Jerzy Świniarski
BE-ABP
jswiniar@cern.ch

Linac4 – DTL

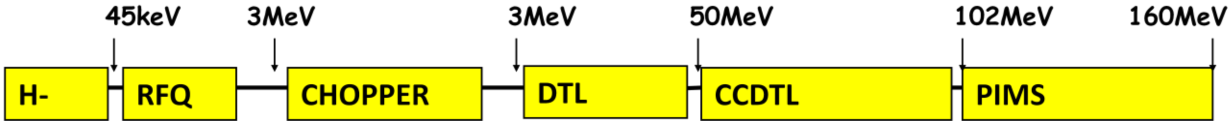
Acceptance studies report

Introduction:

The linear accelerator is the first vital stage of any hadron accelerator complex. The linac generates the initial transverse and longitudinal beam emittances and thereby defines the beam quality for the next stages of acceleration.

The present CERN proton linac (Linac2) consists of three drift tube linac tanks accelerating the beam to 50MeV. The main Linac4 parameters are based on the requirements for PSB injection. The basic mechanical concept of Linac2 has been retained for Linac4, although the many improvements were applied, which was made possible by the technological advance in the last 25 years. An additional design constraint is the requirement to operate at high duty cycle for a possible future high intensity facility.

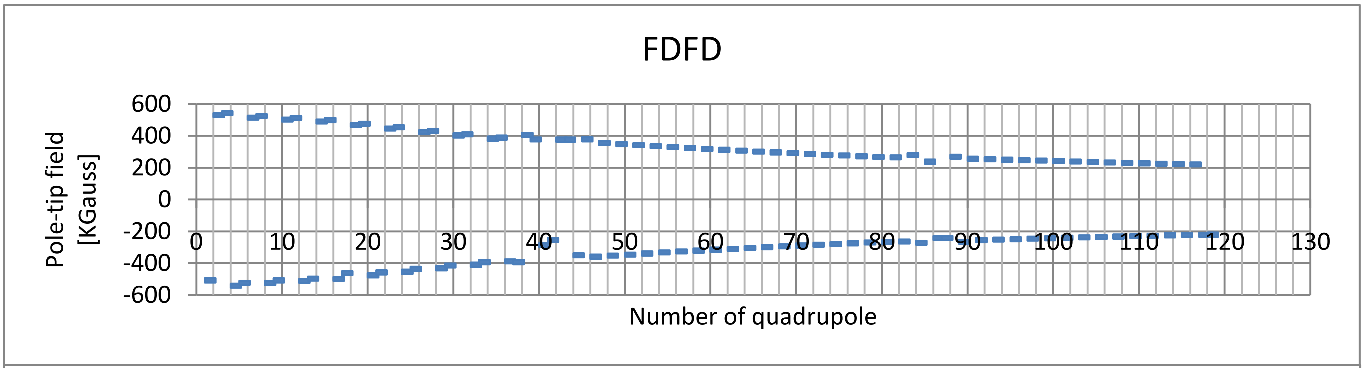
The overall architecture of Linac4 is shown in figure below:

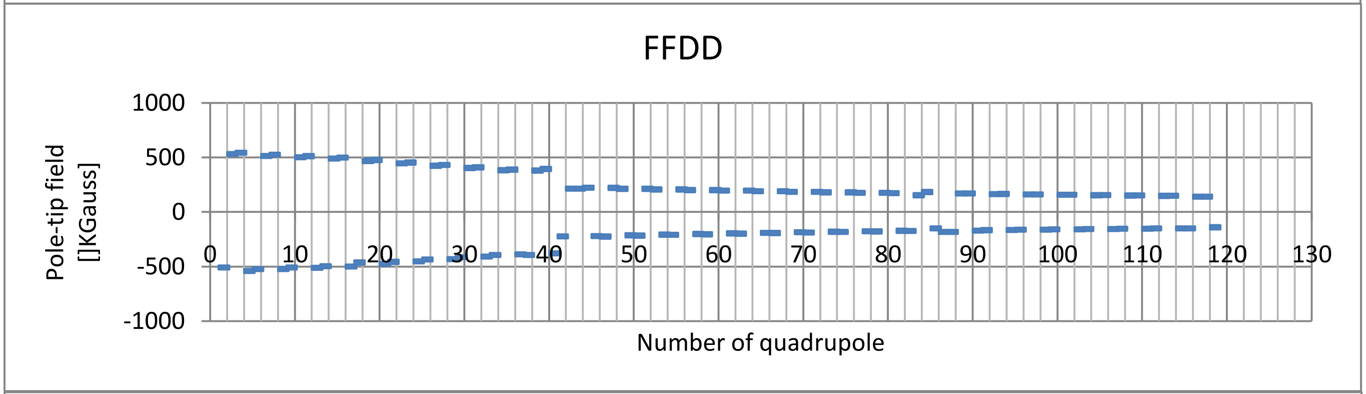


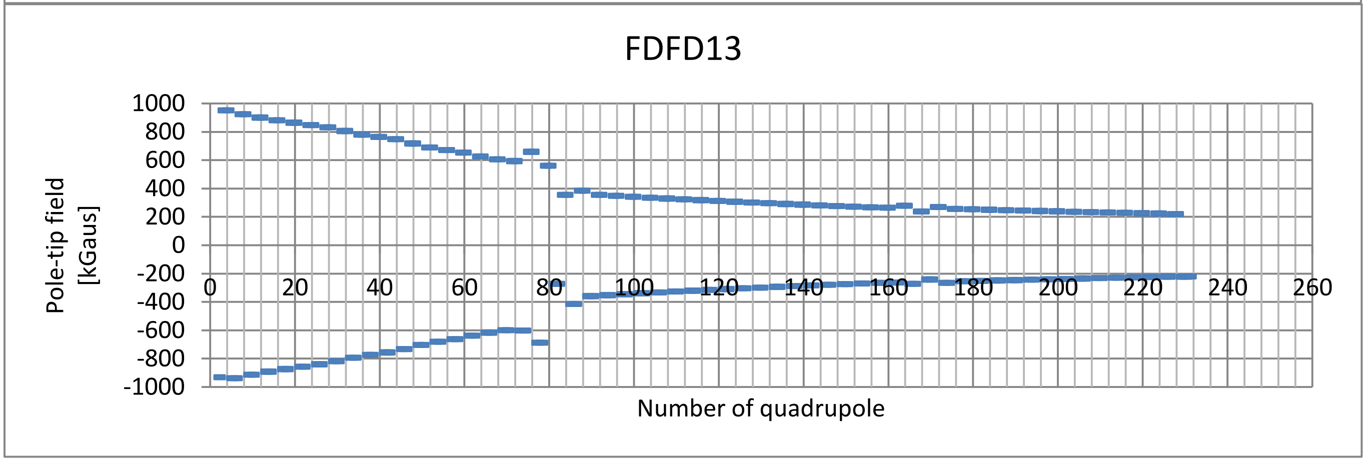
The chosen sequence of accelerating section is standard for modern pulsed linac designs. Three types of accelerating structures bring the energy up to 160MeV: a Drift Tube Linac (DTL) up to 50MeV, a Cell-Coupled Drift Tube Linac (CCDTL) up to 102MeV and Side coupled Linac (SCL) to the final energy of 160MeV.

My studies concerned parameters of DTL following the chopper line, consisting of three Alvarez tanks working at 352.2MHz. All simulations were based on different ways of calculating the acceptance of DTL and its separate tanks.

One compares 3 different lattice designs according to their acceptance and sensitivity to misalignments of quadrupoles. One of them has FDFD lattice in all tanks, but two of them have FFDD focusing in tank 1 and FFDD or FDFD in tanks 2 and 3 – that's the way of naming them in whole report[1]. Figure below shows values of quadrupoles of 3 lattice designs:







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[1] FFDD FFDD FFDD = **FFDD**
FFDD FDFD FDFD = **FDFD**
FDFD FDFD FDFD = **FDFD13**

Acceptance calculations:

Acceptance is an important parameter of accelerating structures in its transverse and longitudinal planes. Acceptance is defined as the area in phase space within which particles can be successfully transported and accelerated without loosing them. Acceptance is usually referenced to the injection point of the structure, however in my simulations because of the code structure acceptance is measured in the half of the first quadrupole of DTL.

Calculation methods:

In purpose of achieving the transverse acceptance 2 methods were applied – scanning and "big beam" method.

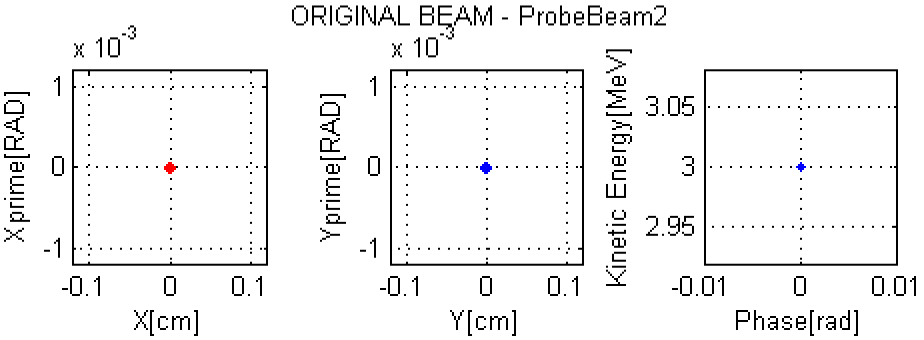
SCANNING

First of them – scanning – is based on shifting the *probe beam* and observing the transmission.

Probe beam is a beam with small emittance in all planes (x-x', y-y', phase-Energy). This gives us an approximation of "point in phase space". Usually the code works badly when simulations of beams with 0 emittance are made, however this would be the real point in phase space. To avoid unnecessary particles spread during the simulations space charge is turned off.

Transmissions can be treated as a binary values – they are usually ≈0% or ≈100%. One observes that the particles at certain point of phase space were successfully transmitted through all the tanks of DTL and other were lost. According to the initial beam position and divergence shift one can plot the transverse acceptance.

Figure below shows the probe beam used for simulations[2]:



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[2] ProbeBeam2 is operational name of the probe beam

"BIG BEAM"

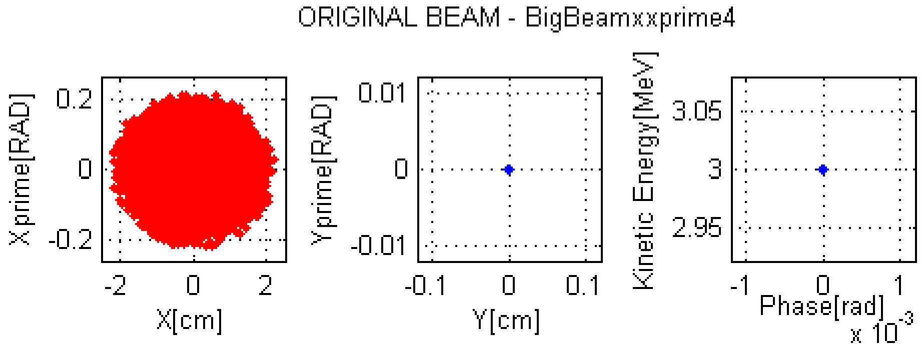
Second way of achieving the acceptance was using a "big beam" and observing the numbers of particles, that stayed alive.

