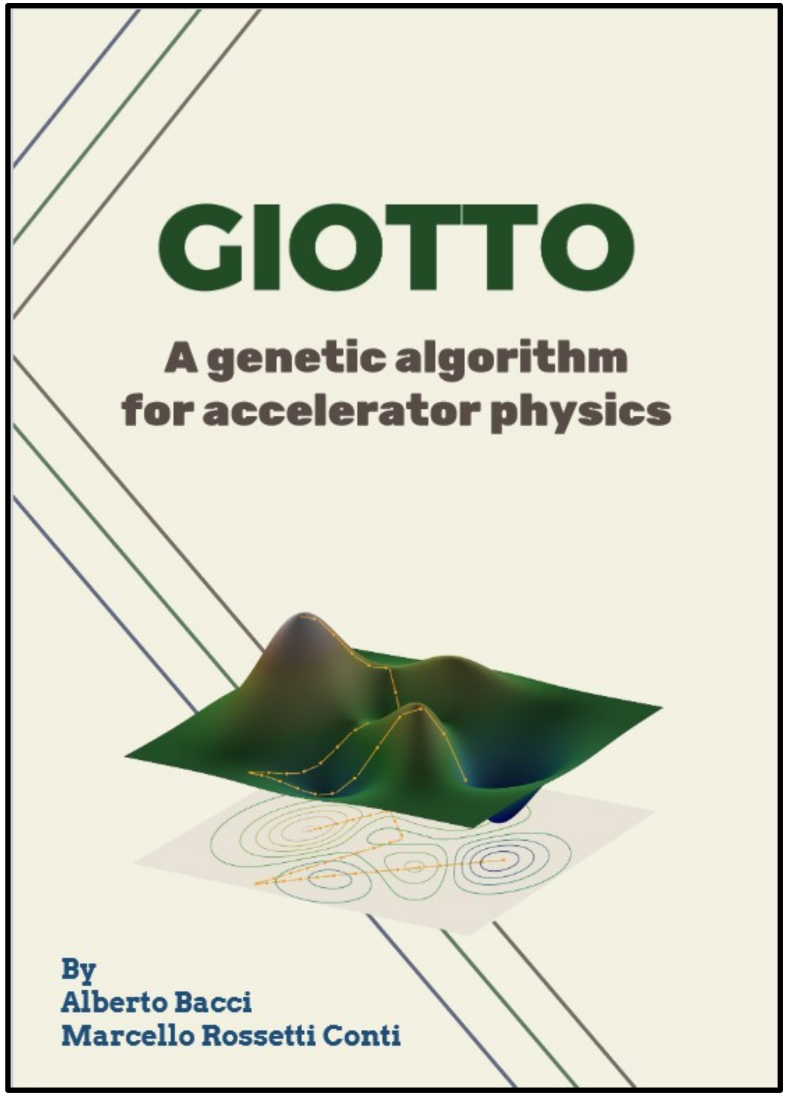
Enhancing Beamline Design with GIOTTO-suite: AI Optimization in Space Charge Dominated Environments

M. Rossetti Conti
On bealf of the Beam Dynamics group, Milano

Ultrafast Beams and Applications, *19 June 2024, CANDLE, Armenia*

AI optimizer

Genetic Interface for OpTimizing Tracking with Optics



One of first AI codes for **beam line design & optimization**.

Solves complex multi-objective problems (correlated parameters, space-charge like) & statistical analysis (machine jitters studies).

Drives the beam dynamics PIC code **ASTRA**. Natively compatible with **NameList** std.

V. 13.0 for **Linux** & **Windows**, parallelized with **MPI**.

Successfully used in important projects, as:

Some contributions to publications:

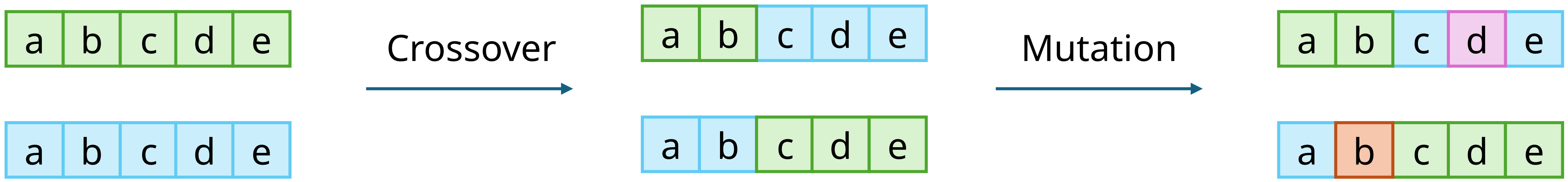
- *New approach to space charge dominated beamline design* – PRAB **26** (2023)
- *Two-pass two-way acceleration in a superconducting CW linac to drive low jitter x-ray FEL*–PRAB **22** (2019)
- *Electron beam transfer line design for a plasma driven Free Electron Laser* – NIM A **909** (2019)
- *Electron Linac design to drive bright Compton back-scattering gamma-ray sources* – JAP **133** (2013)

Coming soon:

- *Innovative solutions for high-brightness low-energy ERL injector design: the BriXSinO approach*

Genetic algorithms

- Invented by John Holland in the ‘60s
- Optimization and search technique inspired by the principles of natural selection and biological evolution



Advantages of Using Genetic Algorithms for **beam dynamics**:

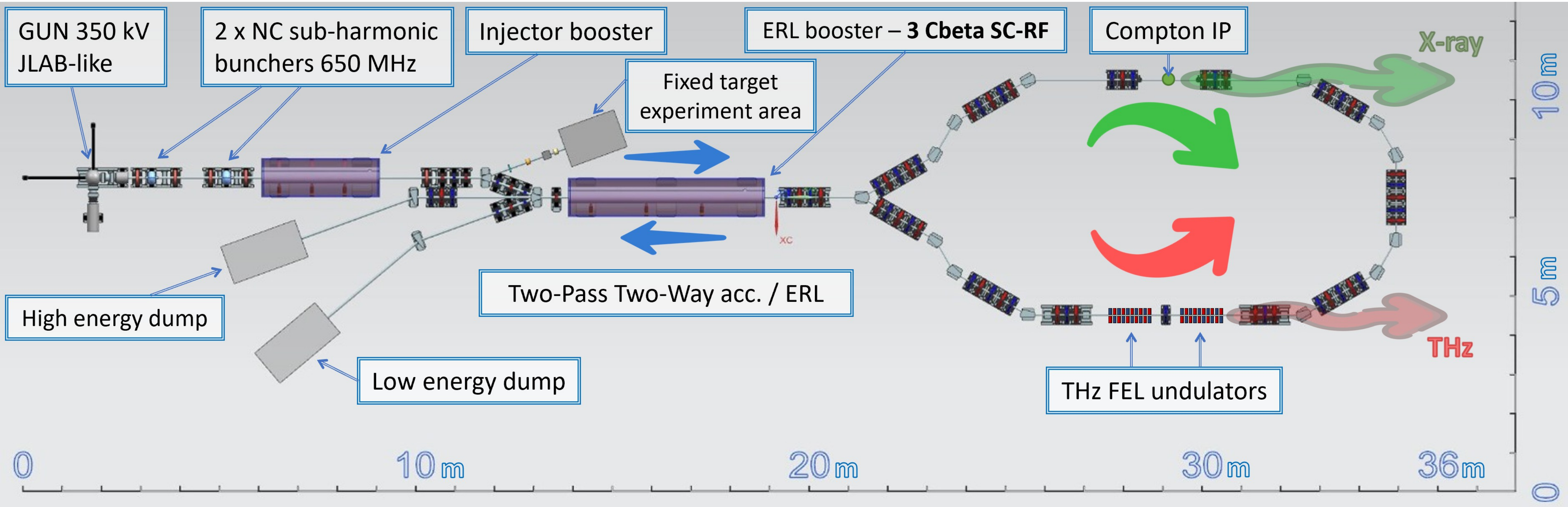
Flexibility:
GAs can handle complex and nonlinear solution spaces, typical of beam dynamics.

Parallelism:
The parallel nature of GAs makes them suitable for exploiting parallel computing architectures, speeding up the optimization process.

Adaptability:
GAs can dynamically adapt to changes in the accelerator’s operating conditions.

