Beam dynamics in LINAC4 at CERN

Alessandra M. Lombardi- presented by Frank Gerigk

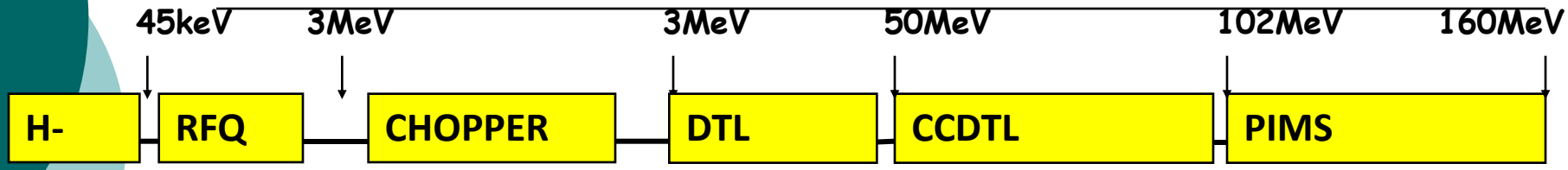
Giulia Bellodi, Romuald Duperrier (CEA),Mohammad Eshraqi, Jean-Baptiste Lallement, Sara Lanzone, Edgar Sargsyan
Didier Uriot(CEA).

Layout and nominal beam dynamics : results of the calculations with codes PATH and TRACEWIN

Special features for injecting into the booster : chopping and energy painting

Effect of alignment error and RF errors : define error budget, correction system and RF tolerances

Linac4 Layout



RF volume source (DESY)
45 kV
1.9m LEBT

Radio Frequency Quadrupole
352 MHz
3 m
1 Klystron
0.6 MW

Chopper

352 MHz
3.6 m
11 EMquad
3 cavities

Drift Tube Linac

352 MHz
18.7 m
3 tanks
3 klystrons
4 MW
111 PMQuad

Cell-Coupled Drift Tube Linac
352 MHz
25 m
21 tanks
7 klystrons
6.5 MW
21 EMQuads

Pi-Mode Structure

352 MHz
22 m
12 tanks
8 klystrons
~12 MW
12 EMQuads

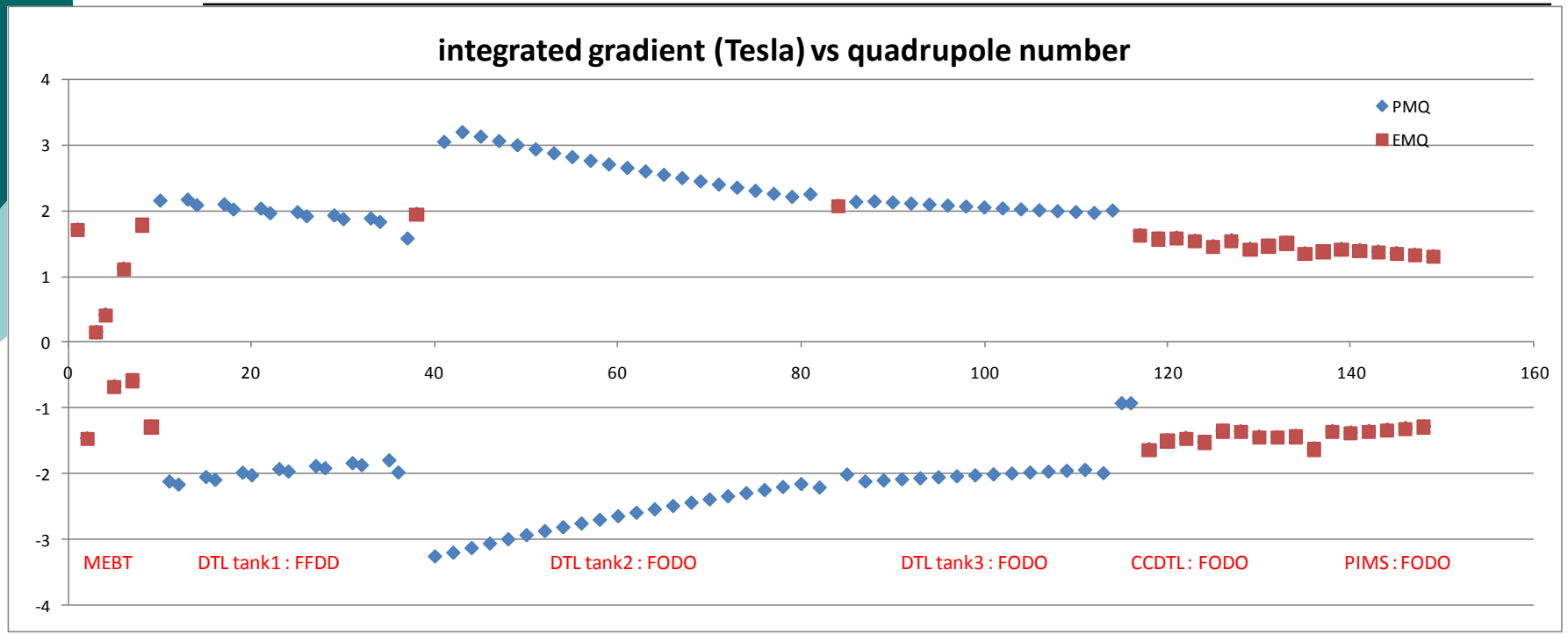
Total Linac4:
80 m,
19 klystrons

Beam Duty cycle:
0.1% phase 1 (Linac4)
3-4% phase 2 (SPL)
(design for losses : 6%)

4 different structures,
(RFQ, DTL, CCDTL, PIMS)

Ion current: 40 mA (avg. in pulse), 65 mA (bunch)