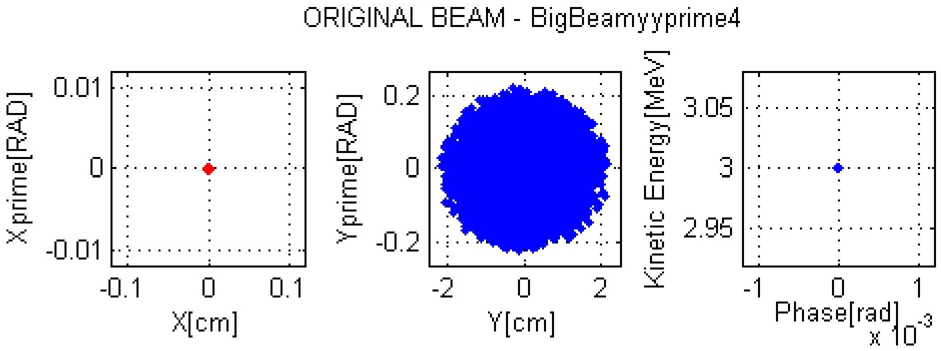
Big beam is a beam with big emittance in one of the planes and small in others. This fact guarantees, that other planes do not affect calculations of the acceptance in plane that interests us at the moment. Exactly as it was in scanning method to avoid unnecessary particles spread during the simulations space charge is turned off.

Because of necessity of other planes not affecting the analyzed one two different beams were needed – one for each plane.

Each particle of the beam has it's number. To plot the acceptance one needed numbers of lost particles. Removing those particles from plot of the initial beam causes leaving only these, that stayed alive. Phase space taken by survivors is acceptance of the DTL.

Figures below show beams used for simulations[3]:





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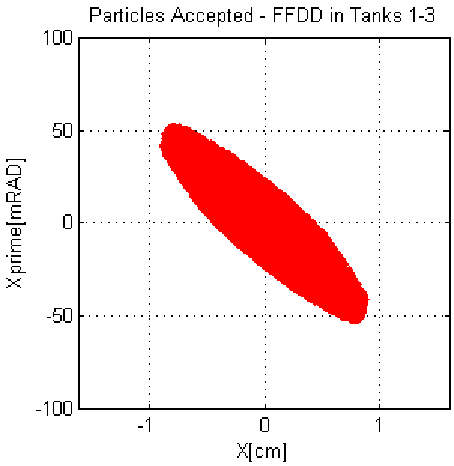
[3] BigBeamxxprime4 and BigBeamyyprime4 are operational names of the big beams

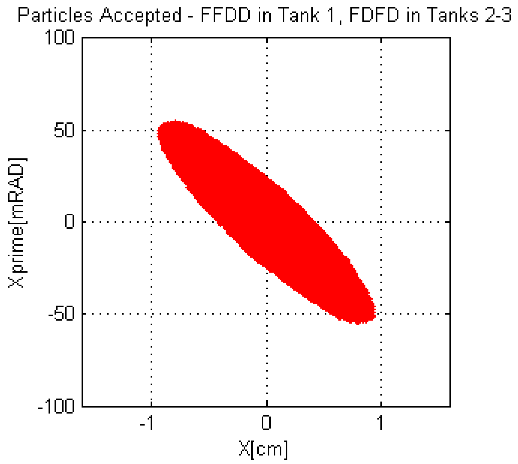
Results and comparison of two methods:

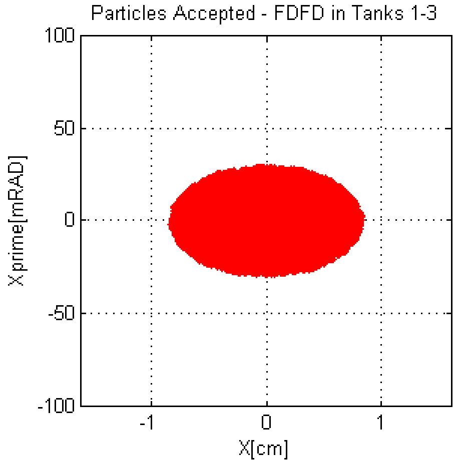
One compares advantages and disadvantages of each method on example of 3 different lattice designs of DTL.

RESULTS - X-X':