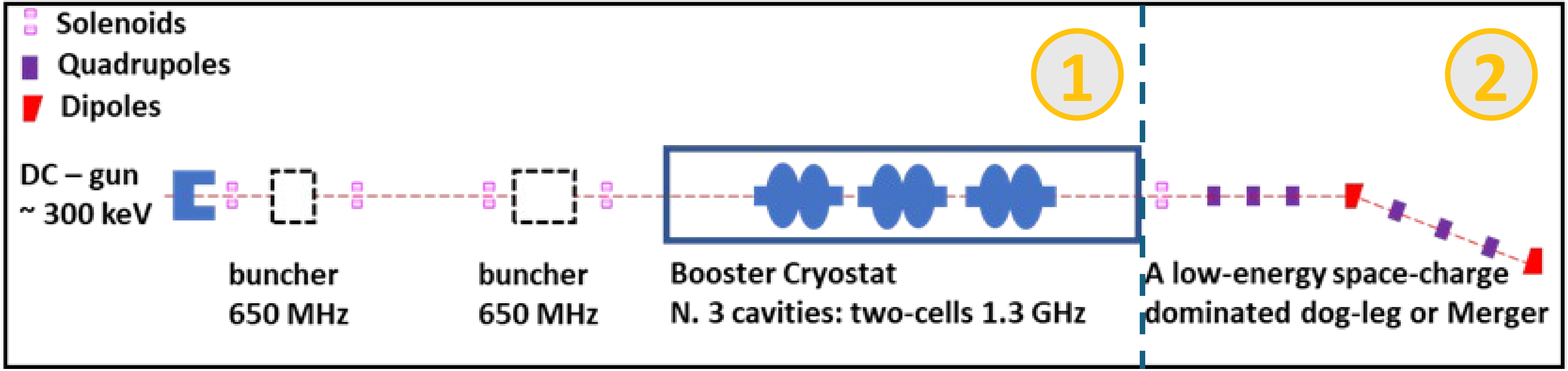
BriXSinO design

When the revolution began



- High flux dual light source (100 MHz rep. rate) based on a Energy Recovery Linac.
- Up to 5 mA average current - 50 pC bunches.
- Test machine for Two-Pass Two-Way acceleration.

The injector



Injector design criteria:

- ERL wasted **beam energy** is equal to the injection energy: the **lower**, the **better**.
- **High brightness** (low emittance and bunch length) required by FEL
- **Low energy spread** to reduce chromatism along the machine.

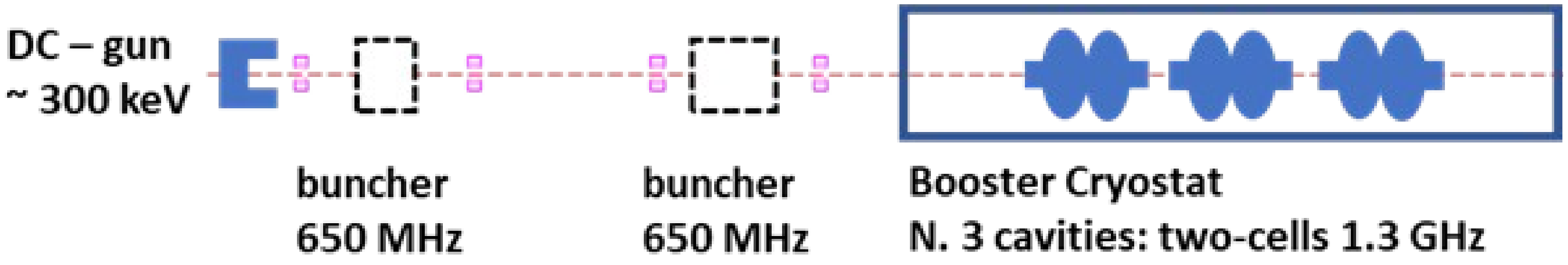
Simulations and optimizations performed with:

ASTRA + GIOTTO

Conservative choices in design phase:

- 100 pC of bunch charge
- 250 kV in DC gun

Injector opt. 1 - challenges



Injector design criteria:
- Low beam energy
- High brightness
- Low energy spread

Several BD techniques are used:
1. Cigar-like bunch shaping
2. Ballistic Bunching
3. Velocity Bunching
4. Emittance compensation

Some **parameters play against each other**. Low energy and bunch length increase emittance and energy spread.

We need to **balance** carefully the **optimization priority** of the parameters!

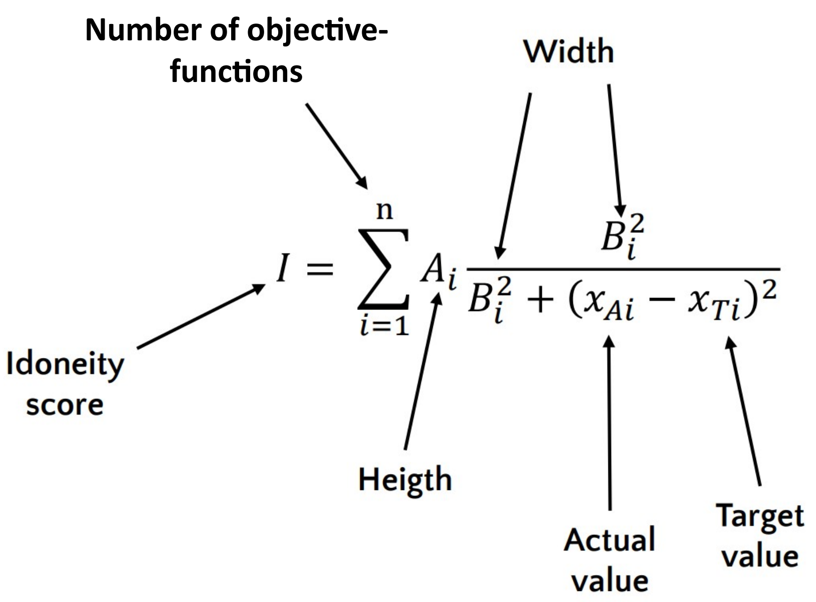
Injector opt. 1 - tactics

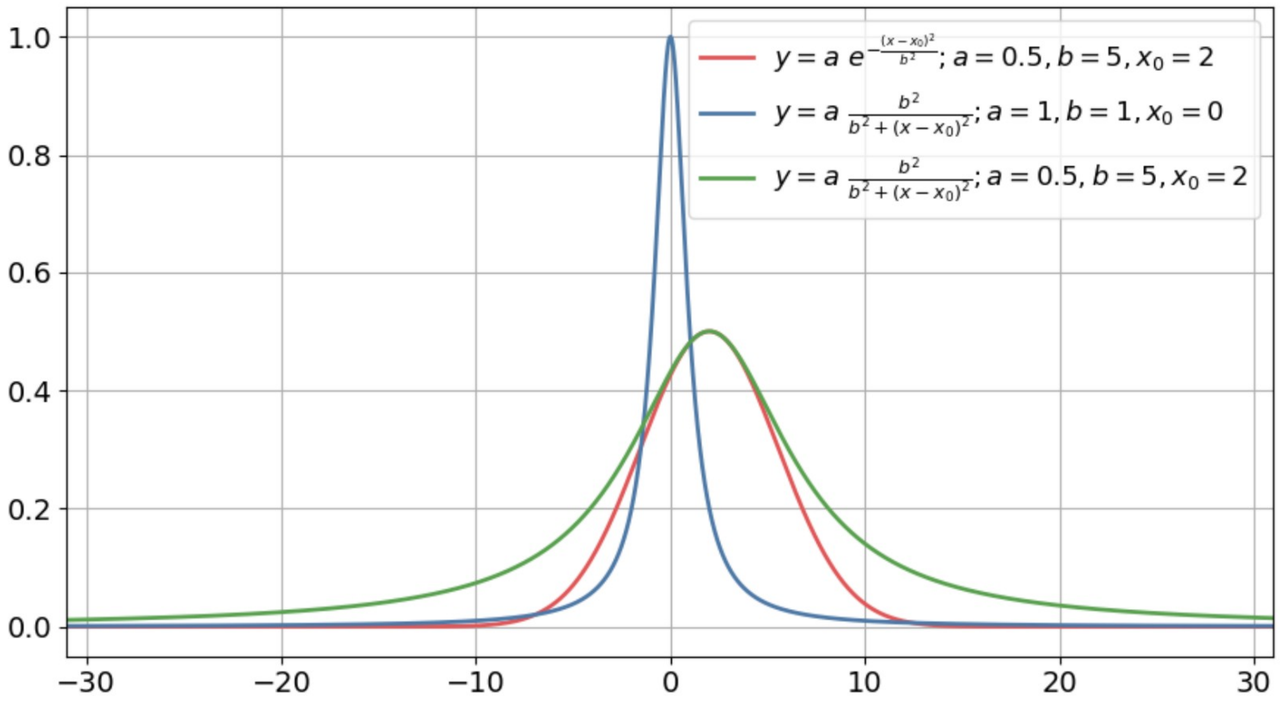
Fitness Function Shaping

Organized way to cope with the objectives, each objective in managed by a **modified Lorentzian function**.
Heigth and **width** change the function slope which is strictly related to optimization **priority**.