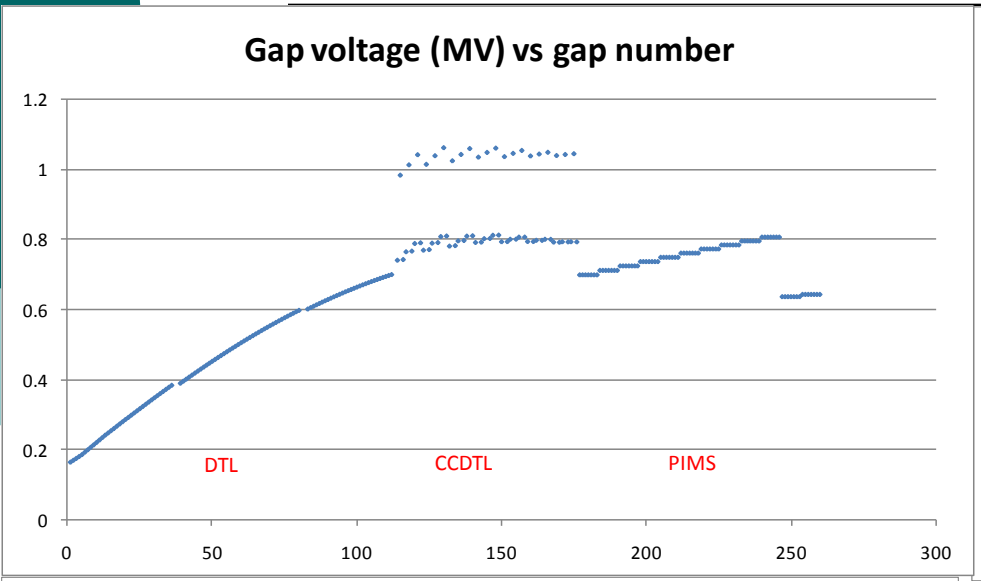
Focusing field

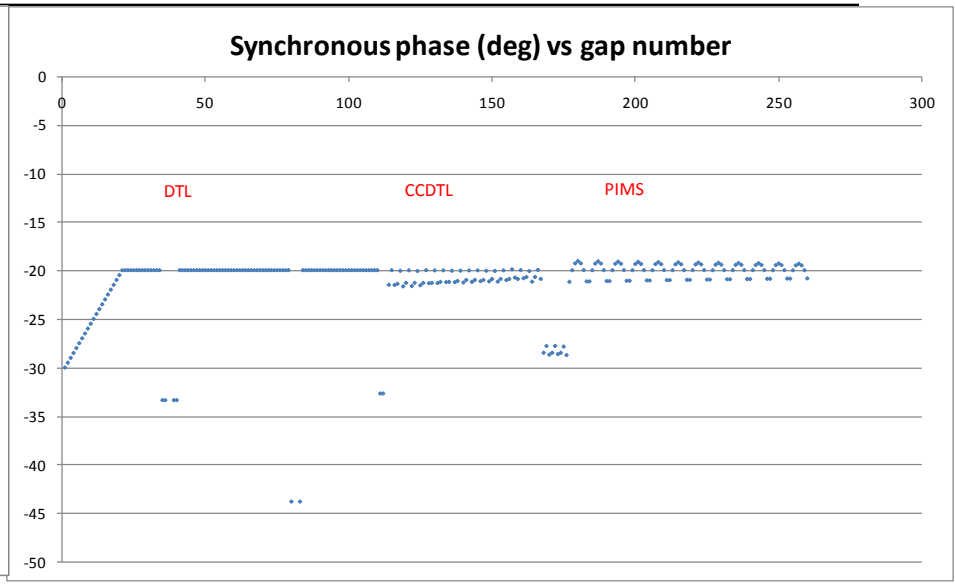


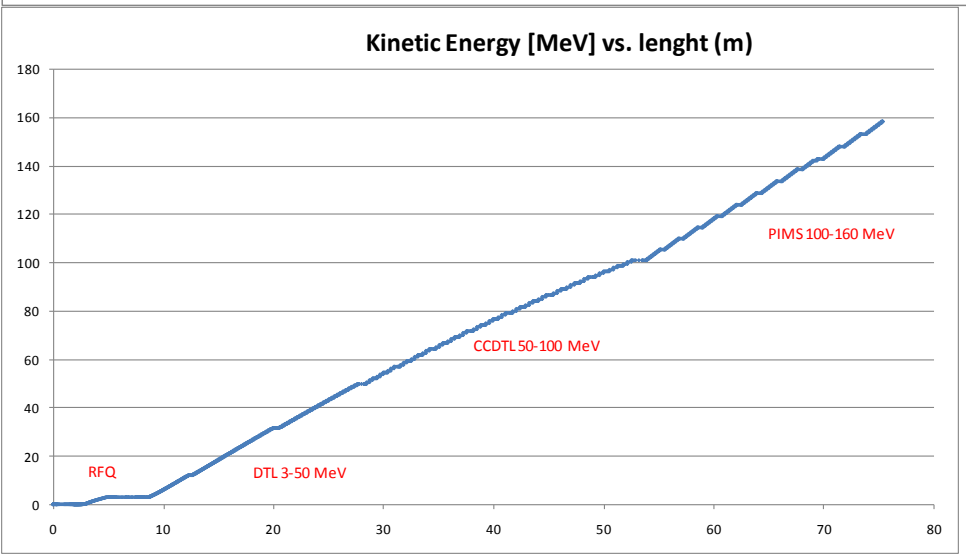
"Locally" irregular due to extra space for intertank and diagnostic