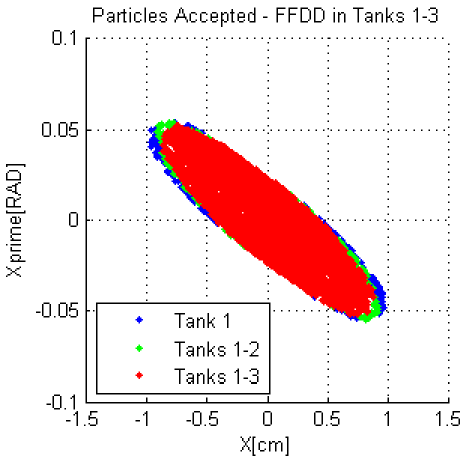
SCANNING

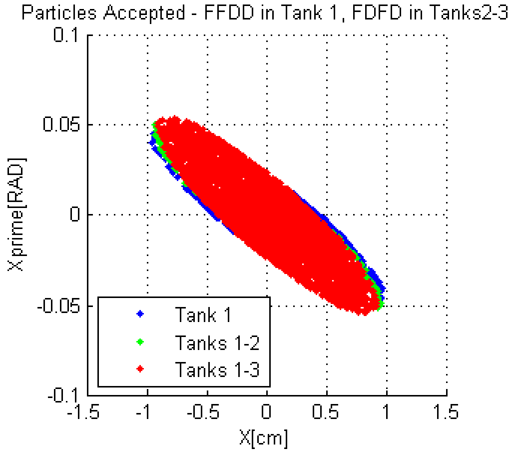


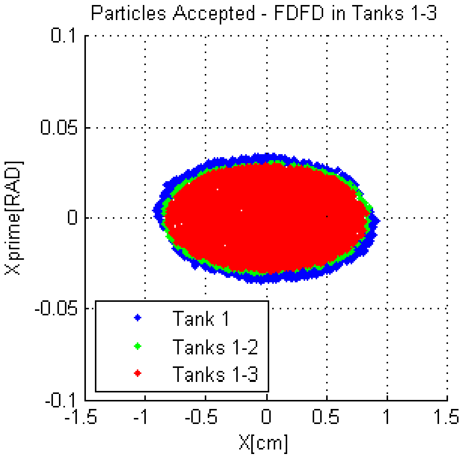




BIG BEAM

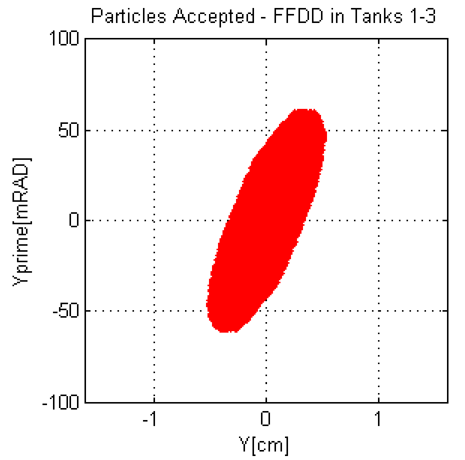


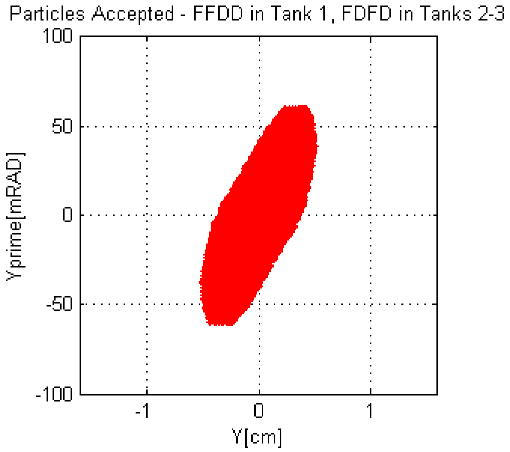


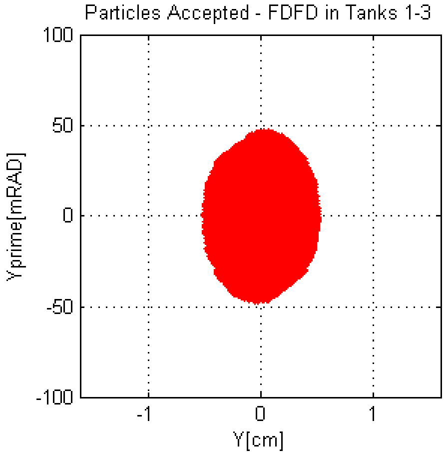


RESULTS - Y-Y’:

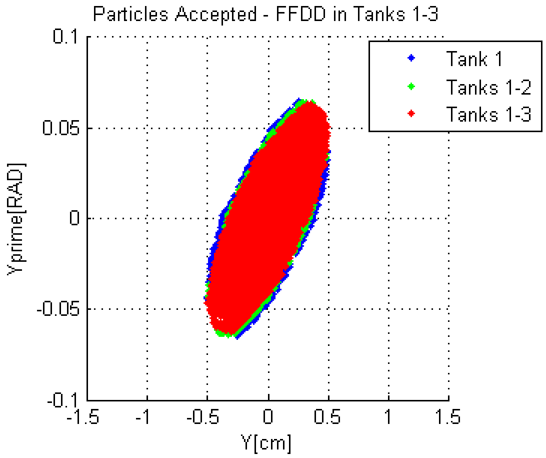
SCANNING

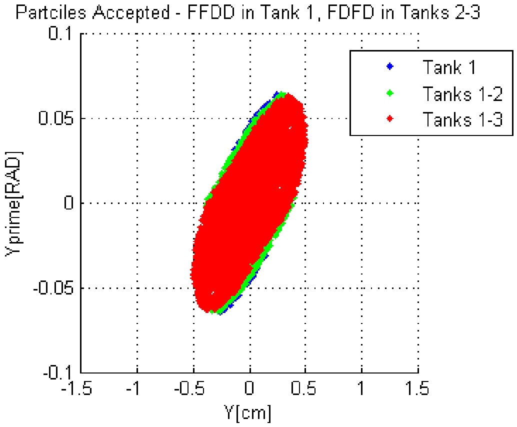


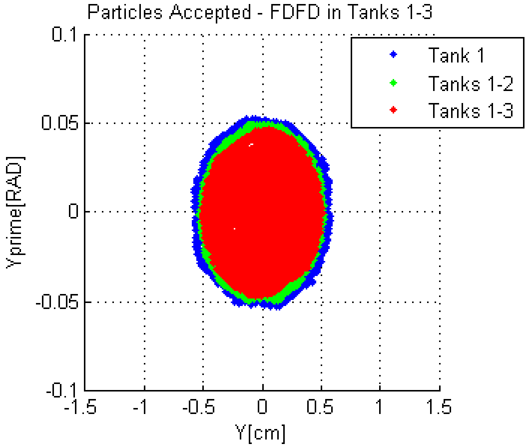




BIG BEAM







Emittances:

One calculates RMS emittances of acceptance in transverse planes [mm*mRad]:

XX'	SCANNING	BIGBEAM	Δ[%]
FFDD	53.428	53.048	0.711
FDFD	54.404	54.454	-0.092
FDFD13	60.030	59.922	0.179

YY'	SCANNING	BIGBEAM	Δ[%]
FFDD	50.555	51.421	-1.714
FDFD	52.152	53.010	-1.645
FDFD13	58.410	58.983	-0.980

As one can see both methods give similar results.