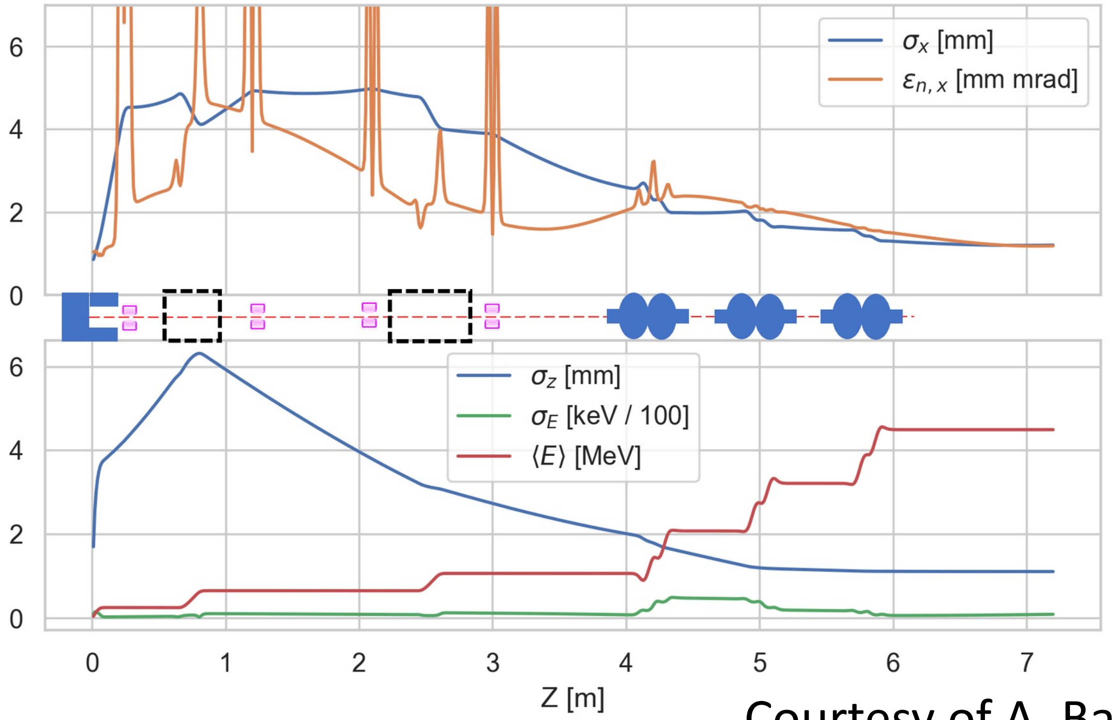
Generic F.F. for n objectives (x_i)

$$I = \sum_{i=1}^{n} A_i \frac{B_i^2}{B_i^2 + (x_{Ai} - x_{Ti})^2}$$





Injector opt. 1 - results



Courtesy of A. Bacci

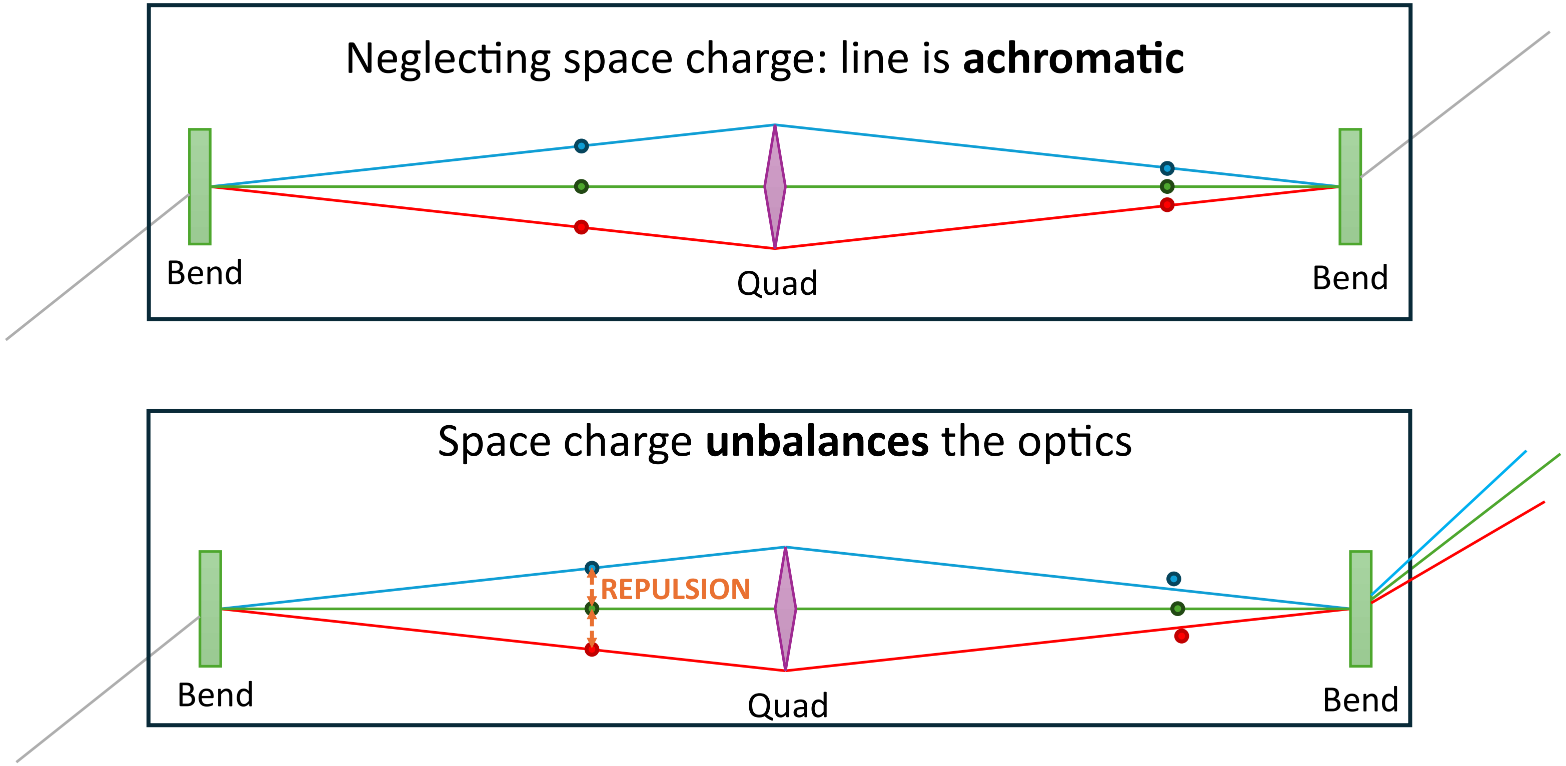
First section parameters

Parameter	Value
$\varepsilon_{n,x,y}$	1.2 mm-mrad
$\sigma_{x,y}$	1.2 mm
σ_z	1.1 mm
E_0	4.5 MeV
σ_E	8.9 keV

- The beam energy is successfully kept at 4.5 MeV
- The bunch leaves the booster in emittance minimum with reduced transverse dimensions
- Energy spread is compensated playing with the booster injection phases
- The bunch gets gradually compressed exploiting the SC dumping with beam energy increase

Injector opt. 2 - challenges

A low-energy space-charge dominated dog-leg or Merger



Internal forces give raise to **chromatism** and **dispersion leak** after the dogleg.

The effect can be compensated if **dispersion can be evaluated**

Injector opt. 2 - tactics

We needed a simulation **diagnostic tool** to study and act on the dynamics in the **dispersive path:**

RotnSlice, a GIOTTO post-processor

1. RotnSlice calculates the rotation angle as:

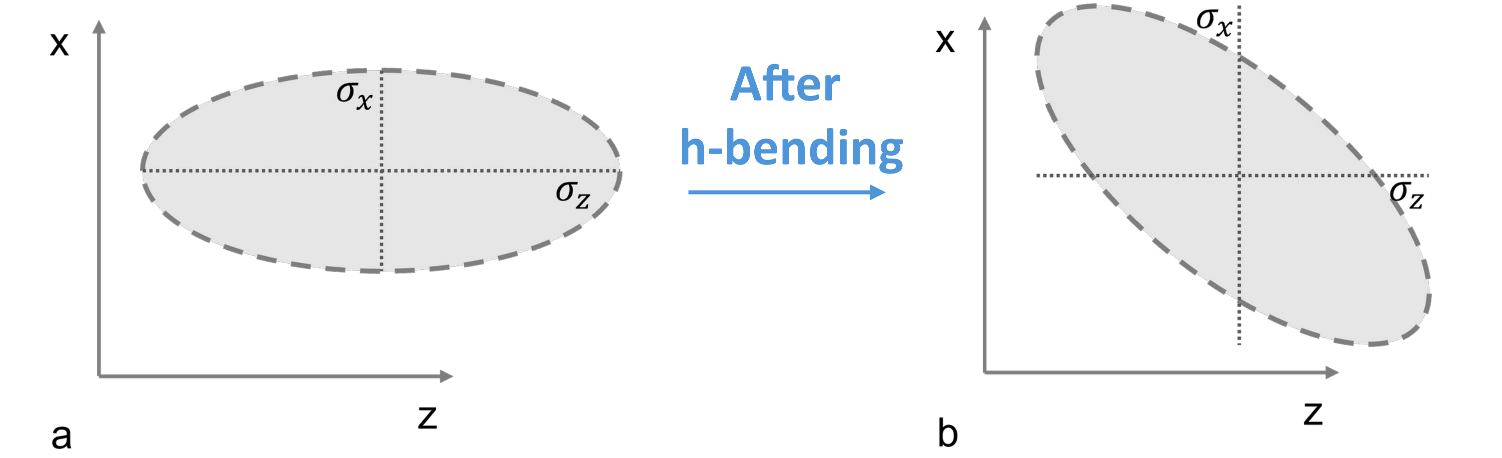
$$\theta_x = \arctan\left(\frac{\langle p_x \rangle}{\langle p_z \rangle}\right)$$