Can match current from 30 to 80 mA, nominal is 70mA

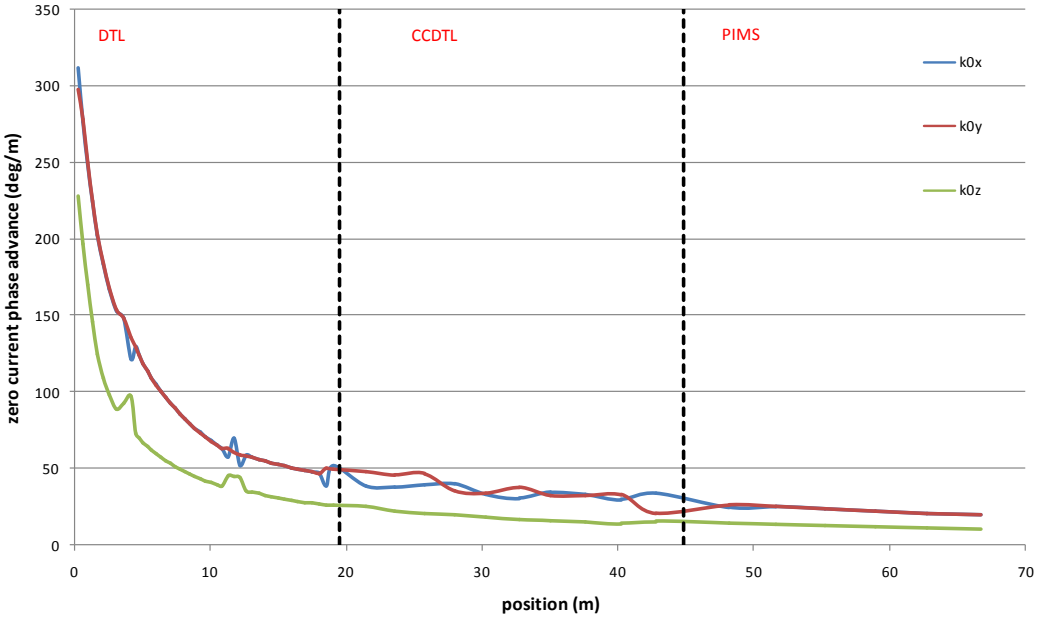
Accelerating field and phase

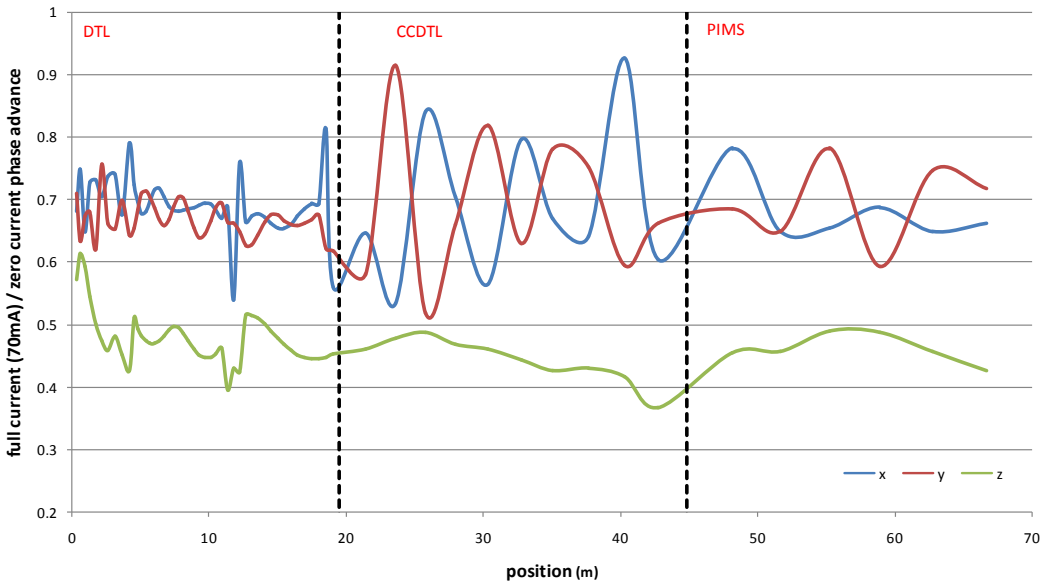






Phase advance





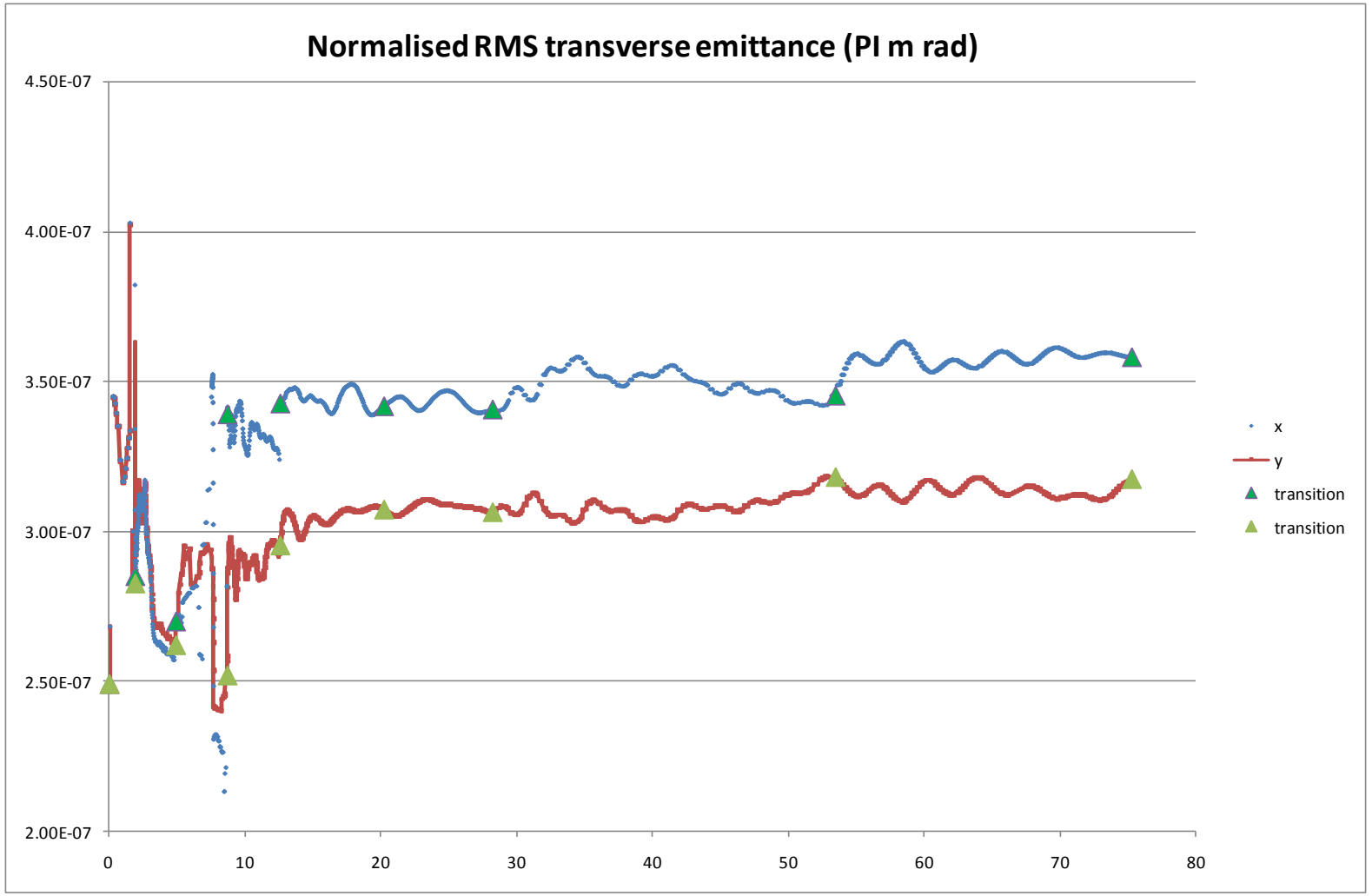
Phase advance is smooth

Ratio long/transv is such as to avoid resonances

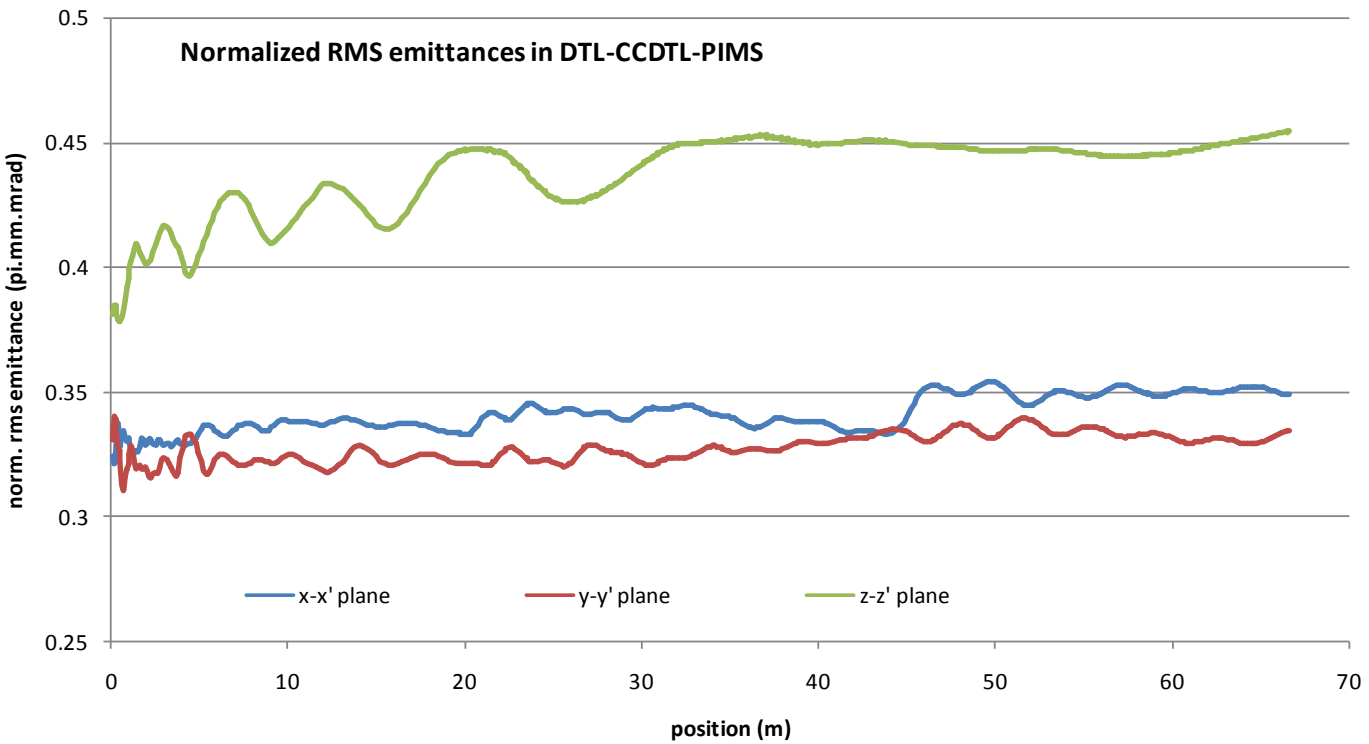
Limit to the max current comes from the longitudinal phase advance

Emittance end-to-end

30-40% emittance growth



Emittance (DTLinput-to-end)