Biggest advantage of “big beam” is time. One run of big beam, which gives all results takes few minutes. To get the same results with scanning one needs few hours or even dozen if bigger accuracy is needed – most simulations were made during night, so exact value of needed time is unknown.

Because of that one can easily plot particles that were accepted by separate tanks.

On the other hand using big beam method is only good for simulations. In real measurements one uses pencil beam and with steering magnets one achieves certain point in phase space.

Longitudinal Acceptance:

Longitudinal acceptance was checked only with scanning method because of revealed bugs in the Travel code, which gave false results while using beams big in Phase-Energy plane. The code is being now corrected so in the future results can be achieved faster and without errors.

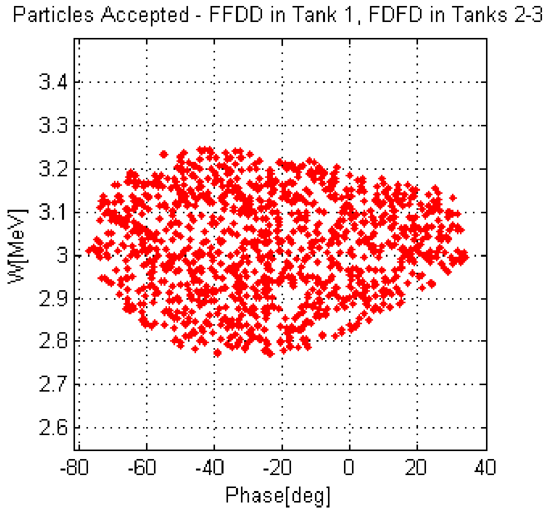
In general scanning in longitudinal plane is similar to transverse scanning – changing other parameters of the beam is obvious, but also filter in energy and phase is applied at the end of DTL, so one observes only particles that were properly accelerated and were in proper phase.

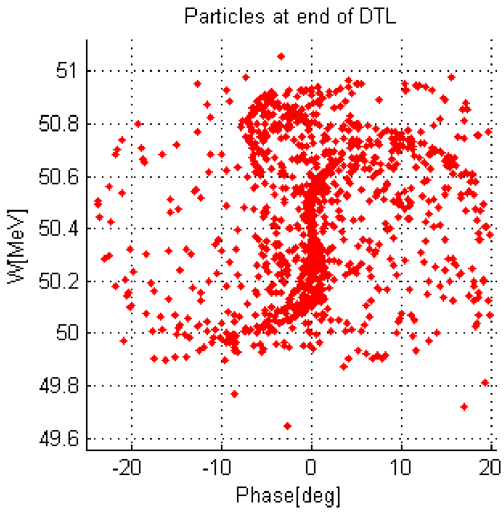
Energy filter left particles with energies between (45;55)MeV. Nominal energy of DTL is 50MeV. All particles, that had different energies were killed in filter, however <u>this doesn't mean, that they were lost in the structure!</u>

The same situation is with phase filter. Particles with phase between (-0.22;0.35)rad were left alive – others killed.

RESULTS Energy-Phase:

As a result one achieves plot of accepted and properly accelerated particles ("tail" of bucket not shown) and accepted particles at end of DTL:


Particles Accepted - FFDD in Tank 1, FDFD in Tanks 2-3


Particles at end of DTL

Calculated RMS emittance of accepted particles:

ε_{phERMS}= 14.685 [rad*MeV]

Error studies – quadrupole misalignments:

Important task of measuring acceptance is structures' sensitivity to production and assembly errors. Statistical simulations were made to compare probabilities of beam losses of 3 lattice designs of DTL according to displacement of quadrupoles.

Because of the time needed to make one whole acceptance measurement with scanning method one decided to use the Big Beam for statistical simulations.

Each run was made as described before in Big Beam method explanation. Only difference was that all quadrupoles of the line had random misalignment errors. All misalignments of quadrupoles have Gaussian distribution (sigma=0.01 for each quadrupole) in x and y – both axes changed in each simulation and are changed independently. Large number of simulations (3000 simulations made for each plane) guarantees, that errors of statistics (picking not exactly the same misalignments) are minimized.

Simulations were made twice – once for each plane using beams described before. As a result one obtains CDFs (Cumulative Distribution Functions) of transmission – probability, that transmission is below assigned value.

Also comparison of FFDD and FDFD structures was made. Important is fact, that each structure has different nominal transmission. Because of that on CDF plots each of them has different normalization factor:

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normalizerXFDFD = 9.341
normalizerXFFDD = 9.653

normalizerYFDFD = 9.3414
normalizerYFFDD = 9.6154
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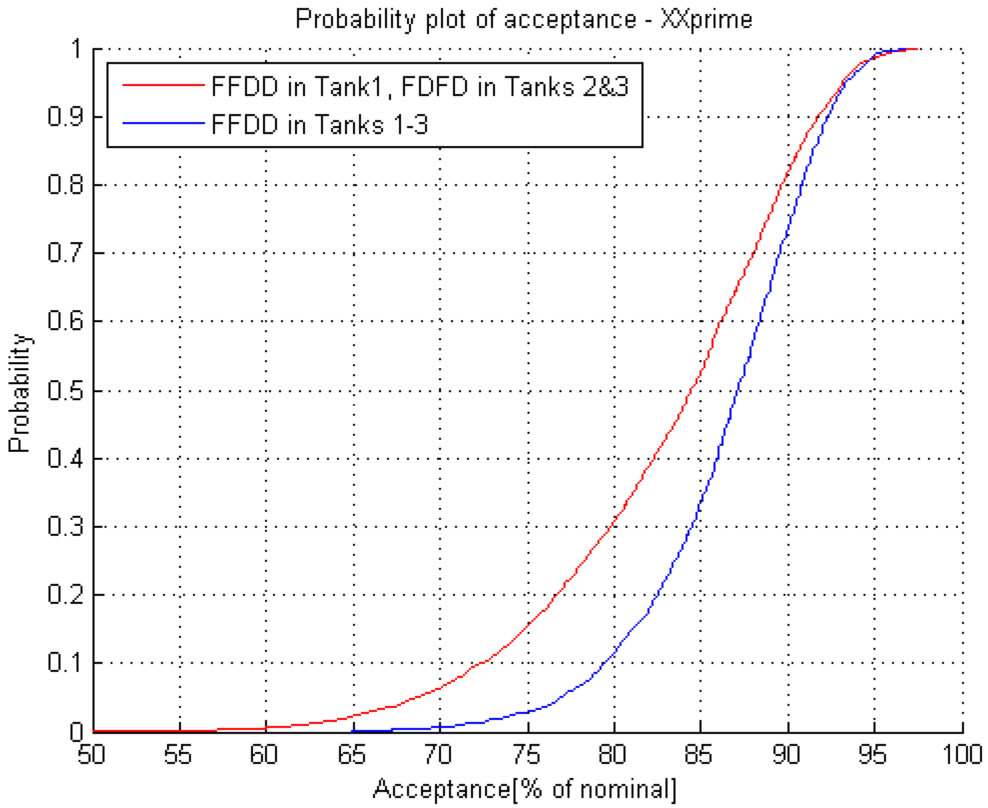
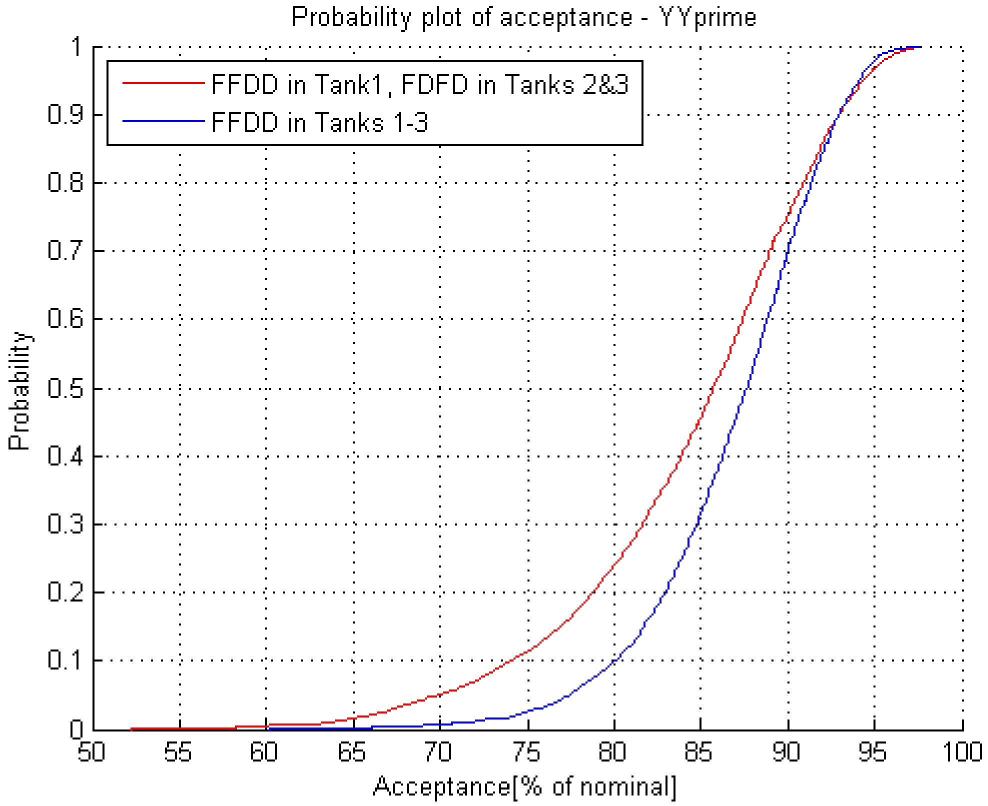


Probability plot of acceptance - XXprime



Probability plot of acceptance - YYprime

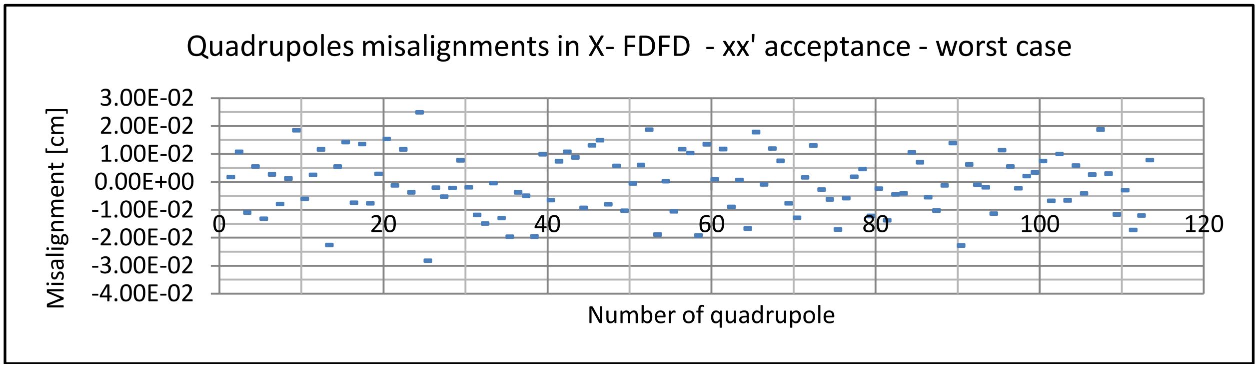
As one sees both structures give similar results, however FDFD structure is slightly more sensitive to misalignments. On the other hand RMS emittance calculated before is bigger in FDFD structure.

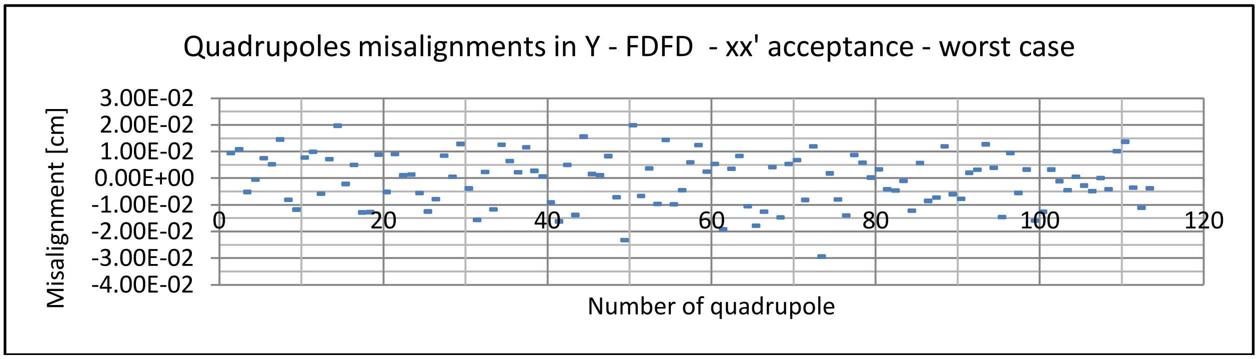
One important property of those structures is that CDF lines cross – that fact indicates, that high acceptances (≈95% of nominal value) are more probable in FDFD structure. This difference is small, so in real conditions this fact may not be noticed.

WORST CASE:

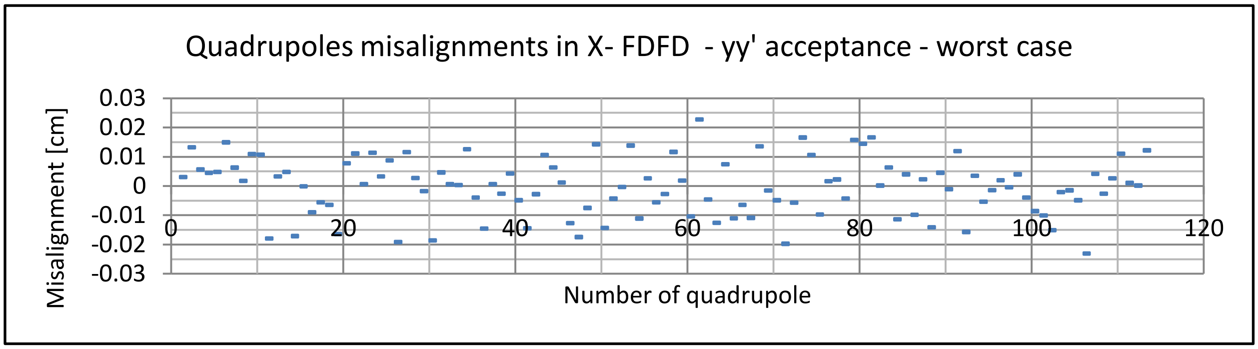
Important parameter is the lowest probable acceptance. Probability of all quadrupoles having big misalignments at the same time is small, however this situation is still probable. Figure shows values of misalignments of each quadrupole and the % of acceptance achieved with those misalignments:

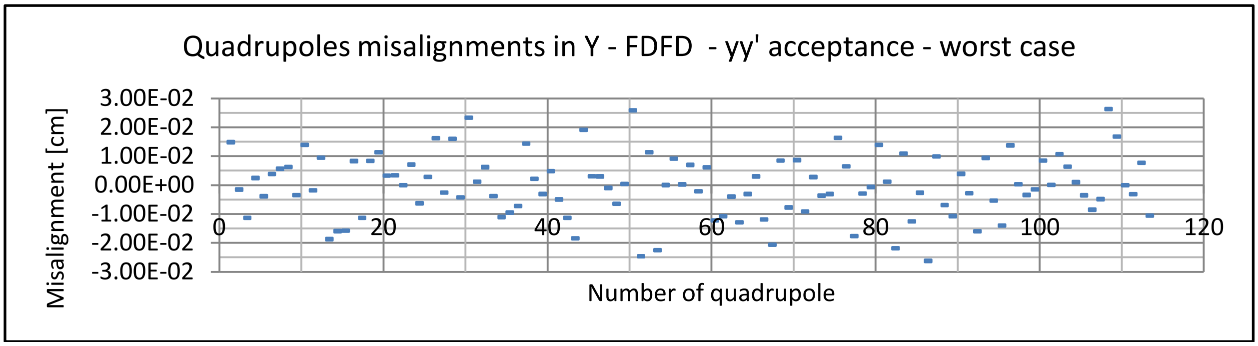
FDFD – XX' Acceptance - 49.5%



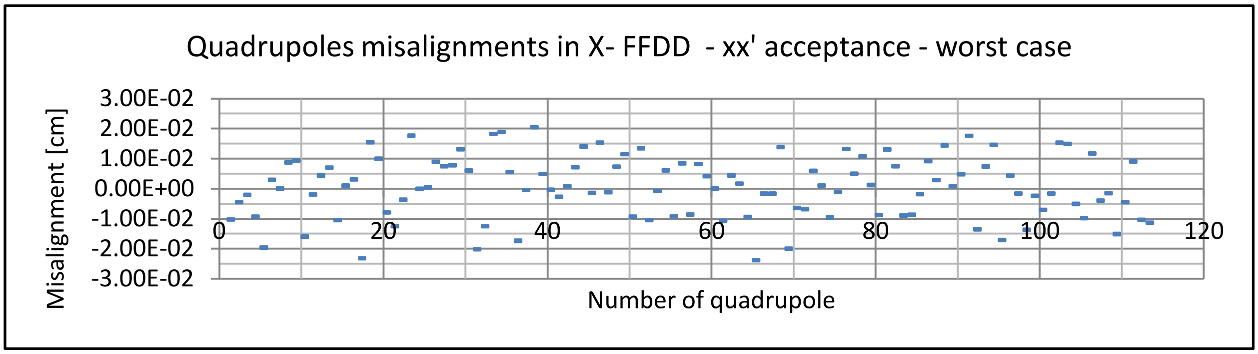


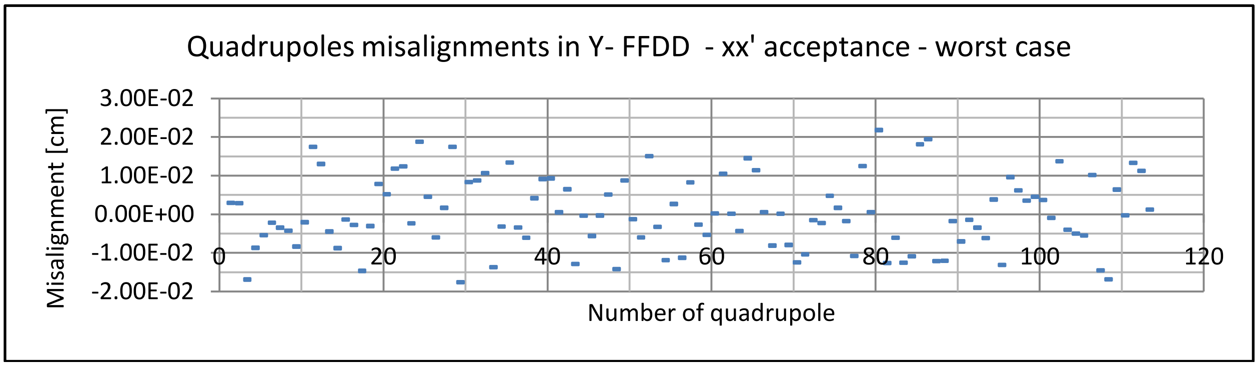
FDFD - YY’ Acceptance - 52.2%



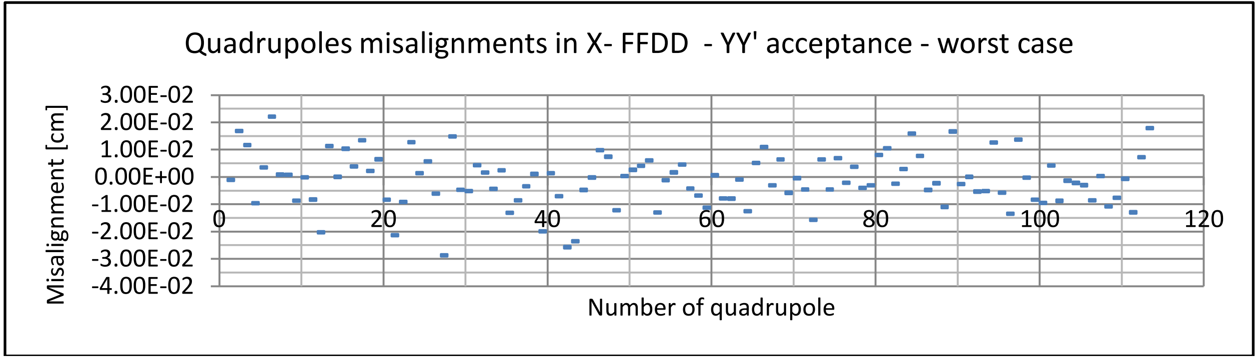


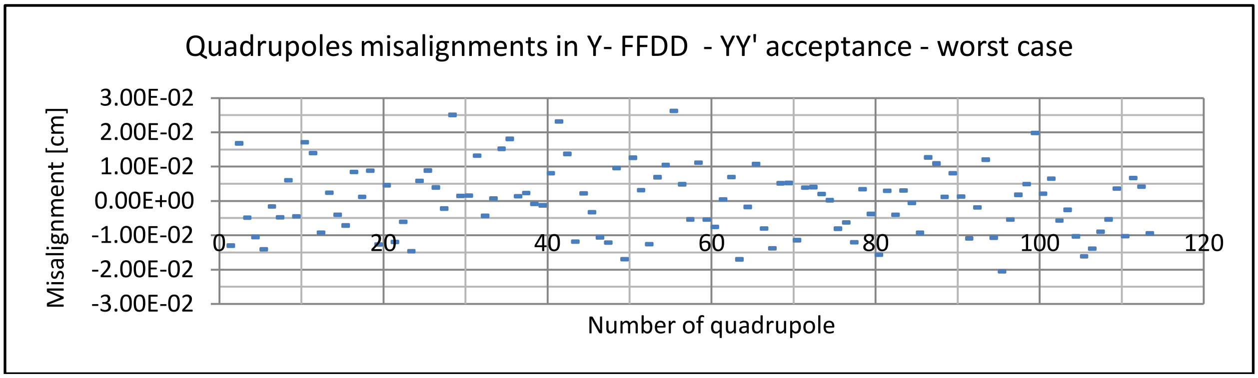
FFDD – XX’ Acceptance – 64.9%





FFDD – YY’ Acceptance - 60.2%





One observes that the smallest transmissions occur when quadrupoles are misaligned alternatingly and with maximum values – for example quadrupole 1 has positive and quadrupole 2 negative misalignment etc. This fact is very intuitive.

Conlusion:

As a result of my work at CERN it was proved, that both methods can be used for checking acceptance of accelerators’ elements. Much more efficient way is “big beam method” and output data of travel in this method are easier to analyze in Excel or Matlab.

Also one has additional information that can help making a decision of chaning lattice of existing DTL or not – acceptance and sensitivity to misalignments of quadrupoles.