2. Applies a **rotation** matrix with (Position centroids have to be removed before and added back after the rotation!):

$$R_y \equiv \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} = \begin{bmatrix} \cos\theta_x & 0 & \sin\theta_x \\ 0 & 1 & 0 \\ -\sin\theta_x & 0 & \cos\theta_x \end{bmatrix}$$

3. Now, local beam parameters and additional analysis can be performed.

The **bunch** gets **rotated** in bendings and bunch parameters get altered in the XYZ system!



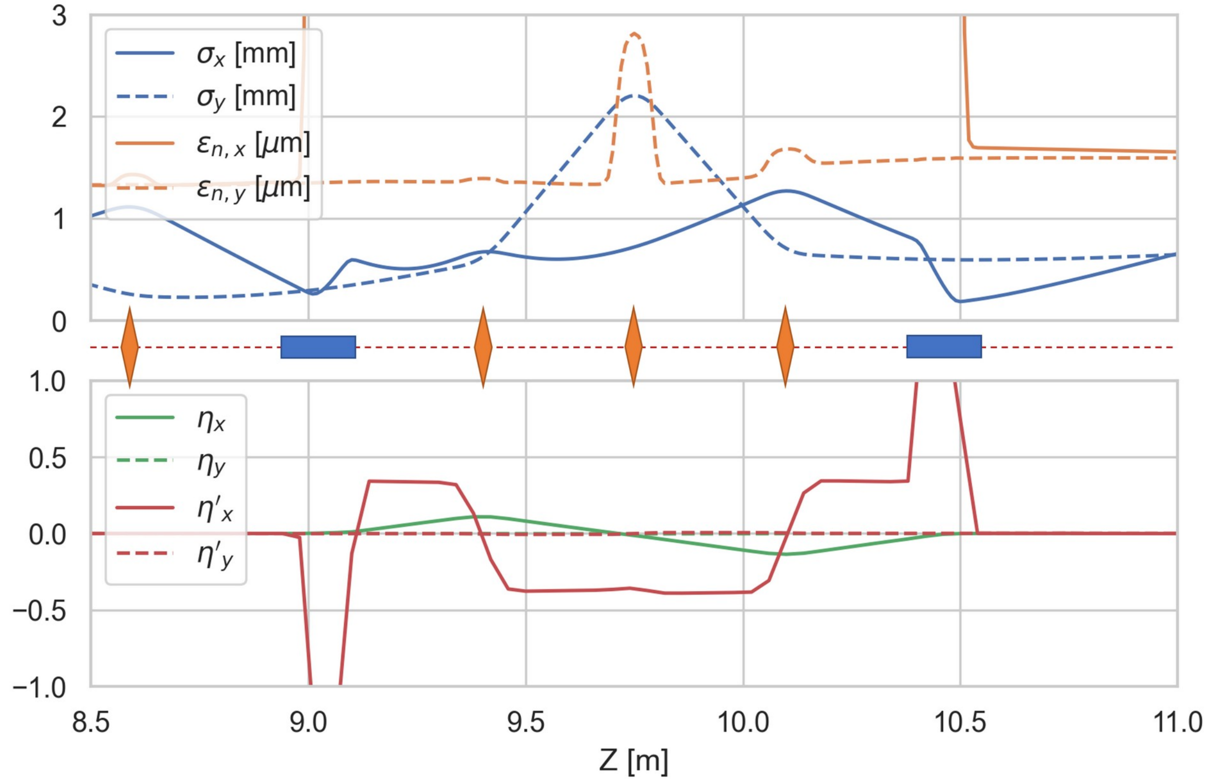
E. g. The distribution **dispersion** is calculated through the **η** parameters:

$$\eta_x = \frac{\langle x\, p_r \rangle}{\sigma^2_{p_r}}, \qquad \eta'_x = \frac{\langle x'\, p_r \rangle}{\sigma^2_{p_r}} \qquad with: p_r = \frac{p - \langle p \rangle}{\langle p \rangle}$$

New capabilities for GIOTTO optimization!

- **Dispersion** parameters
- **Oblique paths** support
- **Multi-position** opt.

Injector opt. 2 - results



Courtesy of A. Bacci

New approach to space charge dominated beamline design – PRAB **26** (2023)

Injector beam parameters

Parameter	Value
$\varepsilon_{n,x}$, $\varepsilon_{n,y}$	1.65, 1.6 mm-mrad
σ_x, σ_y	0.65, 0.65 mm
σ_z	2.0 mm
E_0	4.5 MeV
σ_E	26.0 keV

- The **dispersion** was **closed** in several points after the last bending to ensure a stable result. (**Multi-position optimization**)
- The peculiar asymmetry in the envelope transport is due to the SC compensation.
- The BriXSinO solution, operating under intense space charge conditions (4.5 MeV, 100 pC), stands out as the injector with the lowest energy among modern ERL-based light sources.

More on GIOTTO-suite

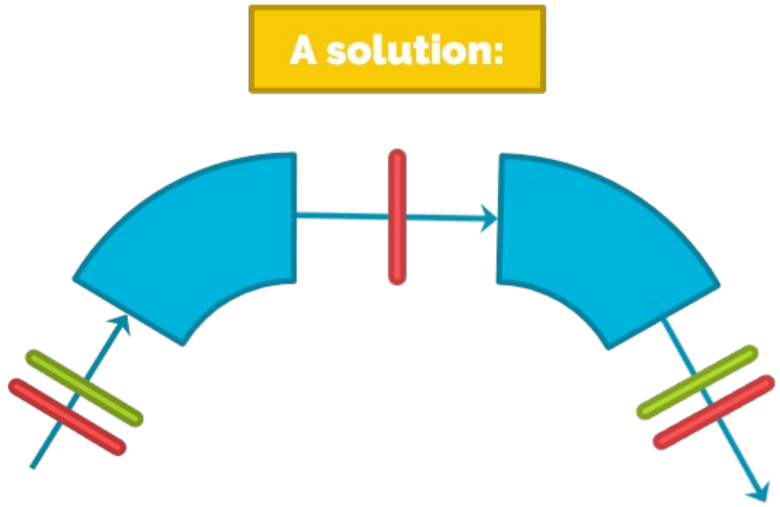
Other successful
applications

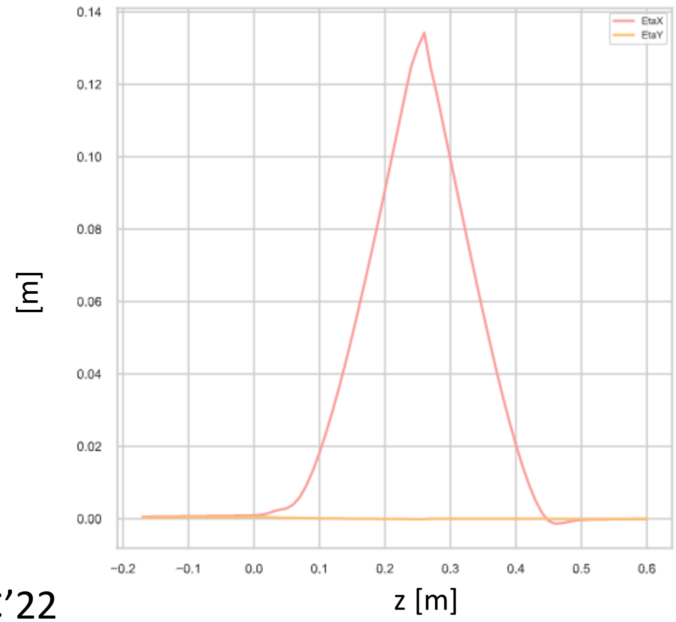
Energy filter optimization

In 2021 **ACTIS** experiment @ Solaris Synchrotron required to build the machine model of Solaris linac.