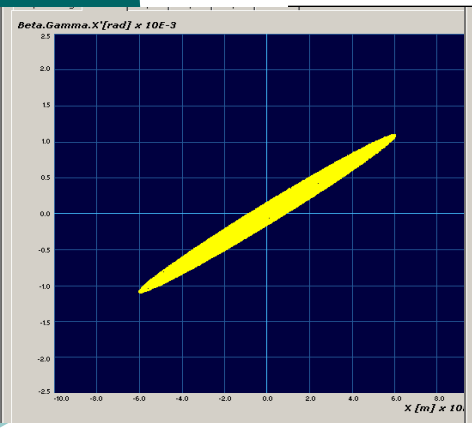
tracewin

at the output

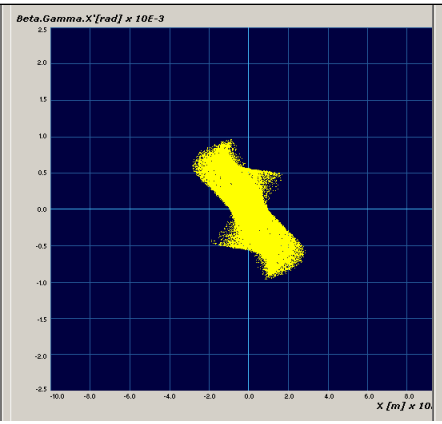
Et=0.34
El=0.46

Rms norm pi mm mrad

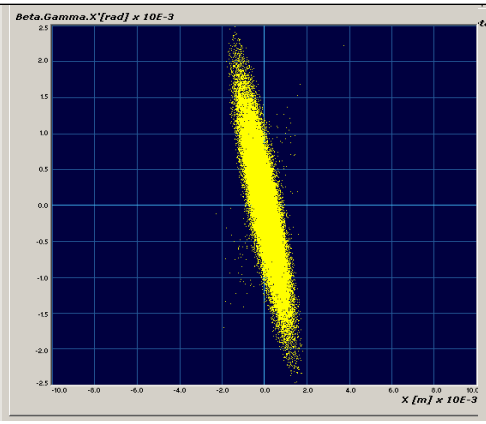
Normalised transverse phase space



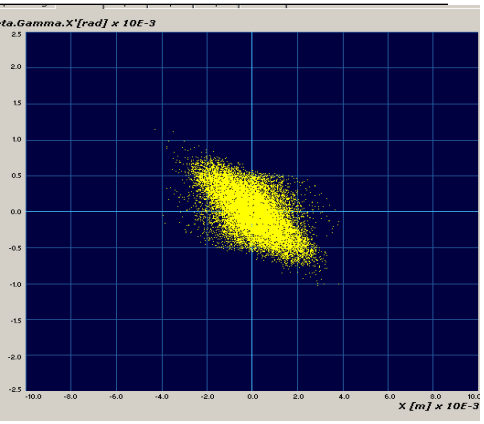
LEBT in (45keV)



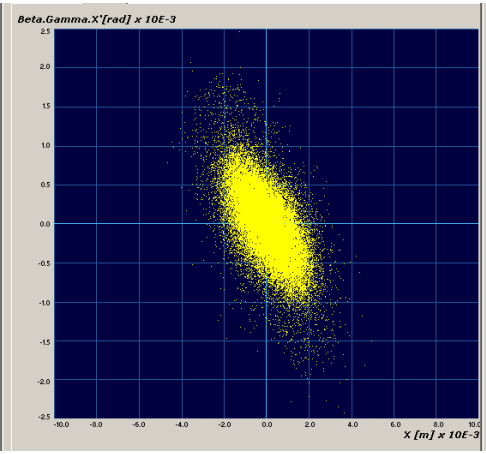
RFQ in (45keV)



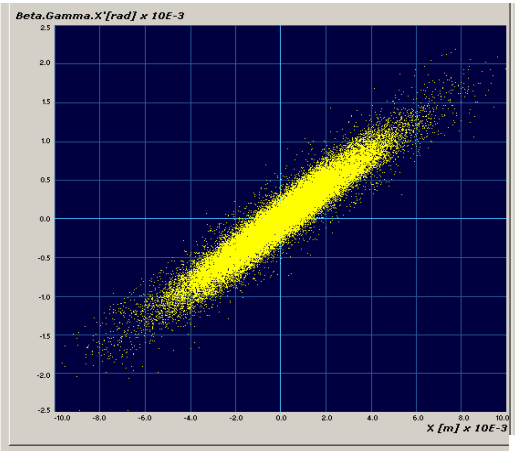
RFQ out (3 MeV)



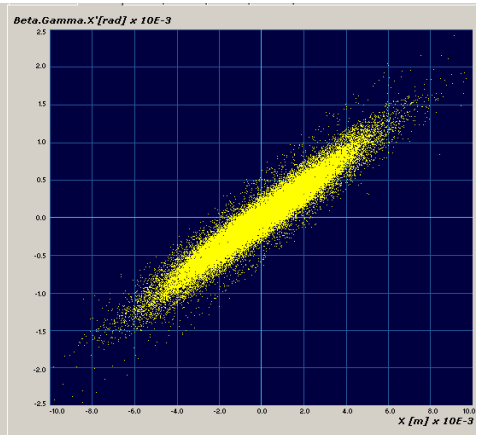
DTL in (3MeV)



CCDTL in (50MeV)



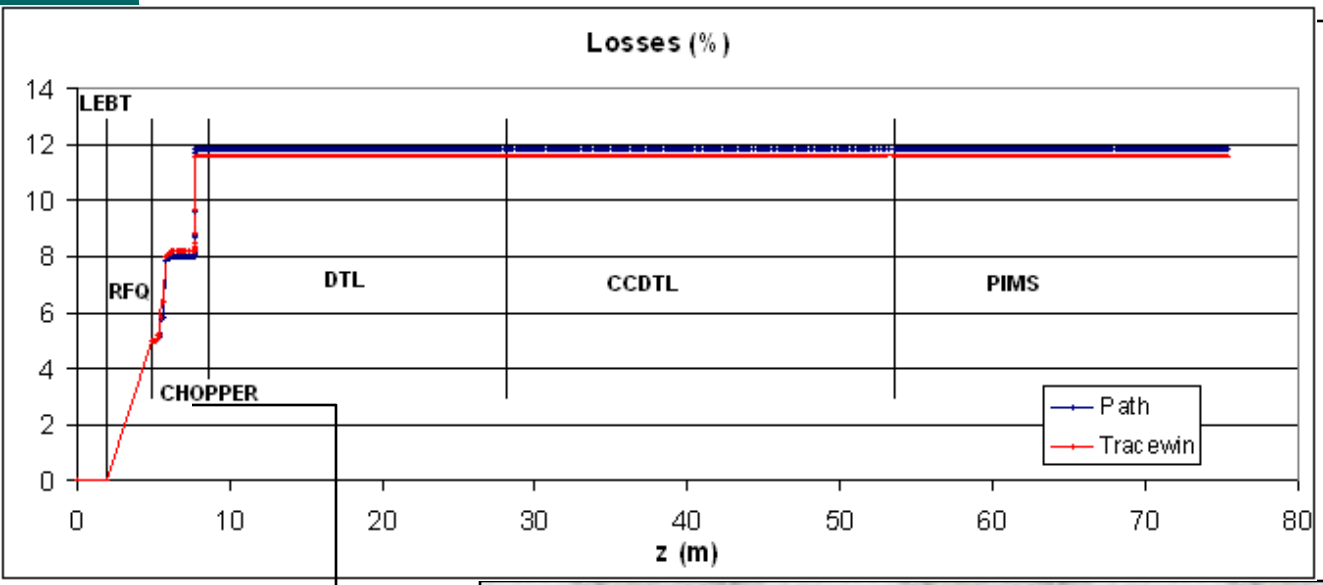
PIMS in (100MeV)



PIMS out (160MeV)

