Application of a Vlasov Solver to investigate the longitudinal beam dynamics in electron linear accelerators

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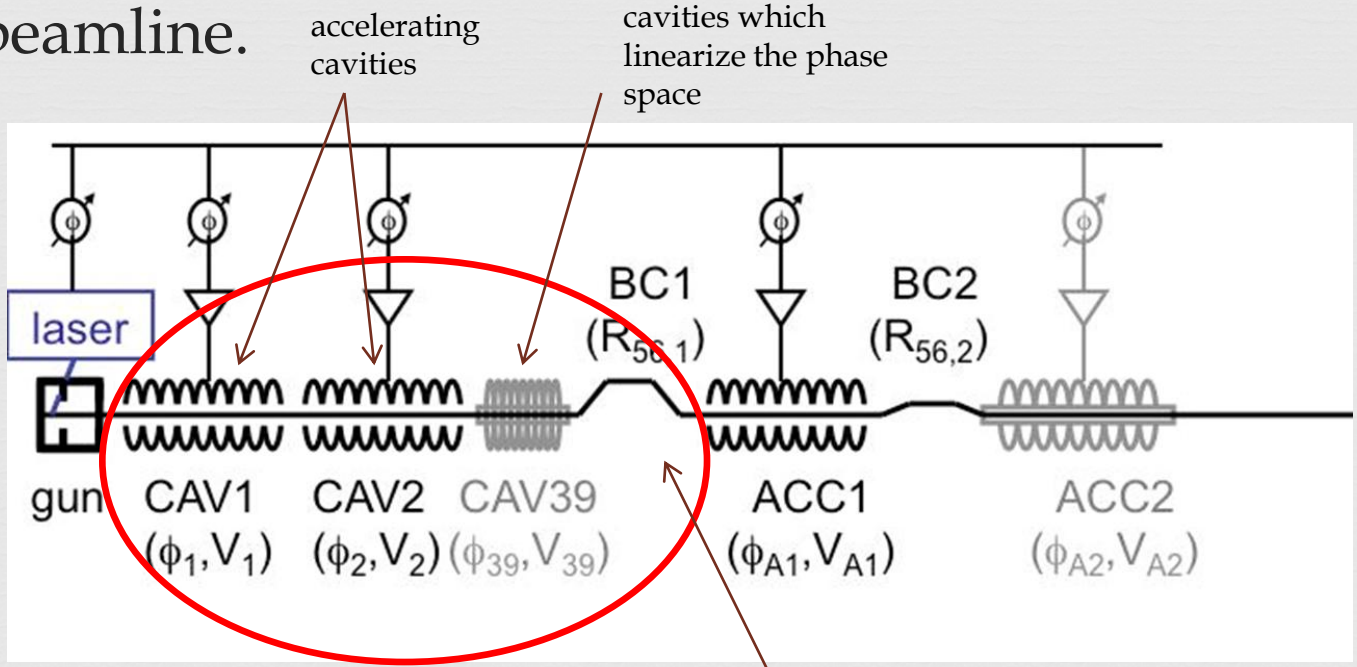
PARTI Summer Internship Program

General overview

- The project is dedicated to simulation of the ASTA (Advanced Superconducting Test Accelerator) beamline.

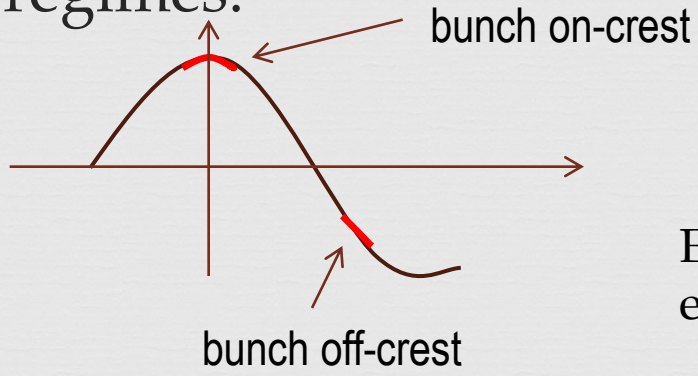


RF cavities

- RF cavities accelerate/deaccelerate charged particles in a bunch, in our case it's relativistic electrons, as after the gun the reference energy is about 4.5 MeV.
- There are two regimes:

on-crest

off-crest



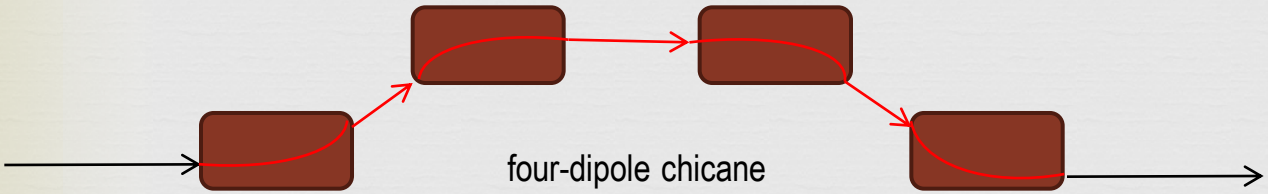
Each particle gains energy

$$\Delta W = e\,U\cos\varphi$$

As the size of the bunch is not negligible, in cavity different particles can gain a bit more or less energy.

Bunch compressor

- Consider a beamline to be a four-dipole chicane and inject electron bunch in the longitudinal phase space (z, δ_W) with variable chirp.

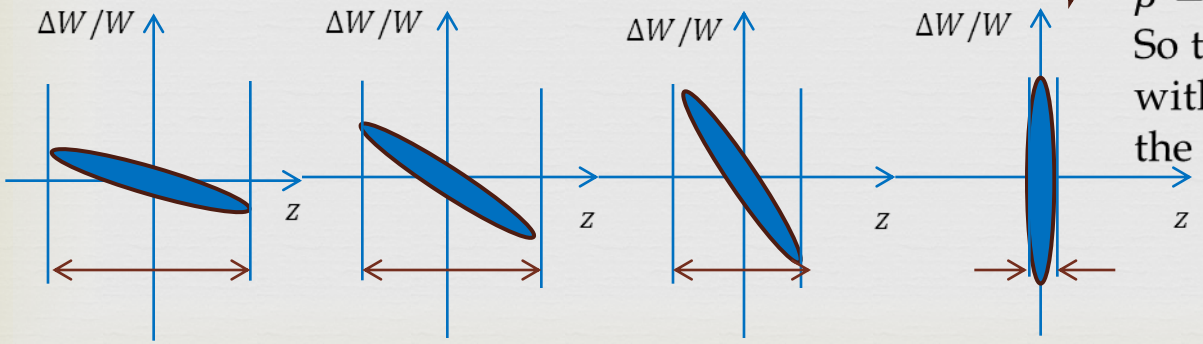


Chirp means differentiation of particles energy relatively to some reference particle

Higher energy patricles are bent less , while lower – more, so they travel a longer path.

$\beta = 1$ *with good precision*

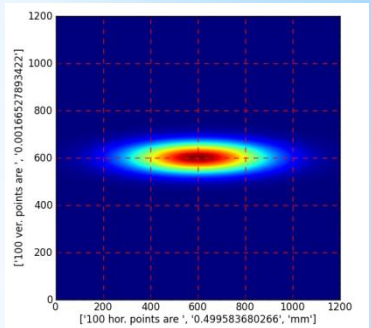
So the tail of the bunch can catch up with the head, and that compresses the bunch.