Big issue: model the **120°** DBA composing the **energy filter** (70 pC, 3 MeV)

- **RotnSlice** was applied to **rotate** the incoming **distribution** and to **optimize** on the **rotated** outcoming **bunch** ($\varepsilon_{nx\text{-}y}$, $\eta_{x\text{-}y}$, $\eta'_{x\text{-}y}$, σ_E, Q)



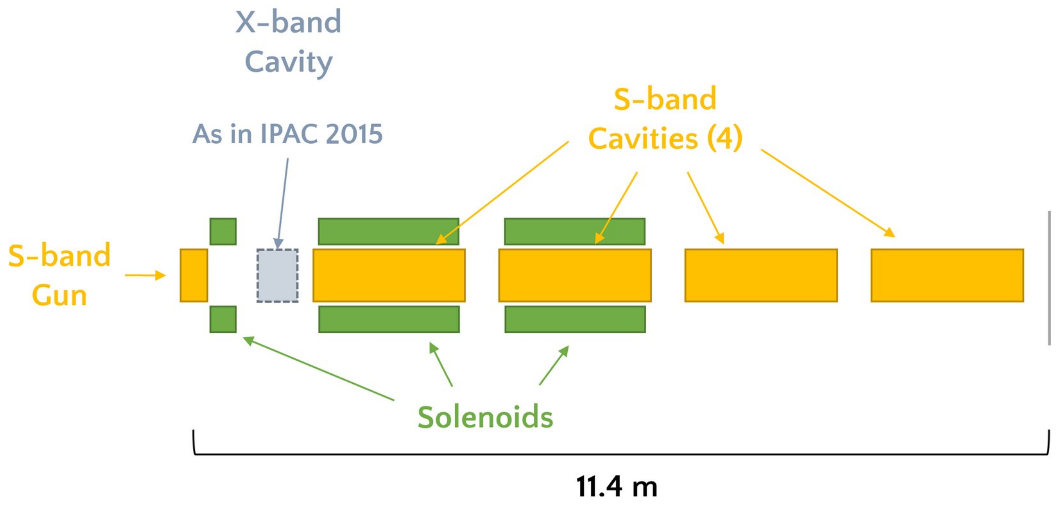


$\varepsilon_{n,x}$	2.31 mm mrad
$\varepsilon_{n,y}$	1.12 mm mrad
η_x	-1.38 10^{-4} m
η_y	-1.65 10^{-6} m
η'_x	3.35 10^{-5} rad
η'_y	8.27 10^{-6} rad
Q	33 pC
σ_E	33 keV

Arc Compressor Test in a Synchrotron - the ACTIS Project – in proc. IPAC’22

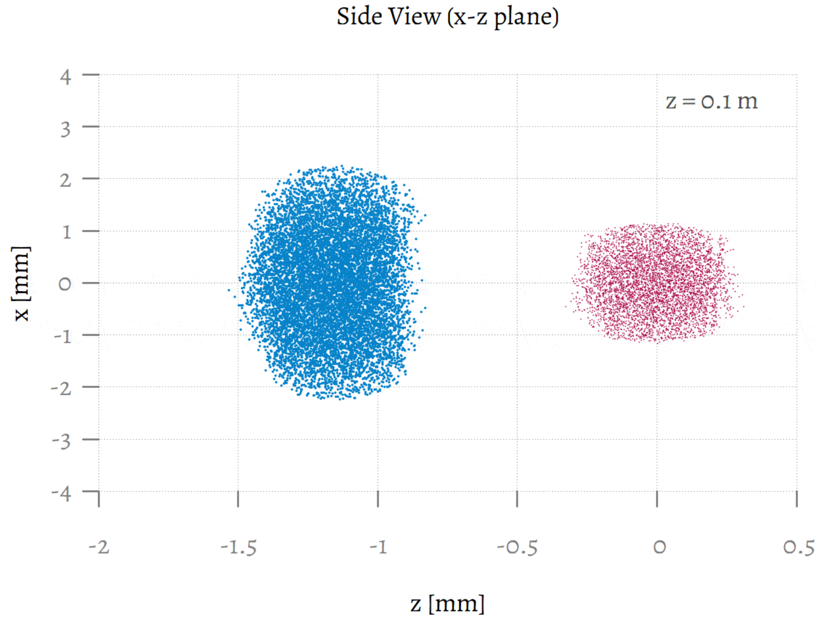
Combed beams support

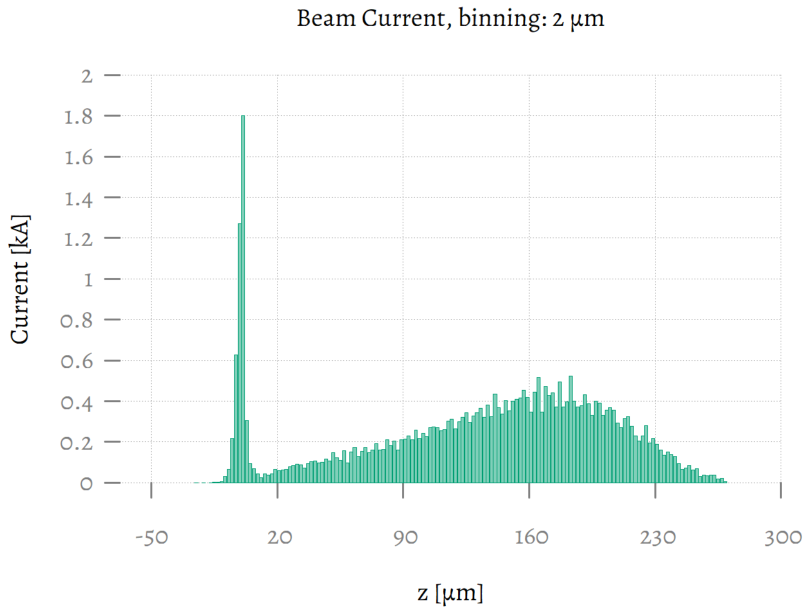
In 2022 we applied GIOTTO to the **EuPRAXIA@SPARC_LAB** injector (combed beam for PWFA).



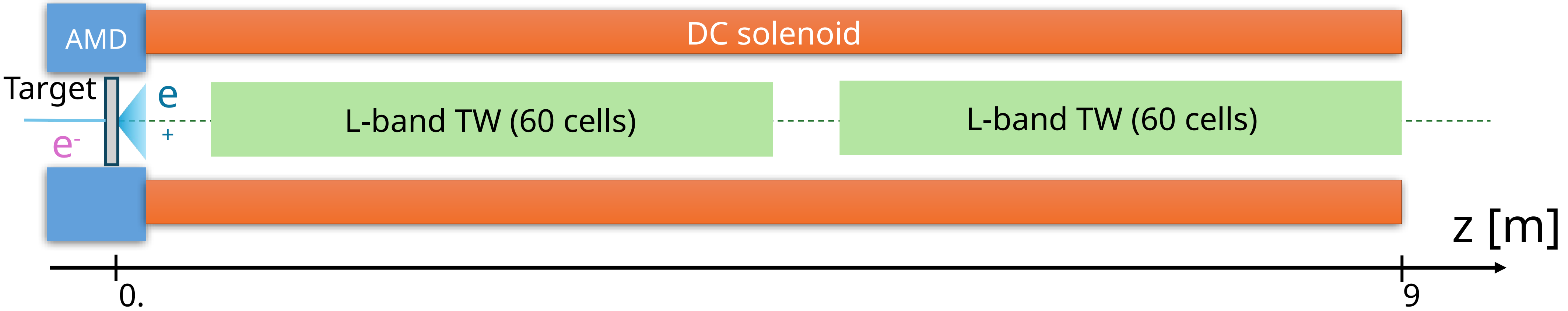
Driver and **witness** must have **very different parameters**, optimization must be tailored on each bunch.
RotnSlice modified to work on multi-bunch beams.