Plot scale :
1cm X 2.5mrad

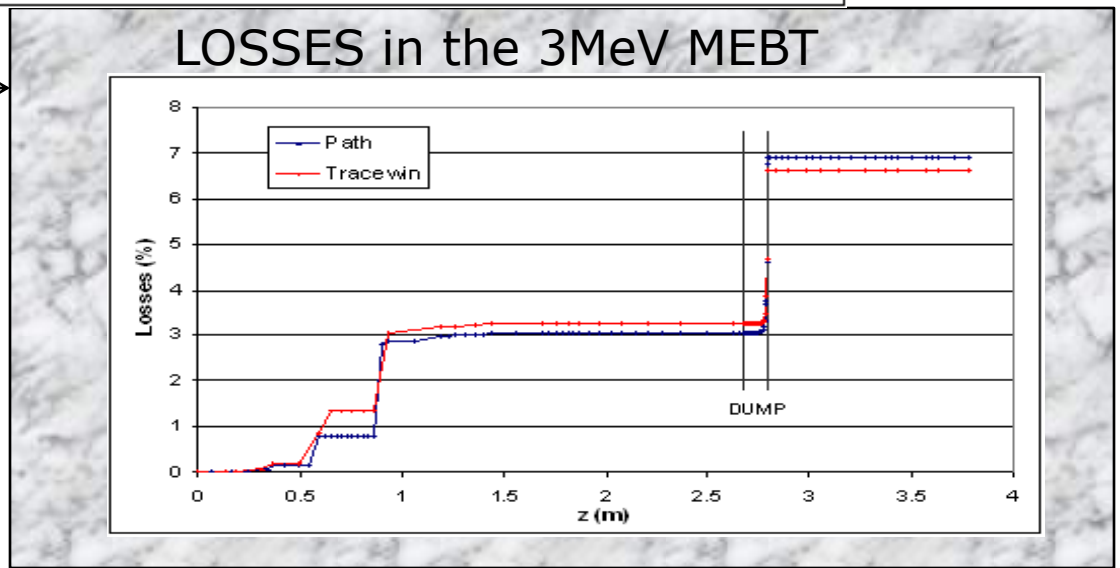
Losses



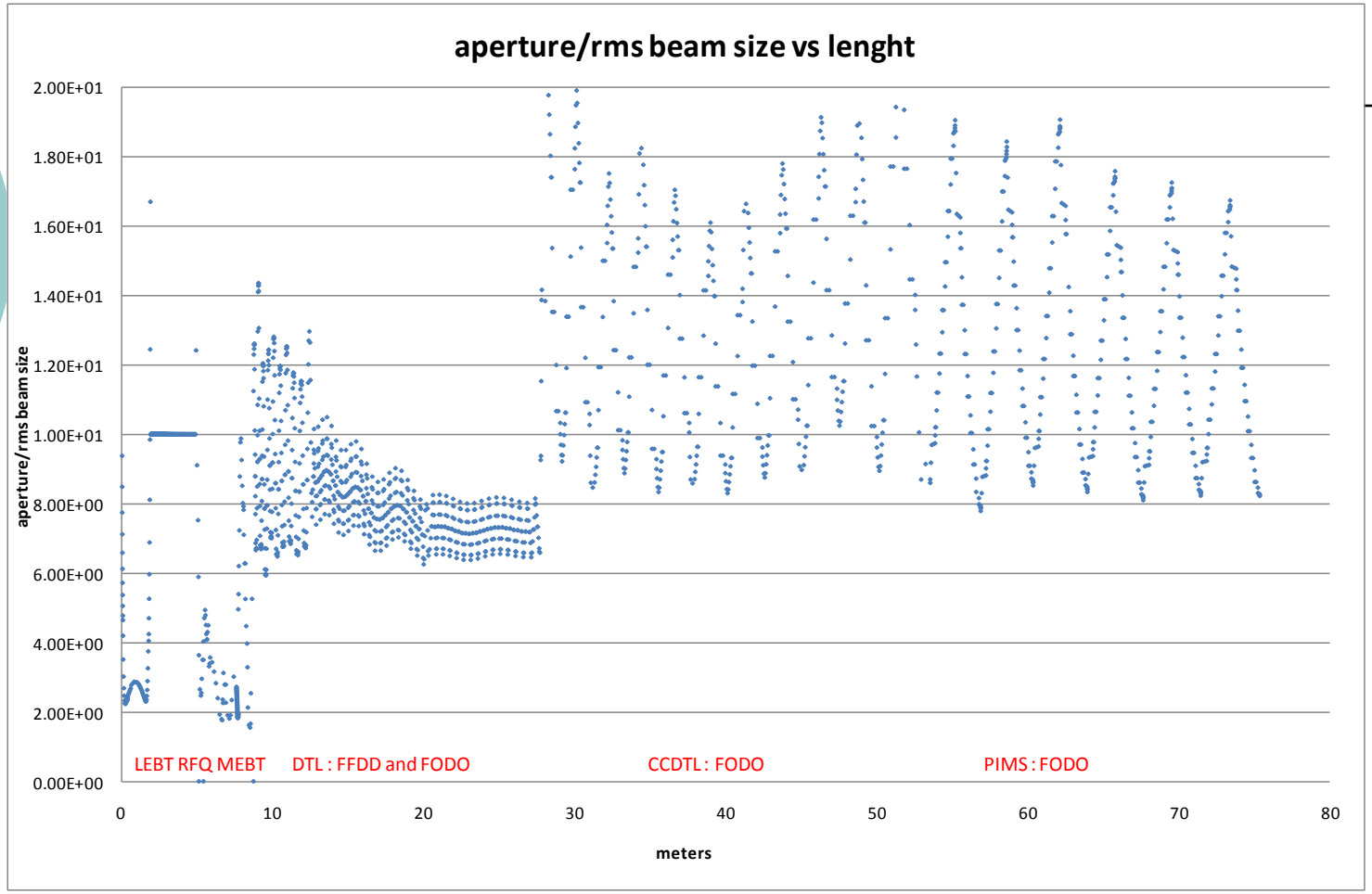
Most of the losses occur before the beam has reached 3 MeV.

Losses are mainly in the RFQ (5%) and the MEBT (7%).

The total transmission is ~85%.



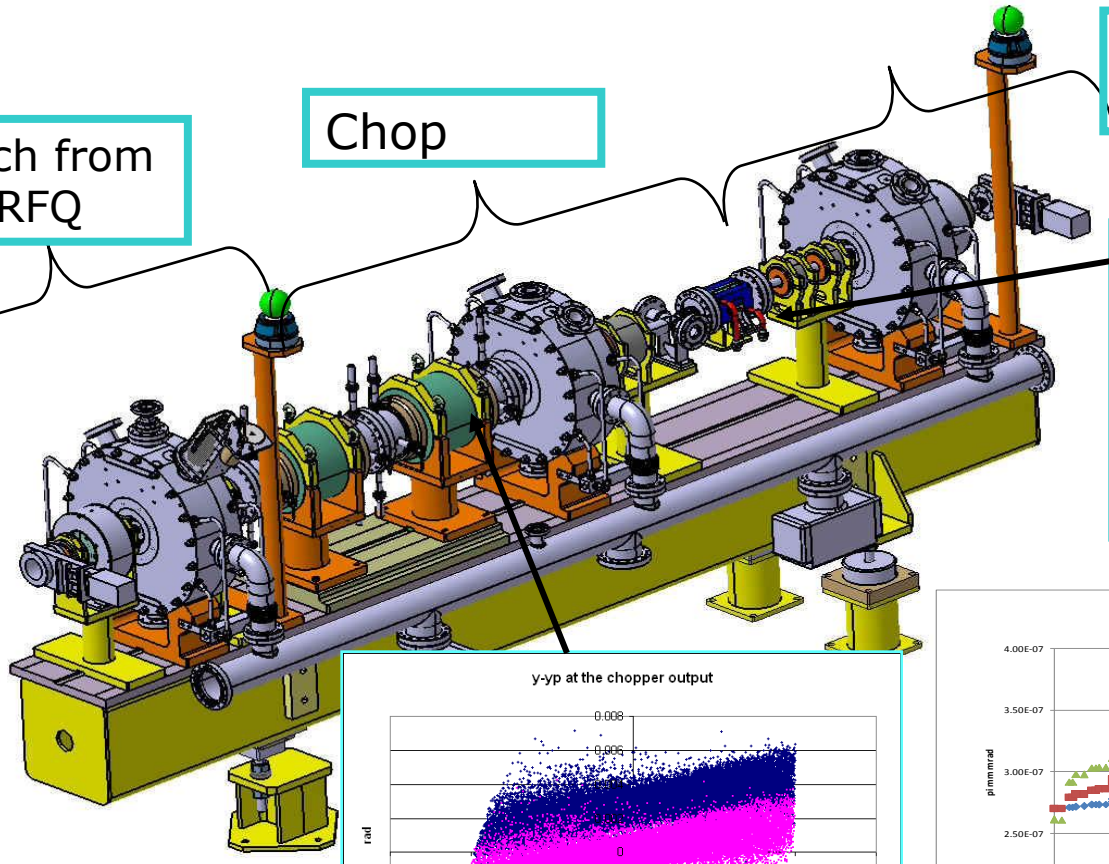
Aperture over rms beam size

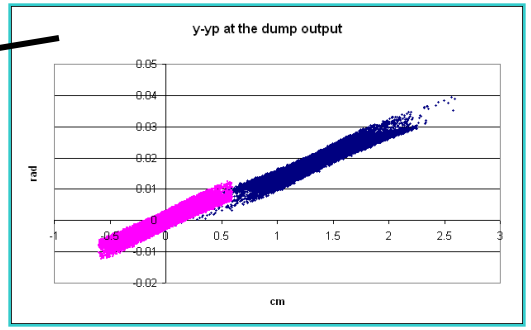


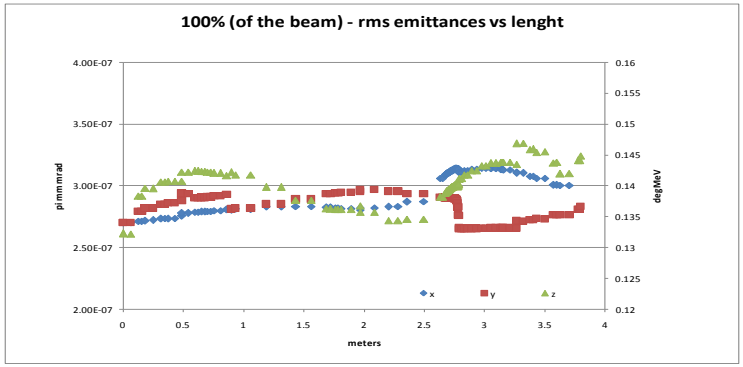
Bottlenecks : LEBT solenoids, chopper plates and Dump (wanted)

Special feature 1: “chopping”

removing microbunches (150/352) to adapt the 352MHz linac bunches to the 1 MHz booster frequency





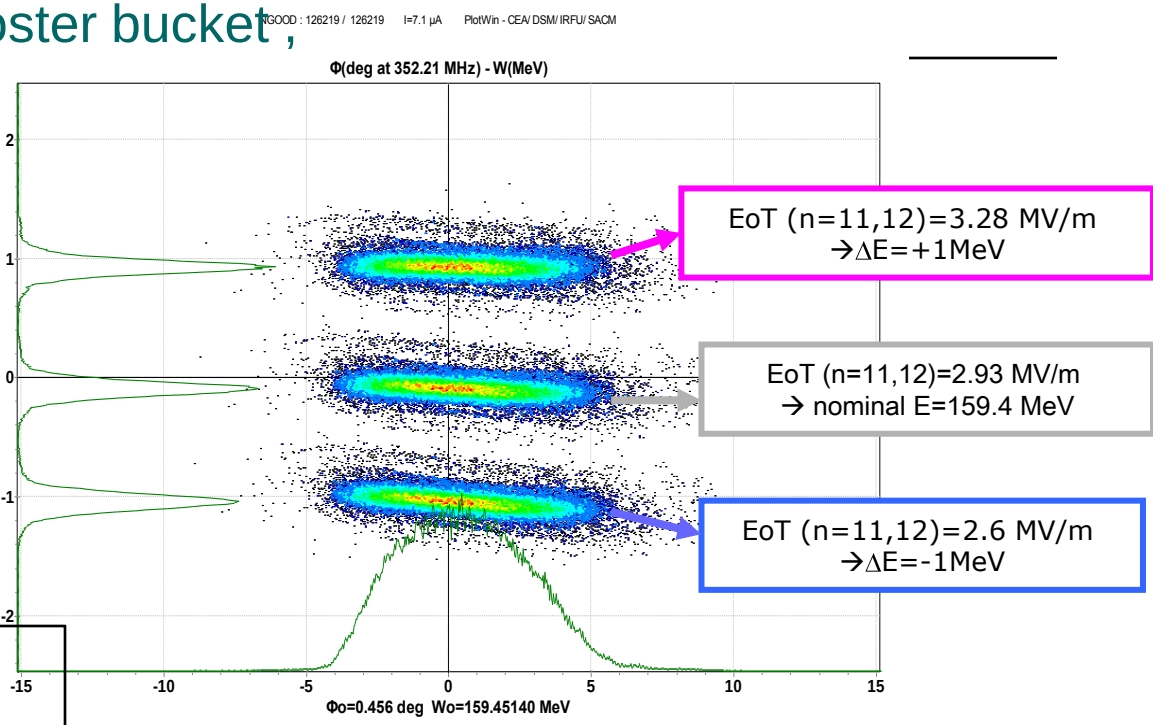


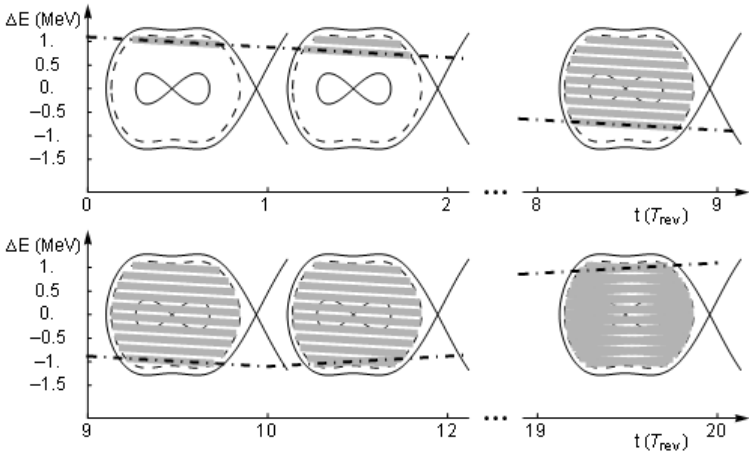
Emittance increase 20-30%

Special feature 2 : “energy painting”

linear energy variation over 10 + 10 µsec (20 turns) to better fit the 100 µsec pulse to the booster bucket”;

The field in the last two tanks of the PIMS is linearly increased /decreased from 2.6 to 3.28 MV/m over 20 µsec to vary the beam energy by ± 1MeV /160 MeV……



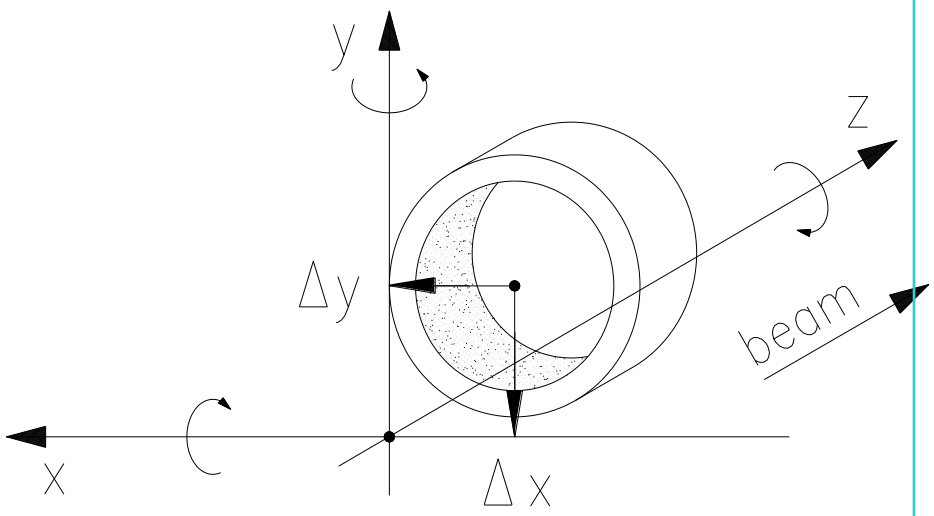


….as a results the booster bucket is uniformly filled (up+down) over 20 injection turns.

Effect of machine and beam errors

- Series of runs (1000-2000) with PATH or TRACEWIN (equivalent results), 50k particles for average quantities, 500k for loss maps.
- Statistical evaluation of beam losses, emittance growth and energy and phase jitter.
- Turn on the correction system for the worst cases (steering procedure as with a real accelerator).
- Add correcting elements/reduce the allowed errors until we reach :
  - Maximum average losses of 1 W/m at SPL duty cycle, 6%. This is dictated by shielding requirements.
  - Maximum longitudinal losses (un-accelerated particles) of 5%
  - Transverse emittance growth of 15-20% (at 2 sigma) with respect to the nominal case. This value is well within the emittance budget of the PS-Booster.
  - Energy jitter (1 sigma) at 160 MeV below ±100 keV (injection iinto the booster, energy paiting and transfer line acceptance)

Transverse Errors

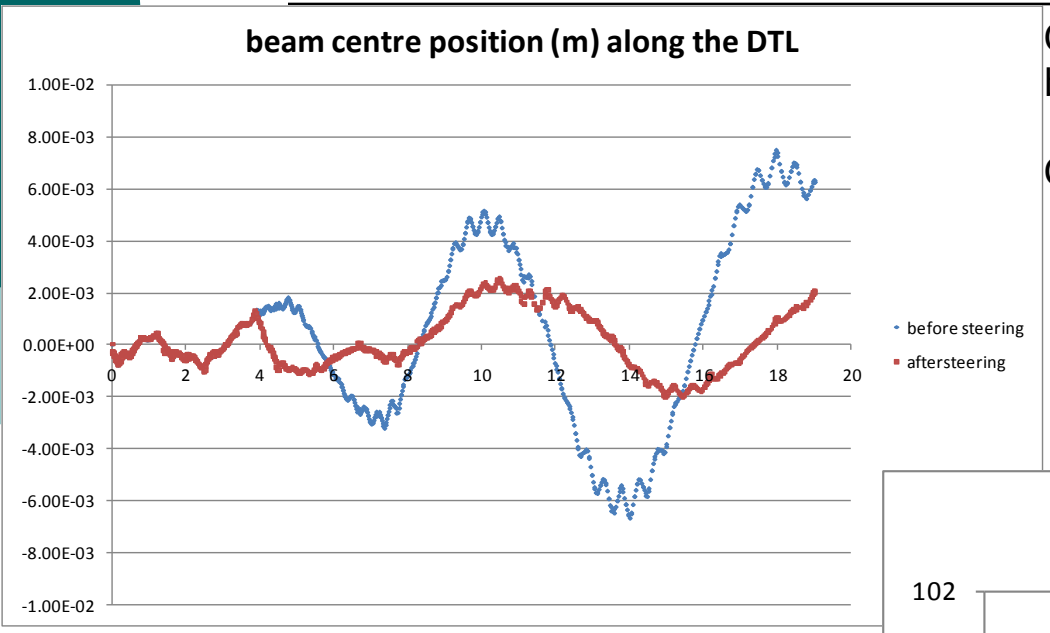


1) Beam position jitter (1σ): ±0.3mm ±0.3mrad
2) Quadrupole gradient (uni) : ±0.5%
3) Quadrupole alignment (1σ): ±0.1-0.2 mm , 0.2-0.5 deg.

Effects : losses and transverse emittance growth

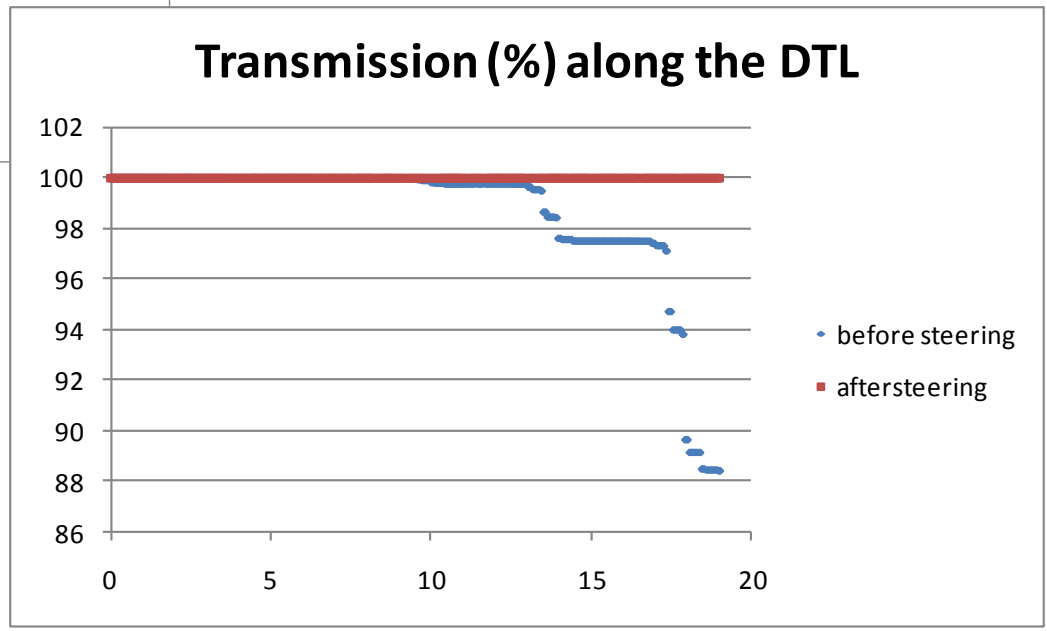
Definition of quadrupole errors :
Gradient errors[%] : they represent the deviation from the nominal field.
Transverse position errors [mm] : they represent the distance between the centre of the magnet and the ideal centre of the beam line in the two transverse planes.
Angle errors [deg] they represent the 3 angles between the ideal beam line reference and the system in which the magnet is a perfect quadrupole

Example DTL (3-50 MeV) - 19 m

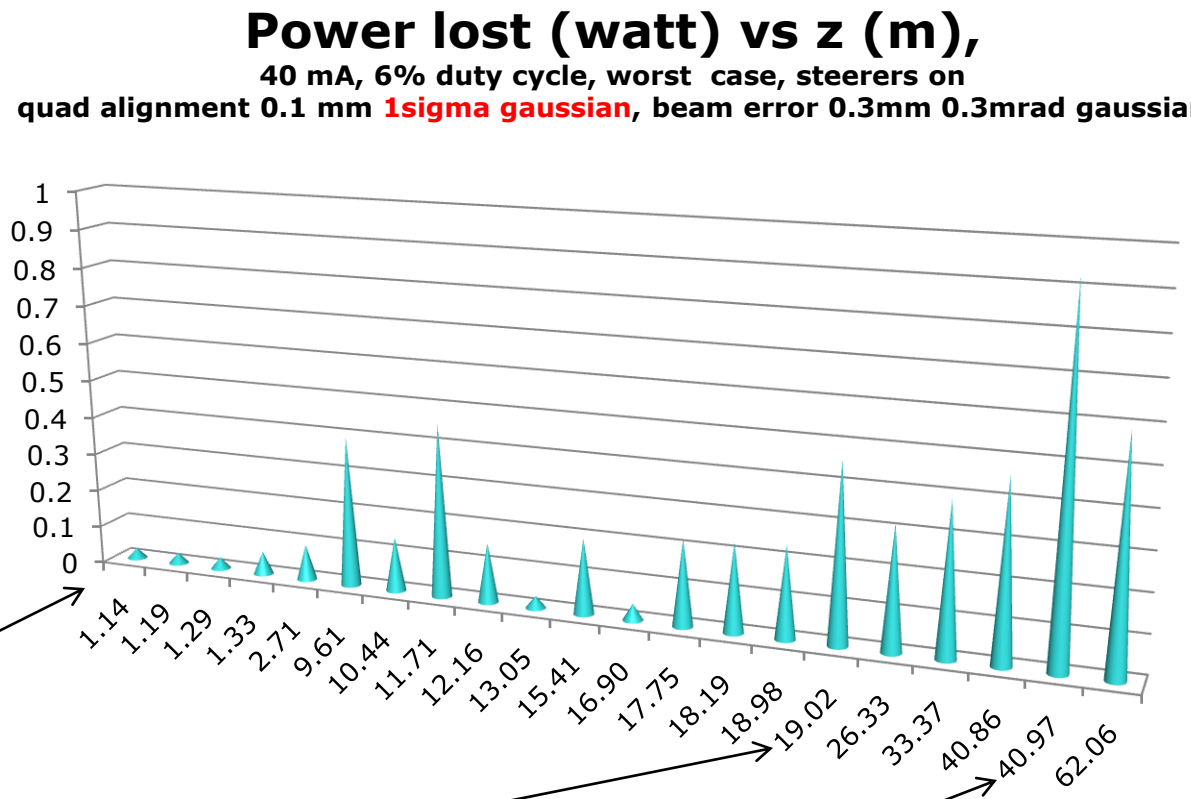


Quads errors (0.1 mm 1 sigma) and beam error (0.3 mm, 0.3 mrad 1sigma)

Correction system : two steerers



Loss map along the LINAC



DTL input (3MeV)

Transition DTL-CCDTL (50 MeV)

Transition CCDTL-PIMS (100MeV)

RF errors : static and dynamic

Jitter (dynamic)	"Gap" (static)
Klystron phase and amplitude errors;	Gap amplitude errors due to tuning and/or manufacturing imperfection;
Affects mostly beam energy and phase jitter;	Affects mostly longitudinal emittance;
Correlated over many gaps, cannot be cured.	Uncorrelated gap-to-gap; can be mitigated by increasing RF power above nominal.

DTL –klystron errors

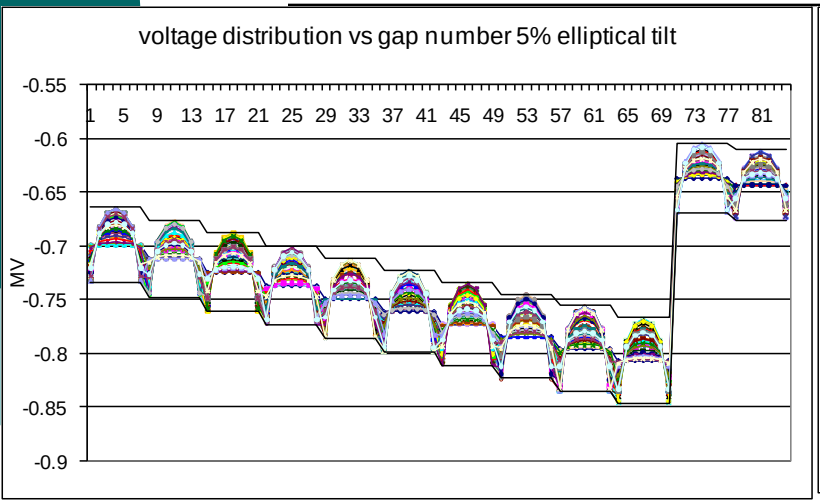
amplitude and phase	Phase jitter [deg] 1 sigma	Energy jitter [keV] 1 sigma	90% Emittance [deg MeV]	RMS Emittance [deg MeV]
nominal			0.734	0.167
0.5% and 0.5 deg	0.82	13	0.745±0.014	0.169±0.003
0.5% and 1 deg	0.88	18	0.751±0.017	0.171±0.004
0.5% and 2 deg	0.92	31	0.774±0.034	0.175±0.009
1% and 0.5 deg	1.6	23	0.7567±0.024	0.1707±0.005
1% and 1 deg	1.6	28	0.7621±0.027	0.1719±0.006
1% and 2 deg	1.83	36	0.78621±0.047	0.1772±0.011
2% and 0.5 deg	5.12	43	0.7940±0.07	0.179±0.014
2% and 1 deg	5.66	46	0.7986±0.07	0.180±0.017
2% and 2 deg	5.9	49	0.82998±0.1	0.187±0.024

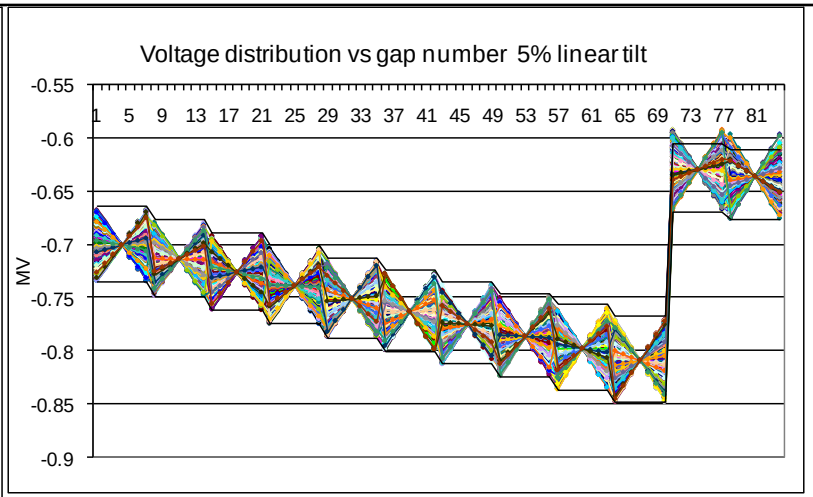
CCDTL – klystron errors

amplitude and phase	Phase jitter [deg] 1 sigma	Energy jitter [keV] 1 sigma	90% Emittance [deg MeV]	RMS Emittance [deg MeV]
nominal			0.769	0.196
0.5% and 0.5 deg	0.5	39	0.7713±0.013	0.196±0.003
1% and 1 deg	1	63	0.7732±0.018	0.196±0.005
2% and 2 deg	2	115	0.7801±0.030	0.198±0.009
5% and 2 deg	4	237	0.7939±0.047	0.200±0.015

Klystron phase and amplitude should be controlled ideally to 0.5% 0.5 deg to control energy and phase jitter at the CCDTL output. (1% and 1deg are still ok)

PIMS – gap errors





Elliptical (left) and linear (right) tilt inside each PIMS tank, Average =Nominal

±2%	Elong 90%,deg MeV (nominal=0.740	Elong RMS, deg MeV (nominal=0.180)
Elliptical tilt	0.744	0.181
Linear tilt	0.754	0.182
±5%		
Elliptical tilt	0.748	0.182
Linear tilt	0.757	0.182

Error budget and correction system

- Quadrupole alignment and gradient :
  - ±0.1 mm 1 sigma
  - ± 1 mrad 1 sigma
  - ±0.5% uniform on the nominal gradient
- Beam alignment :
  - ±0.3 mm
  - ±0.3 mrad

Can be tolerated with a correction system made of 15 H&V stereers and screens

- RF errors :
  - Klystron : ±0.5-1% amplitude , ±0.5-1 deg phase
  - Gap : amplitude of 2% in DTL and CCDTL and tilt of up to 5% in PIMS

Can be tolerated by adjusting the average field to the nominal value

Summary

- Nominal beam dynamics has been calculated with 2 independent codes and both indicate satisfactory beam performance.
- An error budget for the alignment , gradients, RF phase and amplitude has been established.
- The location of the losses and the main causes of emittance growth have been identified.
- Collimation doesn't seem to be necessary for low duty cycle operation. Space (minimal..) has been left for adding collimators later. Collimation in the transfer line to the booster could be implemented if needed.
- The settings could be further optimised when measurements of the source beam will be available.