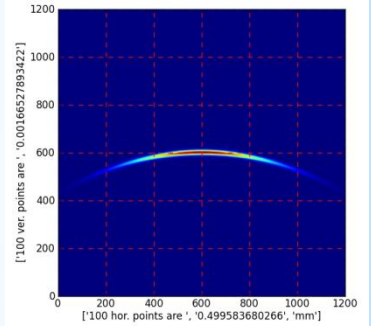


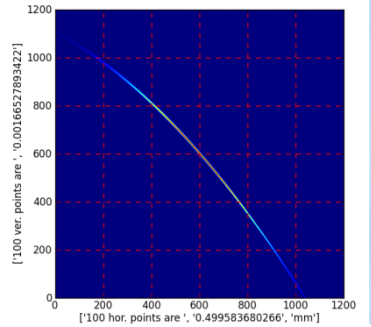
Specifications

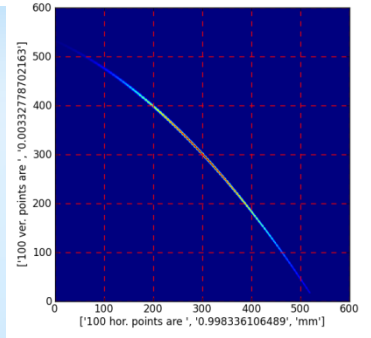
- Initial distribution of a bunch in phase-space is bi-Gaussian, with $\sigma_z = 1\,mm$, $\sigma_{\delta_W} = 0.00074$ with the reference energy $W_0 = 4.5\,MeV$ at total charge $Q = -3.2\,nC$
- First cavity with $U_2 = 25\,MeV, \varphi_2 = 0$ is accelerating on-crest.
- Second cavity has a phase to maximize the compression, $\varphi_3 \approx 0.31$, $U_3 = 25\,MeV$
- Third cavity – CAV39 is a third-harmonic cavity and included to eliminate second-order terms appeared in previous cavities, $U_4 = \frac{k^2}{k^2{}_4}(U_1 + U_2 + U_3)$,

$$\varphi_4 = \pi + \mathrm{acos}\left(\frac{U_1+U_2+U_3\cos\varphi_3}{U_1+U_2+U_3}\right)$$





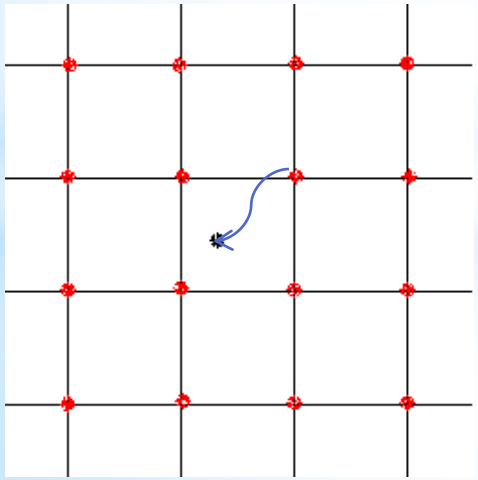




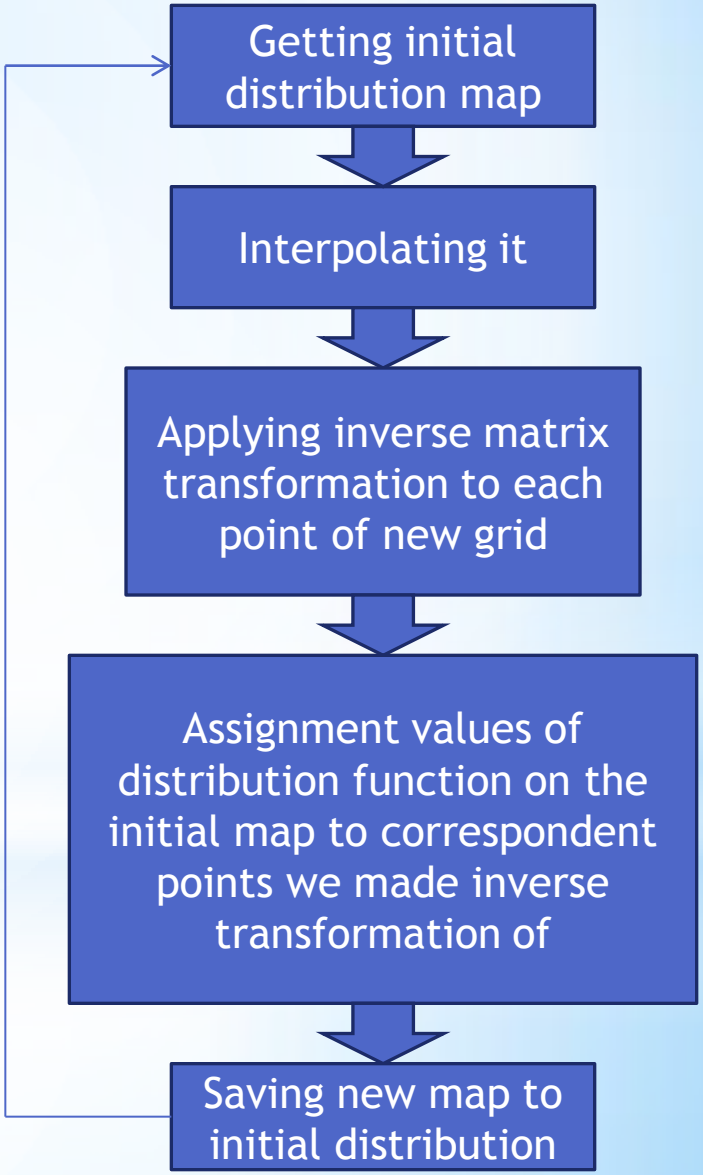
Method of simulation

For each element of the beamline we have to run this algorithm

* Instead of common method of macroparticle simulations I use Vlasov solver, developed by Francois Ostiguy. This method follows the beam distribution function in time and is not so vulnerable to statistical fluctuations when considering collective effects like space charge of CSR (coherent synchrotron radiation).



We calculate where red point (in phase space) was before the element of the beamline



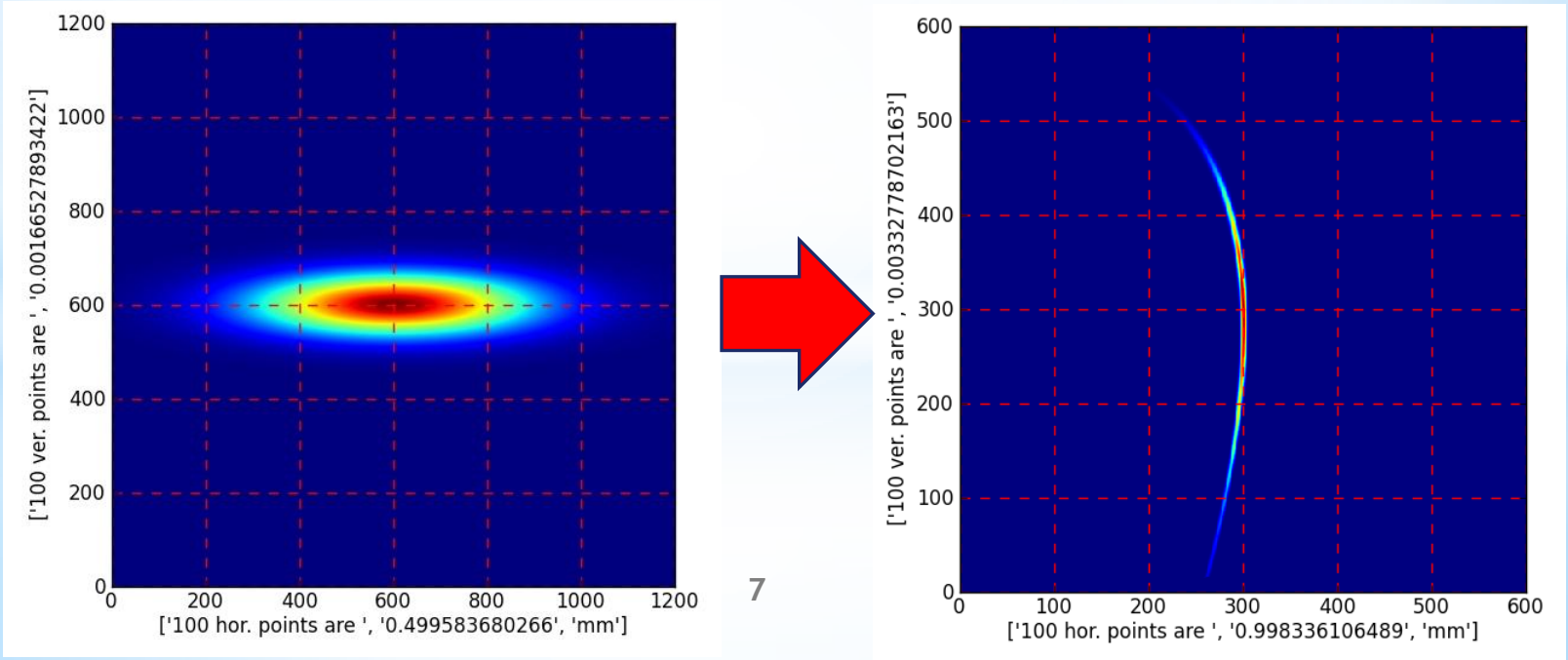
Inverse maps formulae for beamline elements

* For RF cavities and bunch compressor we use following formulae, up to 2nd order of δ:

* $z_i = z_f + L_B \left[\frac{\theta_0}{\sin\theta_0} - \frac{1}{\cos\theta_0}\right]\delta + \frac{1}{2} L_B \frac{sin^2\theta_0}{cos^3\theta_0}\delta^2$ for dipole

* $z_i = z_f - L_S \frac{sin^2\theta_0}{cos^3\theta_0}\delta + \frac{3}{2} L_S \frac{sin^2\theta_0}{cos^5\theta_0}\delta^2$ for drift

* $\delta_i = (\delta_f W_f - eU[\cos(\varphi + \Delta\varphi) - \cos\varphi])/W_i$ for RF cavity



COLLECTIVE EFFECTS

- Main purpose of this simulation is to see how microbunching instabilities caused by space charge or CSR affect on bunch compression quality.
- ***1) SPACE CHARGE – repulsive coulomb force***

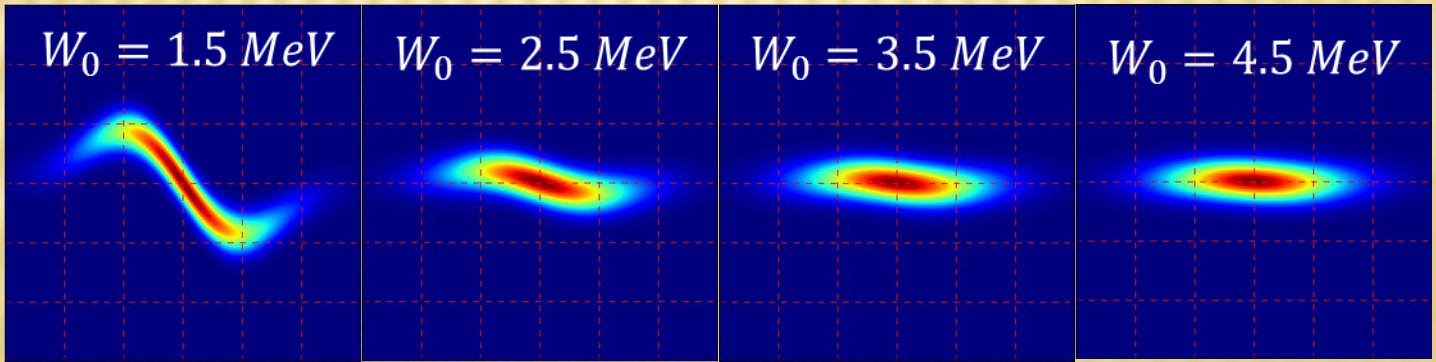
We introduce space charge kick before and after each element in a beamline.

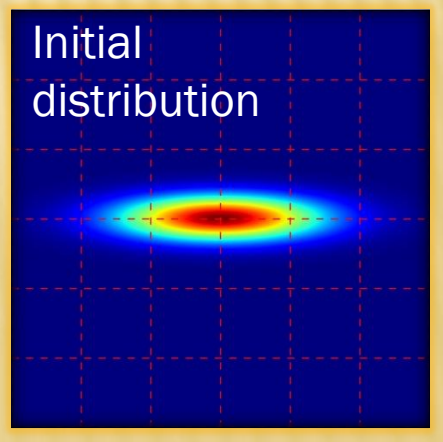
Space charge forces are increasing an energy spread in the bunch.

We consider that each electron going through the element with length l , gain/lose energy

$$\Delta W = e\,E_z l = el\frac{g_0}{4\pi\varepsilon_0\gamma^2}\frac{d\lambda}{dz}, where\ \lambda \text{ is a linear density } \lambda(z)$$

Space charge in a drift before the 1st cavity

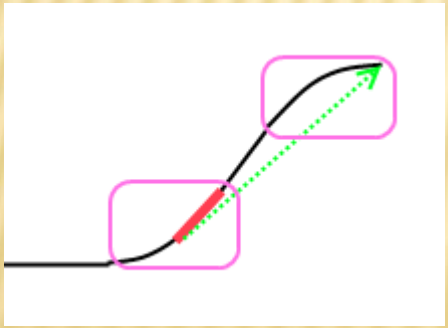




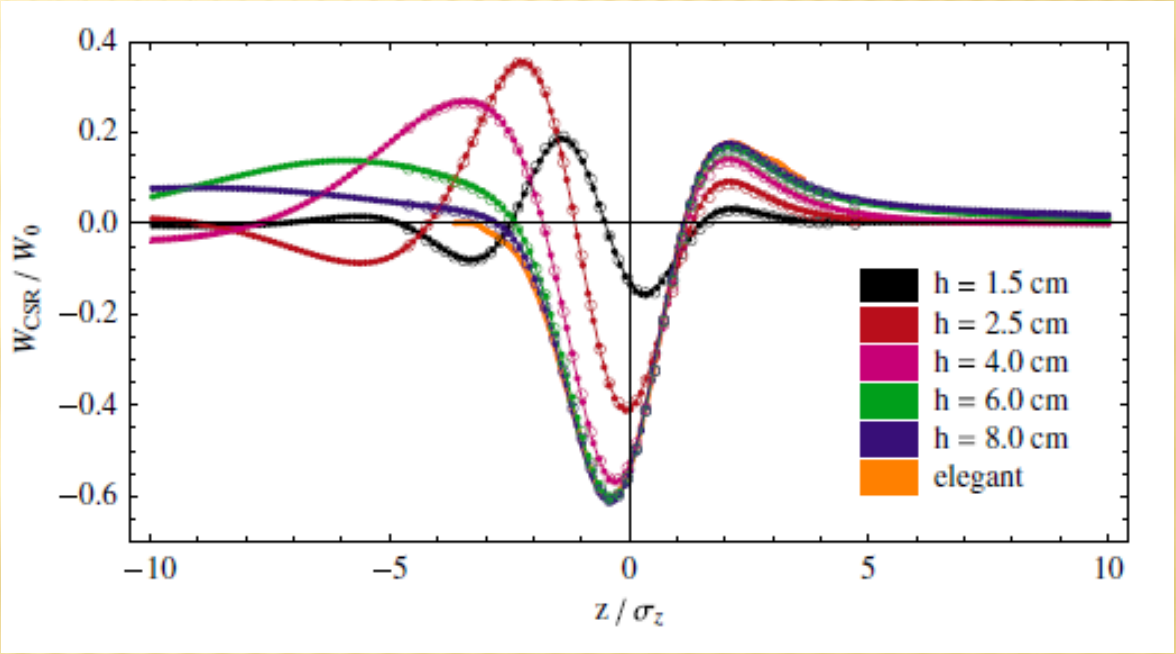
CSR

CSR kicks has to be implemented the same way as space charge ones were introduced.

The example of how CSR can influence on bunch energy distribution



Picture 1



On picture 2 whole bunch loses some energy while its head ”catches” some of it.

CONCLUSION

- **Achievements:**
- Simulation of the described part of ASTA beamline was complete
- Compression reduced bunch length 25 times with invariant emittance.
- Space charge was implemented. Suggestion, that it does not affect much on bunch compression quality, was checked.
- CSR accounting is in process

I wish to say *thank you* to my supervisors **Tanaji Sen**, **Francois Ostiguy** and **Philippe Piot** for help and inspiration during this program.

THANK YOU !

for attention