Driver 200 pC			Witness 30 pC				Full Beam	
σ_x	σ_z	$\varepsilon_{n,x\text{-}y}$	σ_x	<I>	σ_z	$\varepsilon_{n,x\text{-}y}$	<E>	Δ_z
µm	µm	mm mrad	µm	kA	µm	mm mrad	MeV	µm
218	55	1.54	522	1.00	2.6	0.43	102	150





FCC-ee positron capture system



Genetic knobs: Variation range:

	Variation range
AMD: Length	2-6 cm
AMD: peak field	5-18 T
AMD low field (DC solenoid)	0.3 - 1.2 T
Cavity 1: inj. phase	± 180°
Cavity 2: inj. phase	± 180°
Cavity 1: acc. gradient (peak)	± 20-40 MV/m
Cavity 2: acc. gradient (peak)	± 20-40 MV/m

Evolutionary **objectives** in 1st bucket:

1. Maximize Yield
2. Contain $\varepsilon_{n,x}$
3. Contain σ_x
4. Contain σ_z
5. Contain σ_E
6. Keep E ↑

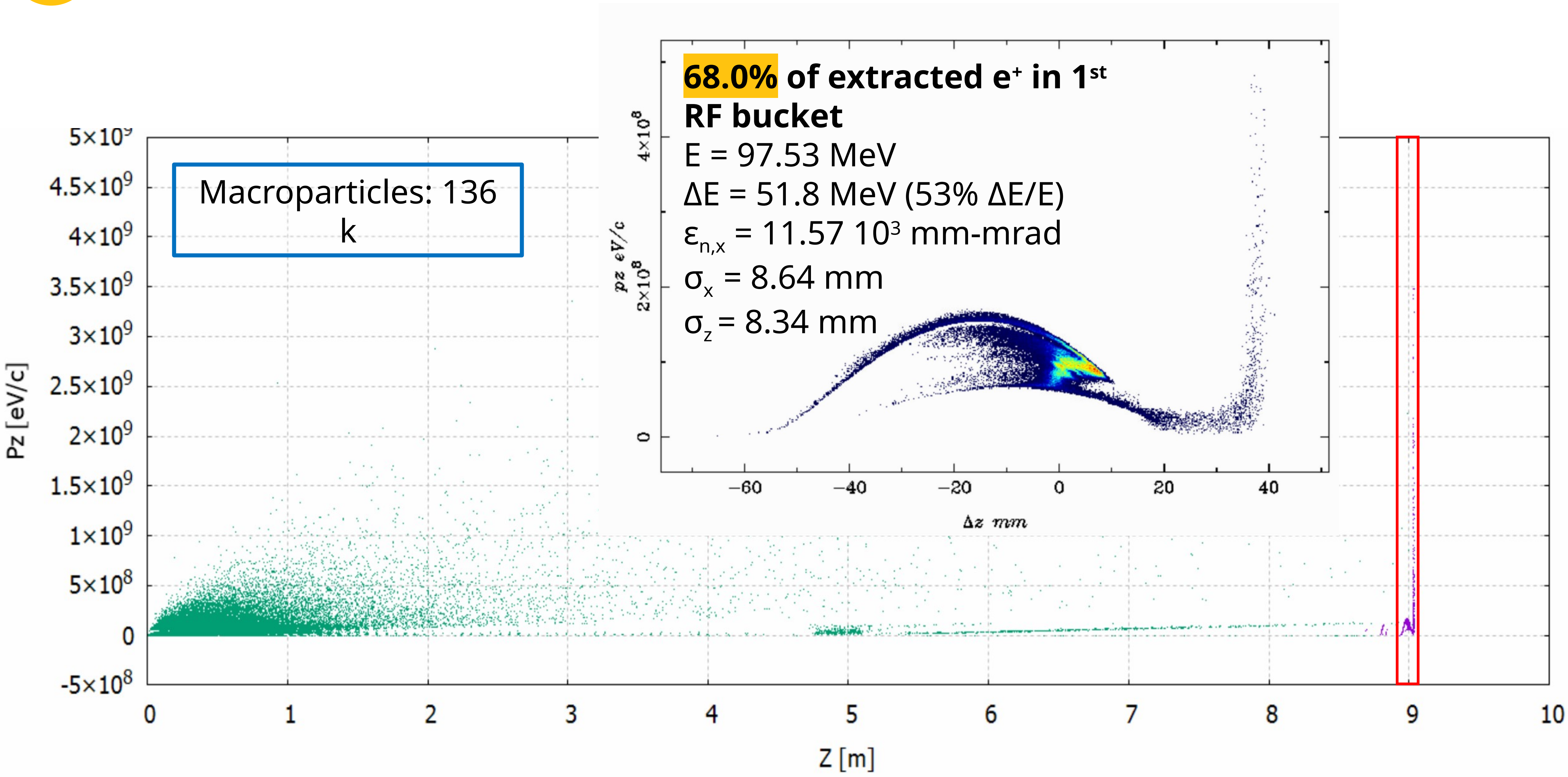
Wide range search:

Macroparticles: 5 k

Refinment:

Macroparticles: 136

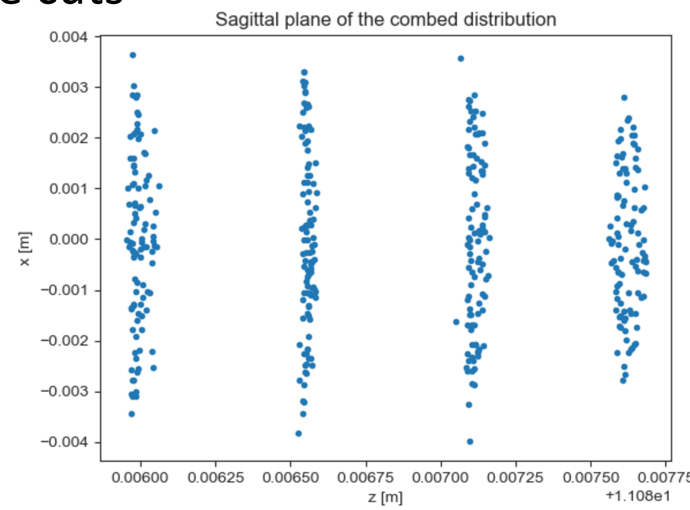
Phase space window optimization



RotnSlice standalone

RotnSlice is designed to be useful also by itself if paired with ASTRA.

- Can **process ASTRA beam files** to calculate ad hoc parameters (**etas**, twiss)
- Can apply cuts to **separate combed beams** and **analyze them**
- Accepts file-lists to display **parameters evolution in curved paths**
- **Rotates bunches** for oblique propagations
- Performs phase space cuts




```
&OUTPARAM
 R_NP= 2*100        ,101        ,100        ,
 R_ENS=  94.710825416337840     ,  89.108381276222090     ,  112.66158024423635     ,  156.03665351558018     ,
 R_XMAX=  3.6455998772269478     ,  3.2946997777028275     ,  3.5674987589860558     ,  2.7929996762875096     ,
 R_YMAX=  3.8422971600416478     ,  3.4850005455973347     ,  5.2303004675223717     ,  2.8714001011217296     ,
 R_SIGX=  1.6619587923008439     ,  1.7900134591181069     ,  1.7408022405917185     ,  1.3674820331654416     ,
 R_SIGY=  1.6866778802983526     ,  1.8155199965606068     ,  1.7796688561516543     ,  1.4094633355859365     ,
 R_SIGZ=  2.4837896571619257E-002,  1.3157077083178504E-002,  2.1146060114984749E-002,  3.2299782328417868E-002,
 R_SIGPX=  49016052.362747438     ,  49242479.777416885     ,  47092656.841494001     ,  40384941.556920826     ,
 R_SIGPY=  49526763.269271635     ,  49977613.685153089     ,  47874563.988275878     ,  41736330.588918723     ,
 R_SIGPZ=  94711573.078544125     ,  89114310.556229532     ,  112662222.74988954     ,  156038990.31462625     ,
 R_EMITX=  5.9104016884486317     ,  6.4854684338515396     ,  4.6219035700937194     ,  3.3268706504326966     ,
 R_EMITY=  5.1368517525174253     ,  6.5421545555008809     ,  7.1483458769176398     ,  3.7935298859550142     ,
 R_CURR=  348.42483116200083     ,  664.33293220794133     ,  417.43997777805248     ,  275.96969534594660     ,
 R_ETAX= -4.9467118780132997E-002, -6.4093970678234316E-002, -1.4986536736104060E-002, -3.1962146272291650E-003,
 R_ETAPX= -1.5457105812672178E-002, -1.9436743272943705E-002, -4.2497765806920806E-003, -1.4417822724774360E-003,
 R_ETAY= -7.3408179106451046E-002,  1.1153565054827274E-002,  4.5841782956976621E-002, -1.0017534459814181E-002,
 R_ETAPY= -2.3640599905633719E-002,  5.5397207146919087E-003,  1.6711263110465838E-002, -1.7770136114910343E-003,
 R_ALPHAX_TWISS= -26.953982193526951    , -26.578331718481028    , -34.696165282282848    , -32.469779422520034    ,
 R_ALPHAY_TWISS= -31.808309083051860    , -27.123193193130678    , -23.303384930668866    , -30.329736888034375    ,
 R_BETAX_TWISS=  87.689645744568907     ,  92.067548844918051    ,  121.48718610081727    ,  104.23144291080958    ,
 R_BETAY_TWISS=  103.91831046187302     ,  93.889410292908877    ,  82.096628517315381    ,  97.108101552973096    ,
 R_GAMMAX_TWISS=  8.65175500335251E-008,  8.07173637606661E-008,  1.04728786020251E-007,  1.06850632445645E-007,
 R_GAMMAY_TWISS=  1.01643413940295E-007,  8.24202950566205E-008,  6.99855441125758E-008,  1.00078007815156E-007,
 R_GAMMA=  187.64239952532787     ,  186.35523218775737     ,  185.29291089602569     ,  185.43756780970446     ,
 R_X_MED= -3.4881124000000006E-005, -7.4914429999999998E-005, -1.1427756237623765E-004, -9.6065175000000069E-005,
 R_Y_MED=  1.6694518700000012E-004,  1.3878091100000007E-004,  6.6823394059405922E-005,  8.1764610000000122E-005,
 R_Z_MED=  11.085994750795201     ,  11.086556117499995     ,  11.087114025742572     ,  11.087622173000002     ,
 R_PX_MED=  4.8097503167809920E-007,  8.1400561612099410E-007,  6.6916585962131324E-008,  3.2126708902069370E-007,
 R_PY_MED=  7.2759576141834261E-014,  5.8207660913467408E-013, -3.2417632934480609E-013,  7.2759576141834261E-014,
 R_EN=  95.374060850803076     ,  94.716319757188614     ,  94.173474745667136     ,  94.247394269434395     ,
 /
```

Conclusion

GIOTTO and **RotnSlice** are being strongly improved for the last 4 years thanks to new challenges we had to deal with. **Several new capabilities** added:

- **Re-organized fitness function** definition
- **Multi-position** optimizations
- **Dispersion** parameters support
- Optimization of **rotated bunches** and diagnostics of **oblique paths**
- **Multi-bunch** tailoring
- **In-window** optimization of the phase space

RotnSlice has become a useful **standalone tool** for ASTRA users.

What next?

A new branch of applications is going to be explored: **GIOTTO is moving to control systems** (starting from **STAR** in Calabria)

Thanks!

Any questions ?

GIOTTO-suite is available for everyone.

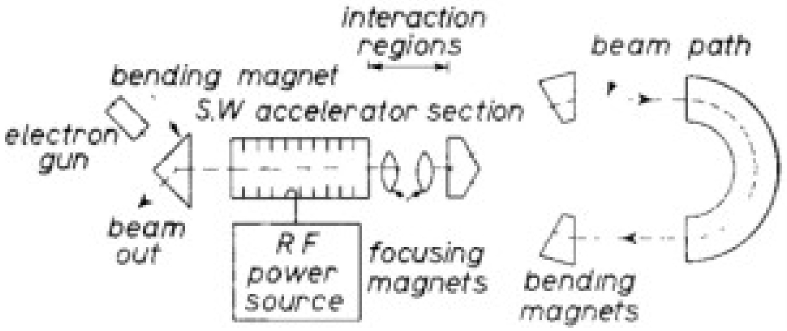
Contact us:
marcello.rossetti@mi.infn.it
alberto.bacci@mi.infn.it

Credits

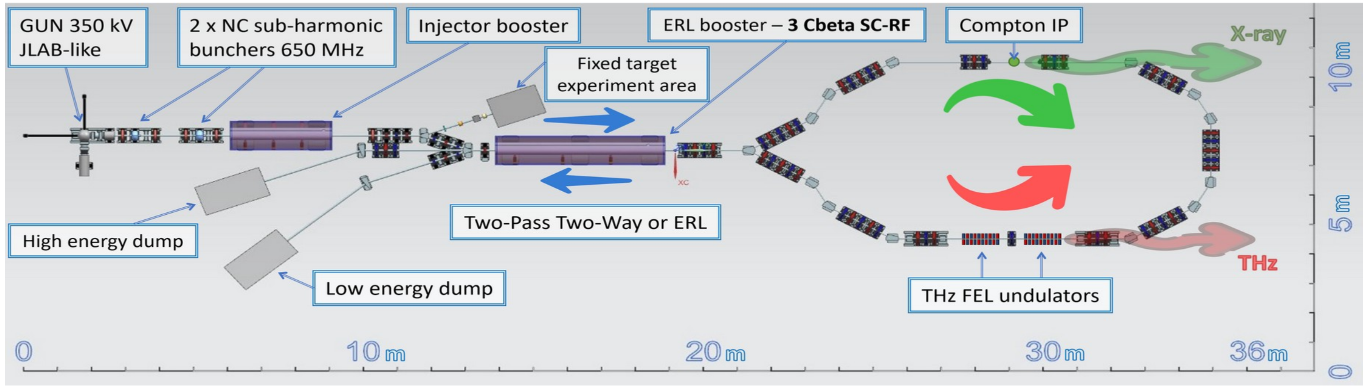
Special thanks to all the people who made and released these resources for free:

- Presentation template inspired by SlidesCarnival
- Icons from Flaticon

BriXSinO Principle of Operati



- A "**newly**" conceived scheme of ERL with **counter propagating beams** is proposed in BriXSinO.
- This **scheme allows** to explore not only the **ERL operation** but also the **two-pass operation** where the beam is reaccelerated when reinjected in the accelerating module at reduced current.

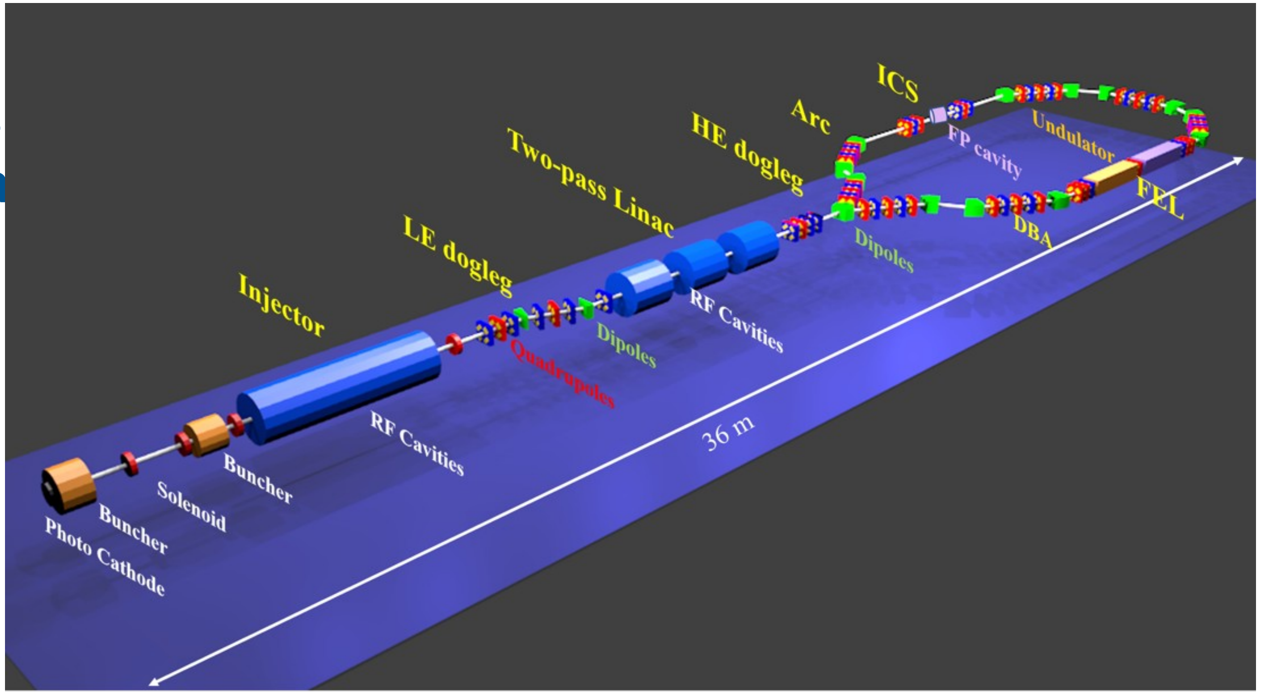


- A further operation mode for BriXSinO is the use of its **injector for fixed target experiments** performed with maximum electron energy of 10 MeV and 5 mA average current. This high intensity beam enables both **experiments of flash therapy** (total charge in a 200 ms time interval up to 1 mC), as well as converting the electron beam into **bremsstrahlung photons with energy peaked at 7 - 8 MeV at an impressive flux of 10^{16} photons/s** (i.e. up to 30 kW X-Ray beam).
- Also experiments of **positronium generation** for fundamental studies of matter-antimatter asymmetry can be conducted at this test station.

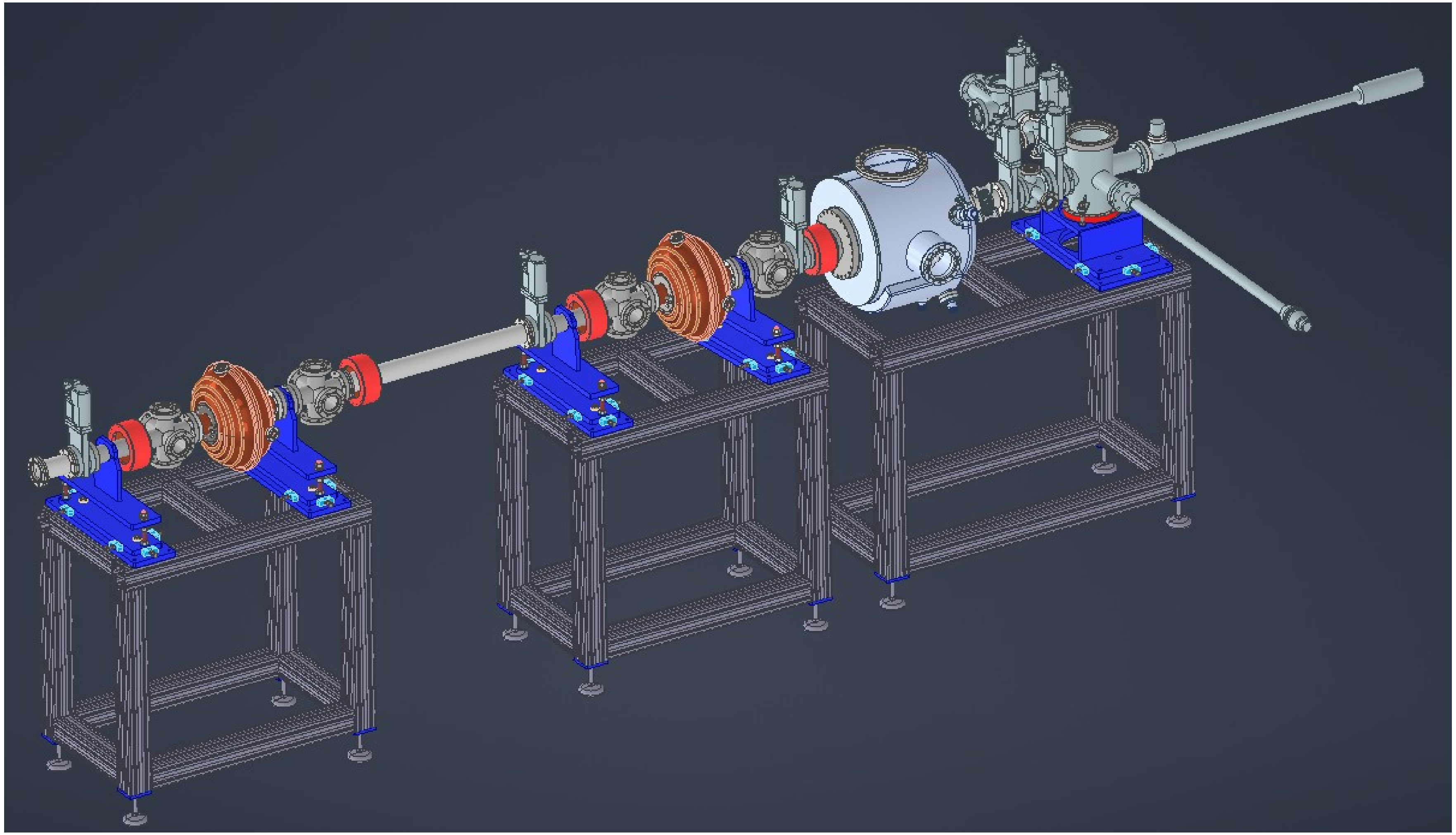
Parameter	two-pass acc.	ERL
Energy (MeV)	80	45
Bunch charge (pC)	100	100
Repetition rate (GHz for CW operation)	$0.9286\ 10^{-3}$	0.9286
Average Current (mA)	$5\ 10^{-3}$	5
Beam power @ dump (W)	$22.5\ 10^{3}$	400
$\varepsilon^{n}_{x,y}$ (mm − mrad)	< 1.6	< 1.6
Energy spread (%)	< 0.2	< 0.2

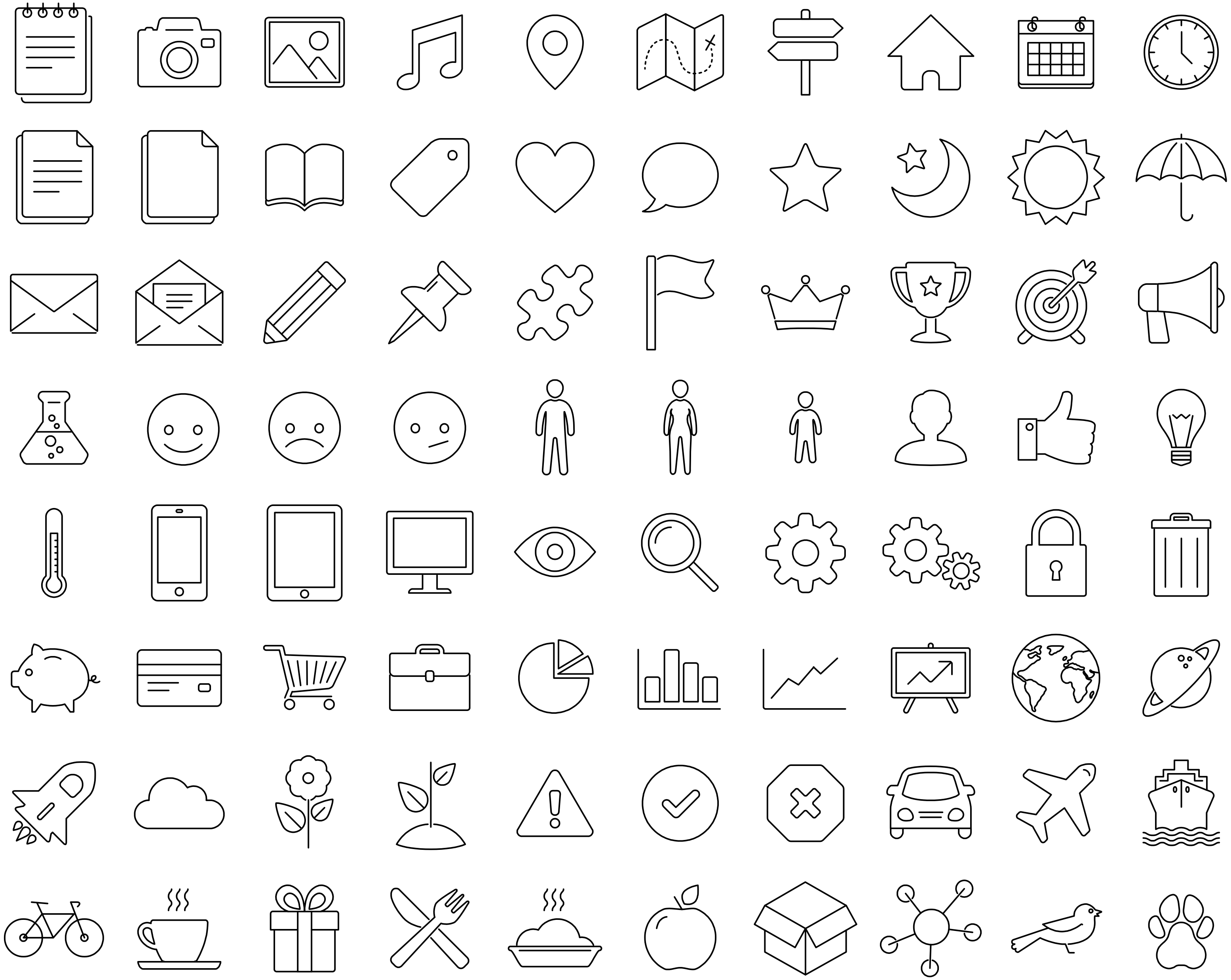
BriXSinO Principle of Operation

- In the ERL operation mode, two experiments are envisioned: **Inverted Compton Scattering (ICS)** and a **THz FEL**.
- **The importance of the full BriXSinO is then twofold.**
- From one hand, it will act as test facility for **fundamental questions of accelerator physics and strategies of Dynamics and Energetic** by hosting experiments for maximizing the energy sustainability and minimizing the AC power consumption.
- From the other hand, **it will work as user facility by providing large qua coherent THz and X-Rays emission** from its high brightness accelerated electron beam, enabling important and advanced applications.



HB^{2}TF Layout





SlidesCarnival icons are editable shapes.

This means that you can:

- Resize them without losing quality.
- Change line color, width and style.

Isn’t that nice? :)

Examples: