ESS DTL

beam dynamics & RF re-design

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DTL Design Parameters

- Energy from **3.62** to **89.91** MeV in **5** tanks.
- Total DTL length: **37.83** m (including intertanks).
- Accelerating field, E_0, constant in each tank [(**3.00**, **3.16**, **3.07**, **3.04**, **3.13**) MV/m].
- Peak electric field threshold:
  - lowered to **1.2** Kilp. in the cell **1**.
  - ramped from **1.2** Kilp. to **1.55** Kilp. in the first **20** cells of the tank **1**;
  - equal and constant to **1.55** Kilp. elsewhere.
- Maximum module (subtank) length equal to **2** m.
- PMQs in vacuum. PMQ diam. = **60** mm, lengths = **45** mm and **80** mm.
- Input RMS Emittance: Trans./Long. = **0.28**/**0.36** mm×mrad (**0.1436** π deg MeV).
- F0D0 PMQ Lattice.
- Power:
  - 1 klystron of **2.8** MW per tank, duty cycle = **4**% .
  - Power at RF tank input = **2.20** MW (**30**% margin for WG losses and LLRF).
  - **2.20** MW > P_{copper} × **1.25** + P_{beam} (I_{beam} = **62.5** mA, **1.25** margin on MDTfish computation).
  - **2** power couplers per tank, Peak power = **1.1** MW each.

DTL Layout

Parameter / Tank	**1**	**2**	**3**	**4**	**5**
Cells per cavity	61	34	29	26	23
Accelerating field [MV/m]	3.00	3.16	3.07	3.04	3.13
Maximum surface field [Kilp.]	1.55	1.55	1.55	1.55	1.55
Synchronous phase [deg]	-35 to -25.5	-25.5	-25.5	-25.5	-25.5
Total power per cavity* [KW]	2192	2191	2196	2189	2195
Power on copper** [KW]	870	862	872	901	952
Quadrupole length [mm]	50	80	80	80	80
Bore Radius [mm]	10	11	11	12	12
Number of modules	4	4	4	4	4
Length [m]	7.62	7.09	7.58	7.85	7.69
Beam output power [MeV]	21.29	39.11	56.81	73.83	**89.91**

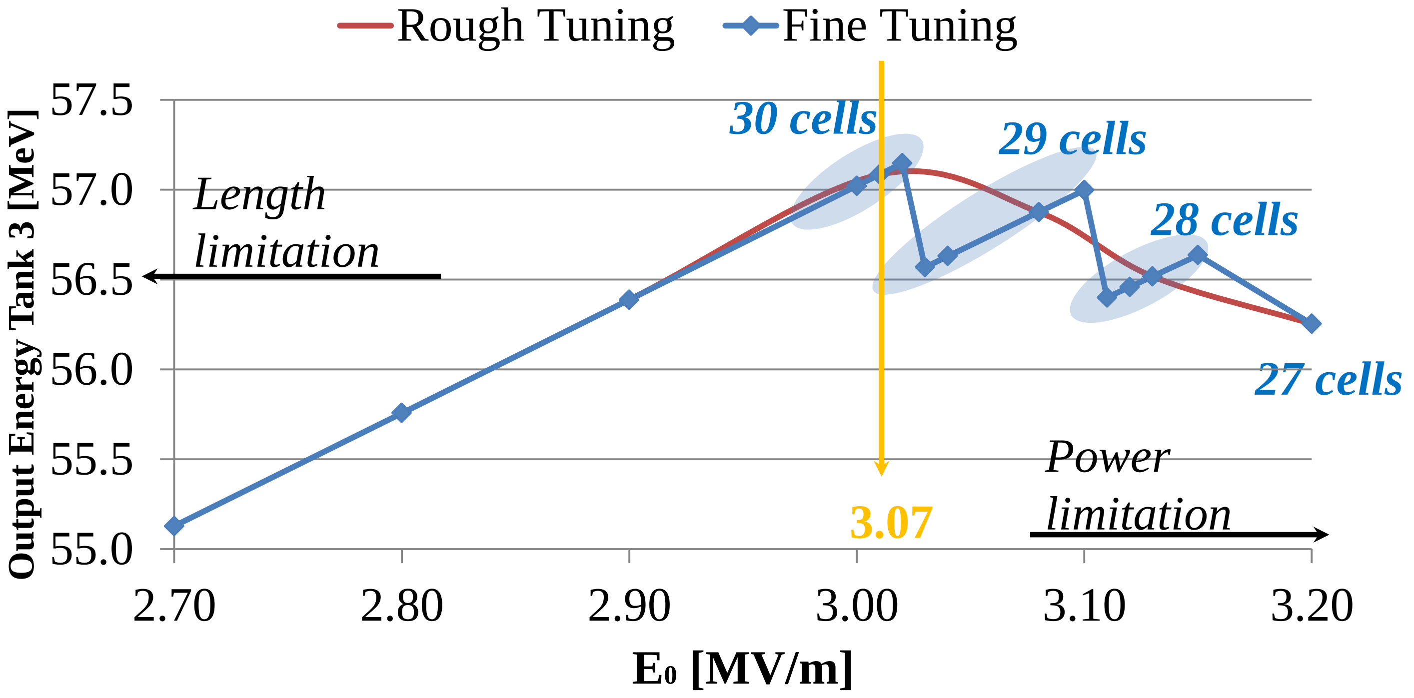
* Total power = 1.25 × Power on copper + Beam Power.

** MDTfish calculation.

Optimum E_0 (i.e. Tank 3)

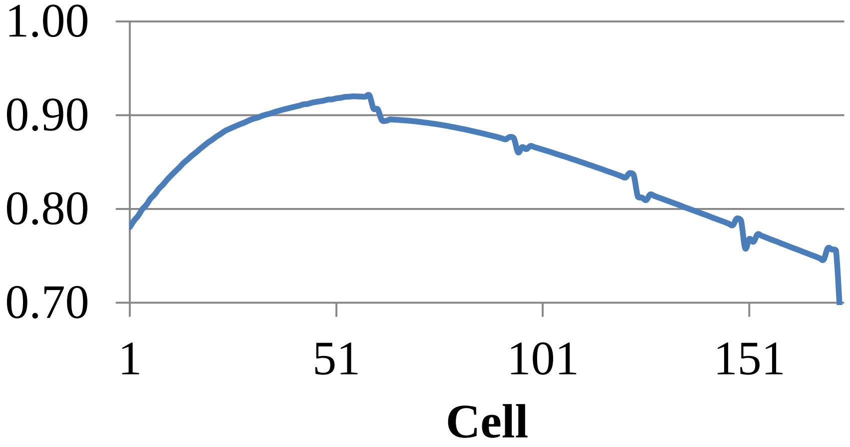
1. Calculation of the ***output energy*** and the ***maximum cell number*** as function of the E_0 (rough tuning - moving on red curve: red curve is drawn by using just one point for each blue ellipse);
2. choice of the ***cell number*** that maximizes the output energy (choice a blue ellipse);
3. tuning on ***E_0*** to reach the maximum desired total power, **2.2** MW, (fine tuning – moving, in the chosen blue ellipse, on the blue curve).

<<< E_0 optimization provides ≈ 0.5 MeV/tank >>>

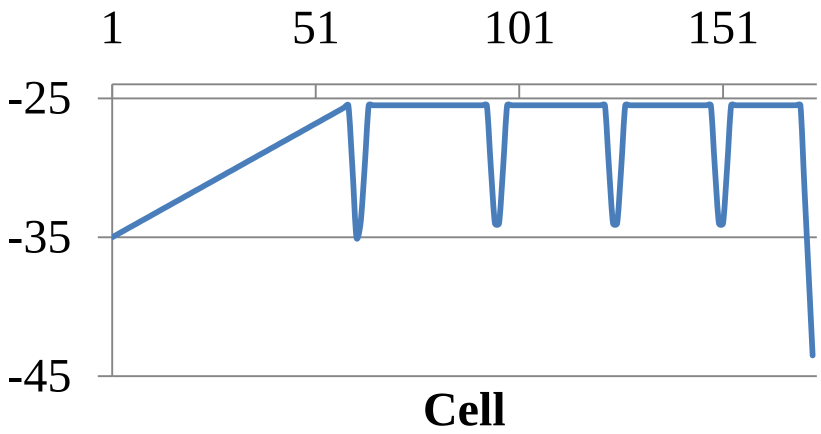


DTL Main Figures of Merit

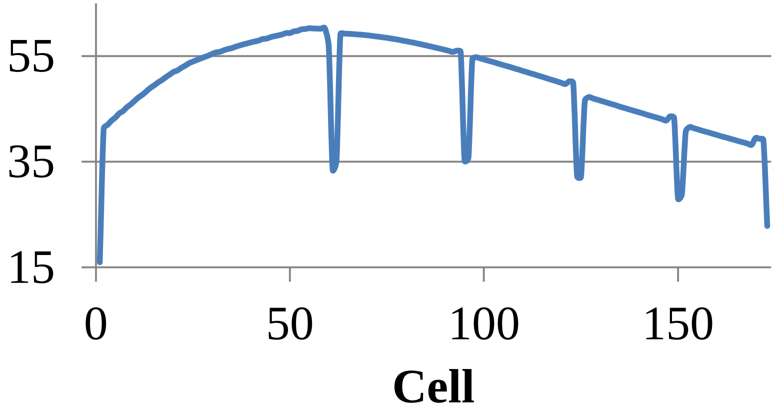
TTF

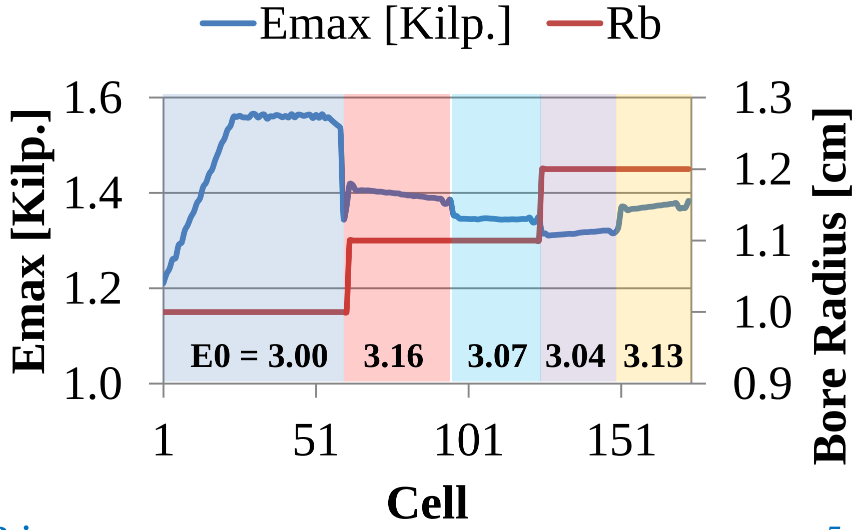


Sync. Phase [deg]

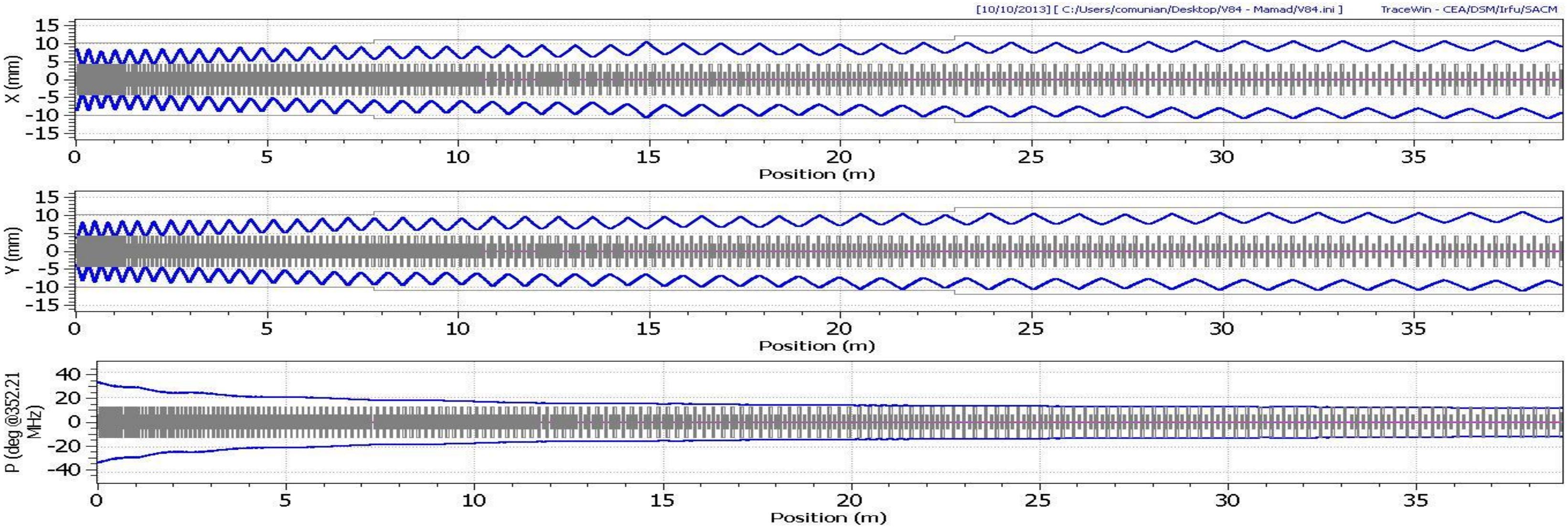


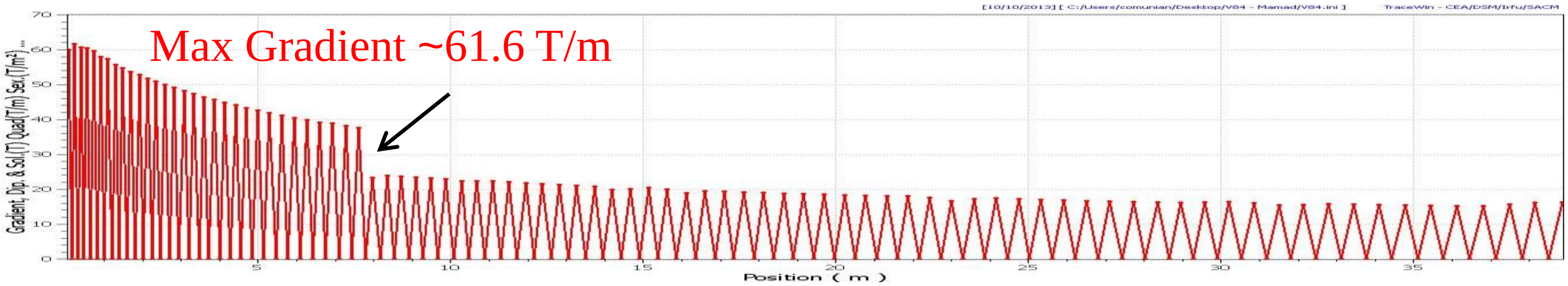
ZTT [MΩ/m]





Focusing Scheme F0D0



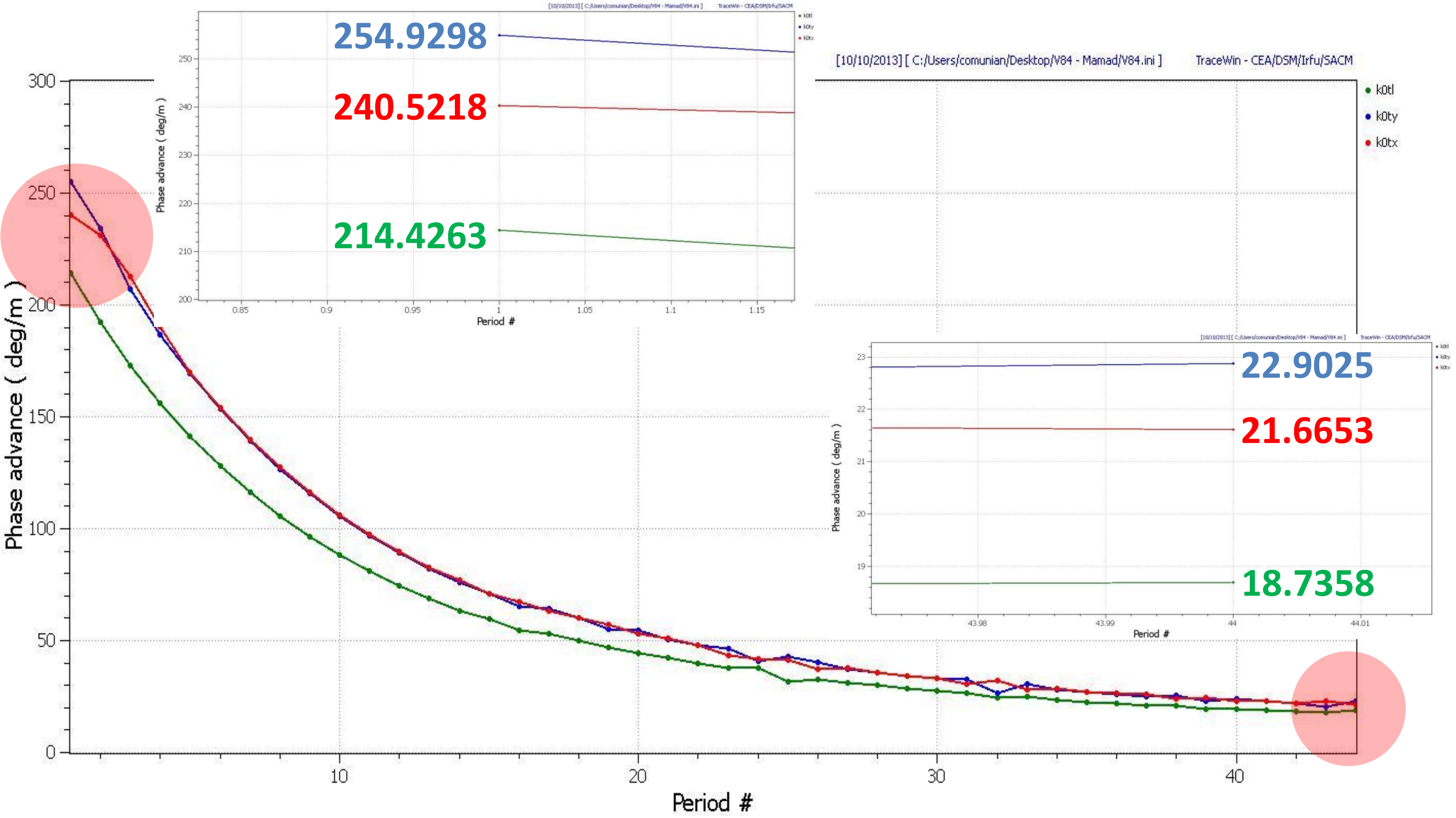


Max Gradient ~61.6 T/m

Intertank Space equal to 1 βλ (min required 150 mm).

Intertank	1/2	2/3	3/4	4/5
Length [mm]	178.30	238.37	283.48	319.16

Phase Advance at Zero Current



254.9298

240.5218

214.4263

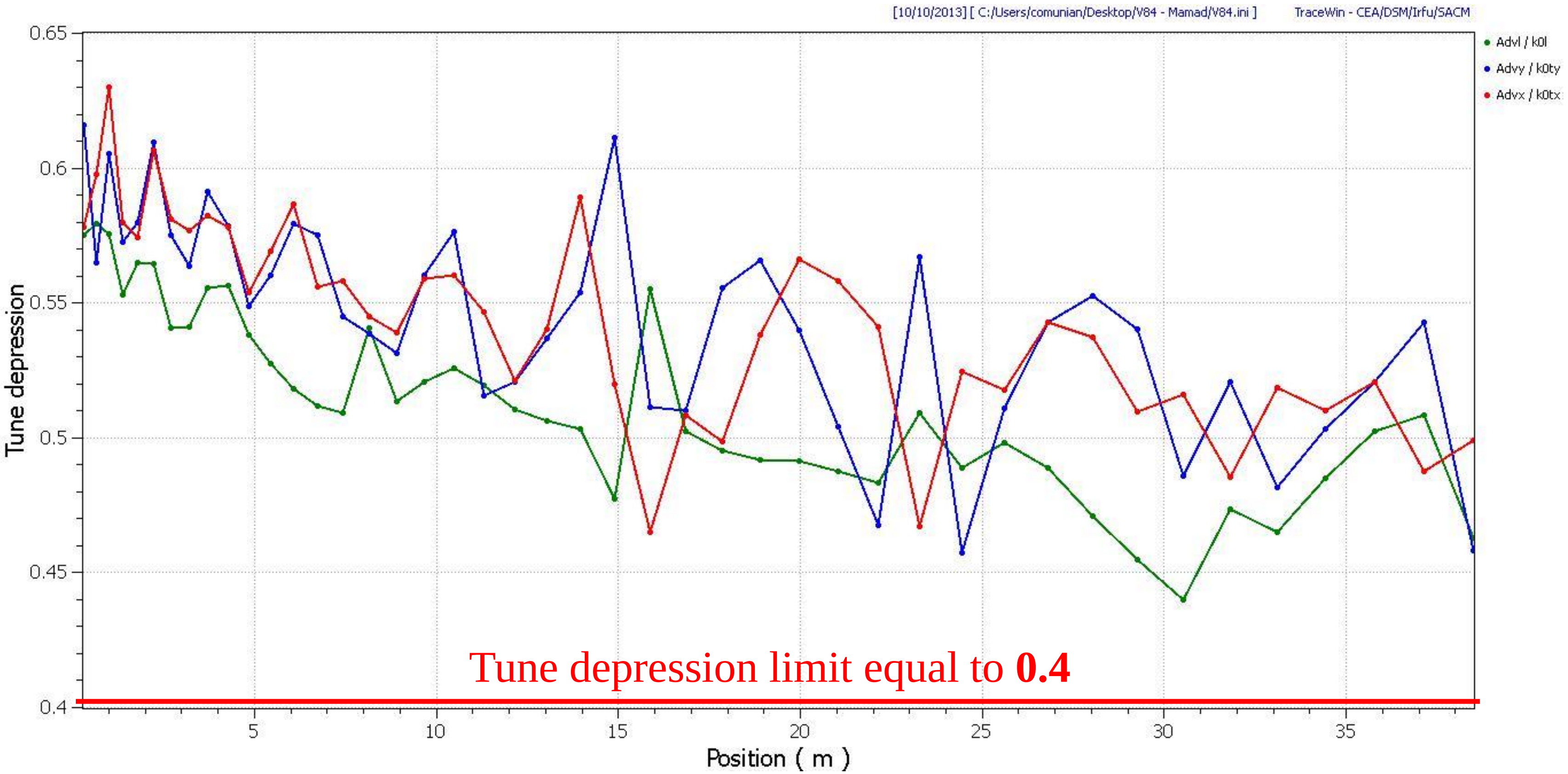
22.9025

21.6653

18.7358

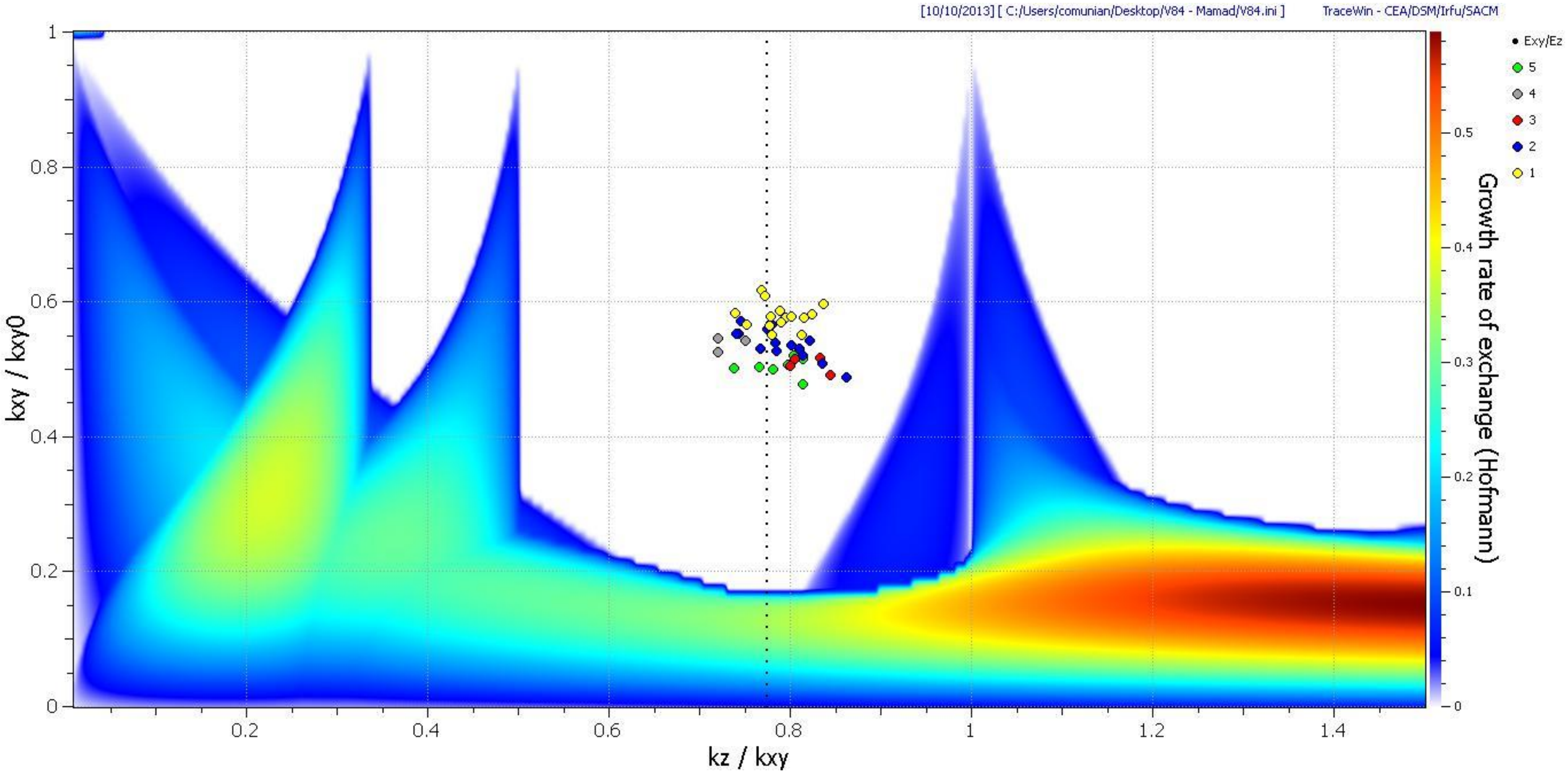
Tune Depression

A “measure” of the sensitivity to mismatch.



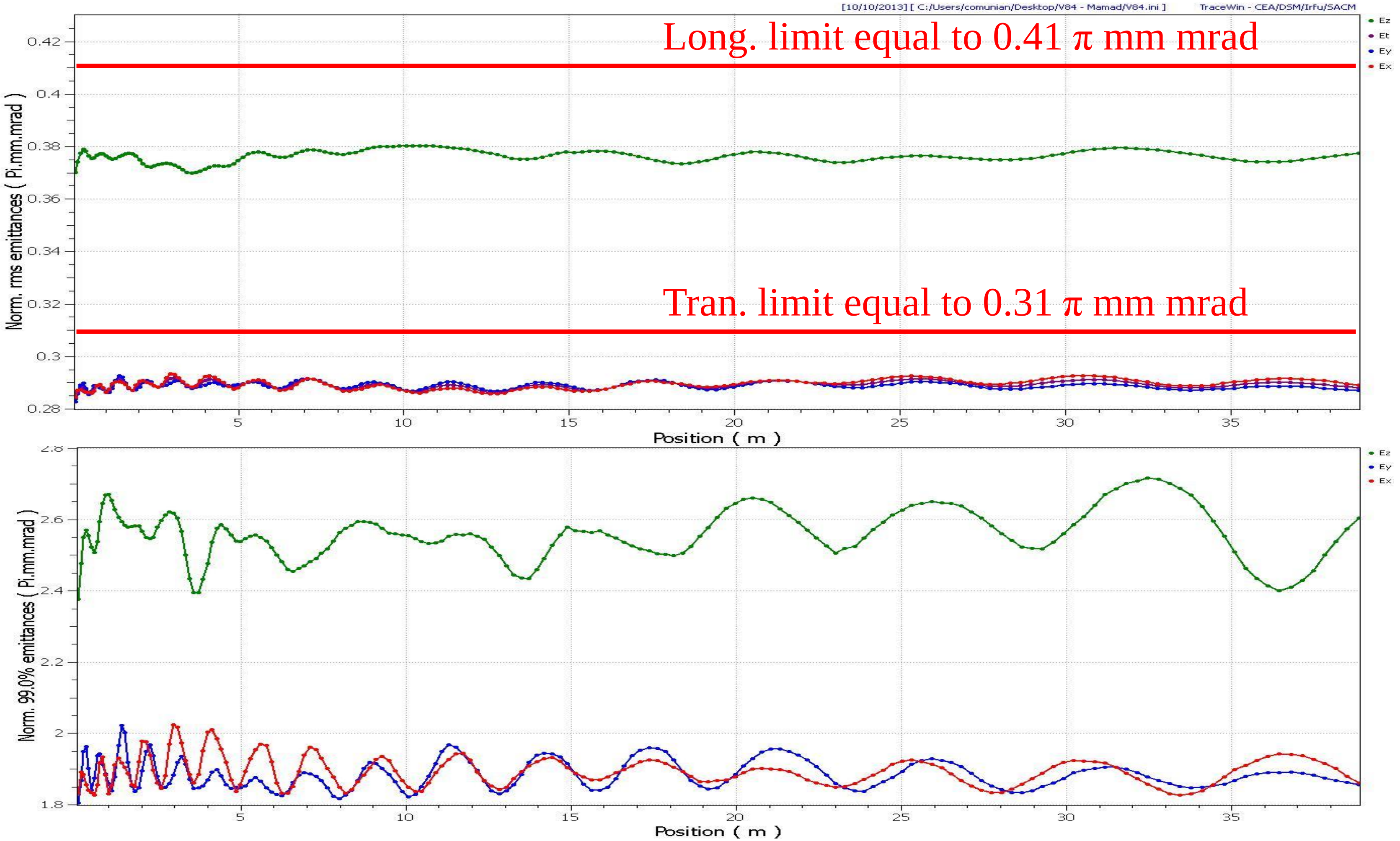
Tune depression limit equal to **0.4**

Hofmann resonance diagram



RMS Emittance

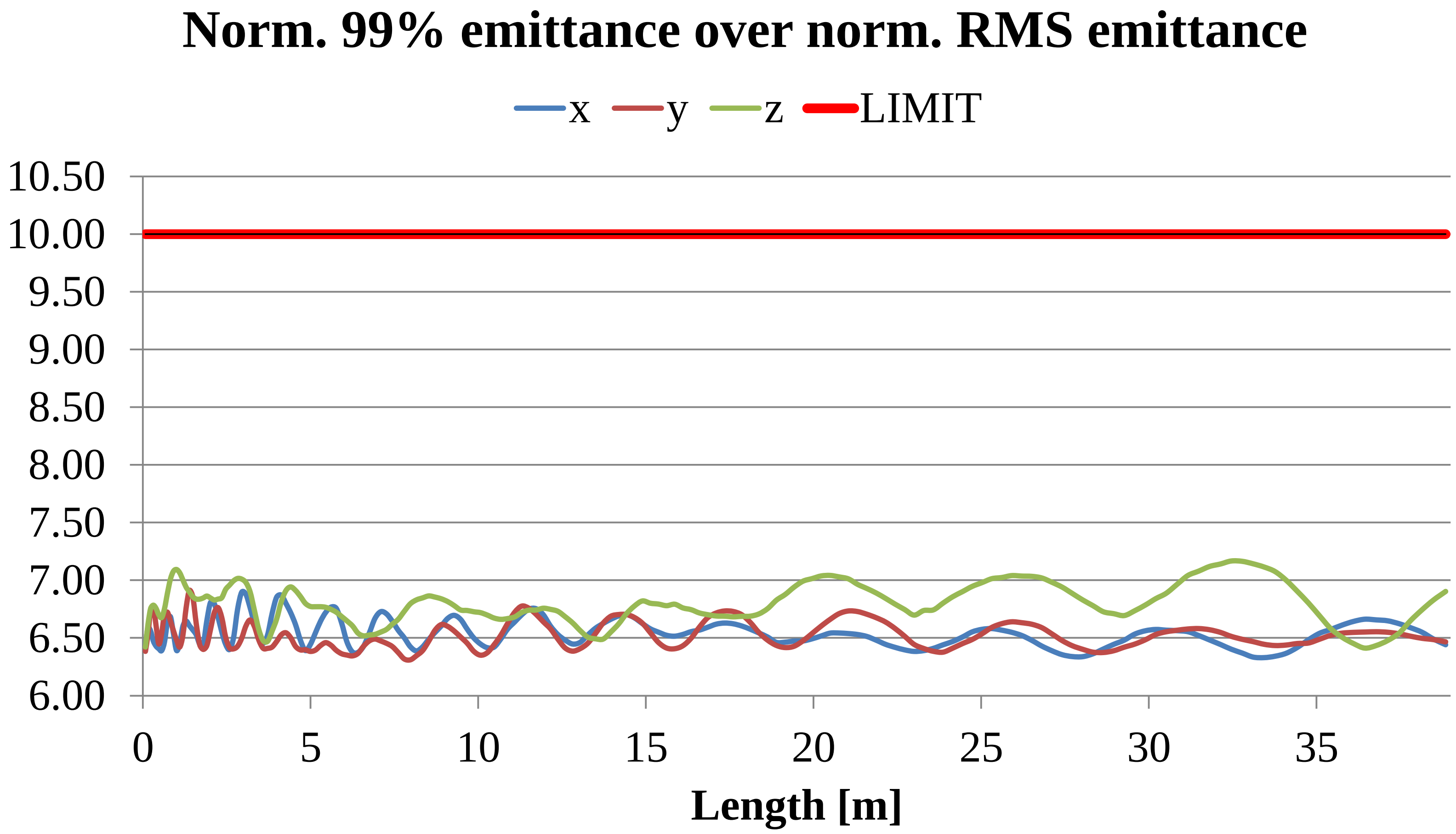
RMS tran. and long. emittance increasing less than 10%.


Long. limit equal to 0.41 π mm mrad

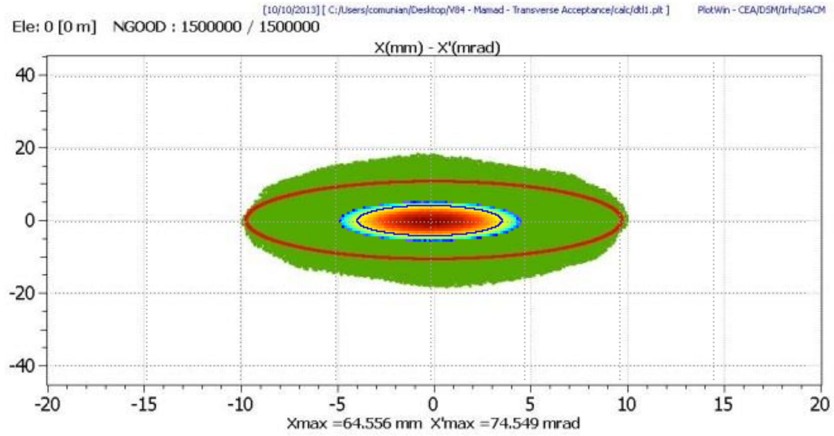
Tran. limit equal to 0.31 π mm mrad

99% Emittance

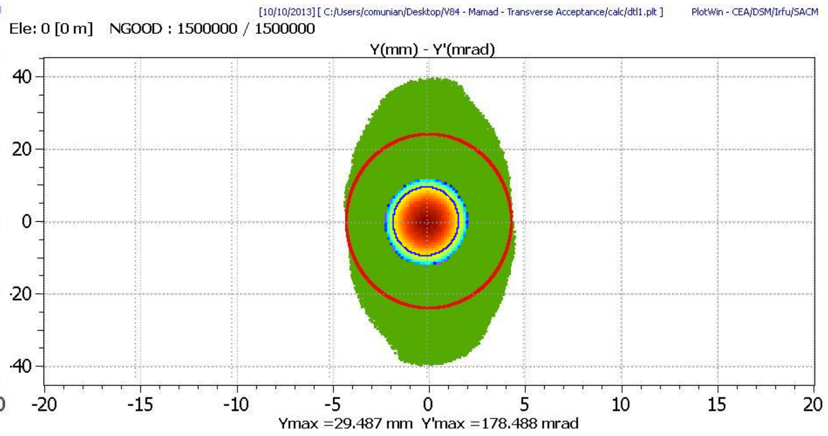
Norm. 99% emittance over norm. RMS emittance less than 10 to limit halo.



Acceptance



εx ~9.1 π mm mrad

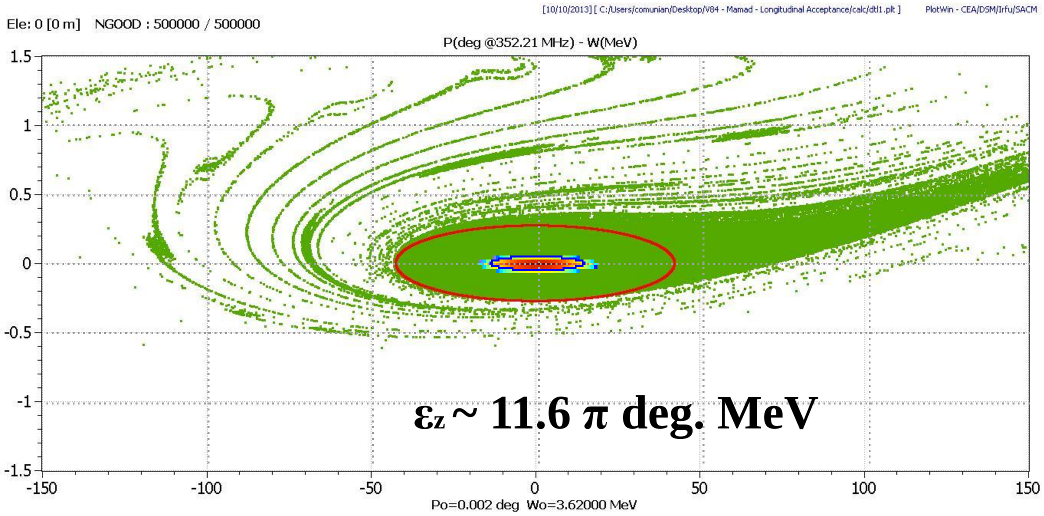


εy ~ 9.1 π mm mrad

$$\frac{\varepsilon_{x,y}}{\varepsilon_{RMS}} \sim \frac{9.1}{0.28} \sim 5.7^2$$

Zero losses at **5.7** σ

(σ means RMS beam size).



εz ~ 11.6 π deg. MeV

Error Study on PMQ

Analysis done by introducing statistical errors on the PMQ transverse displacement (max **0.2** mm) and rotation (max **1**°), longitudinal rotation (max **1**°), gradient (max **1**% of the gradient amplitude).

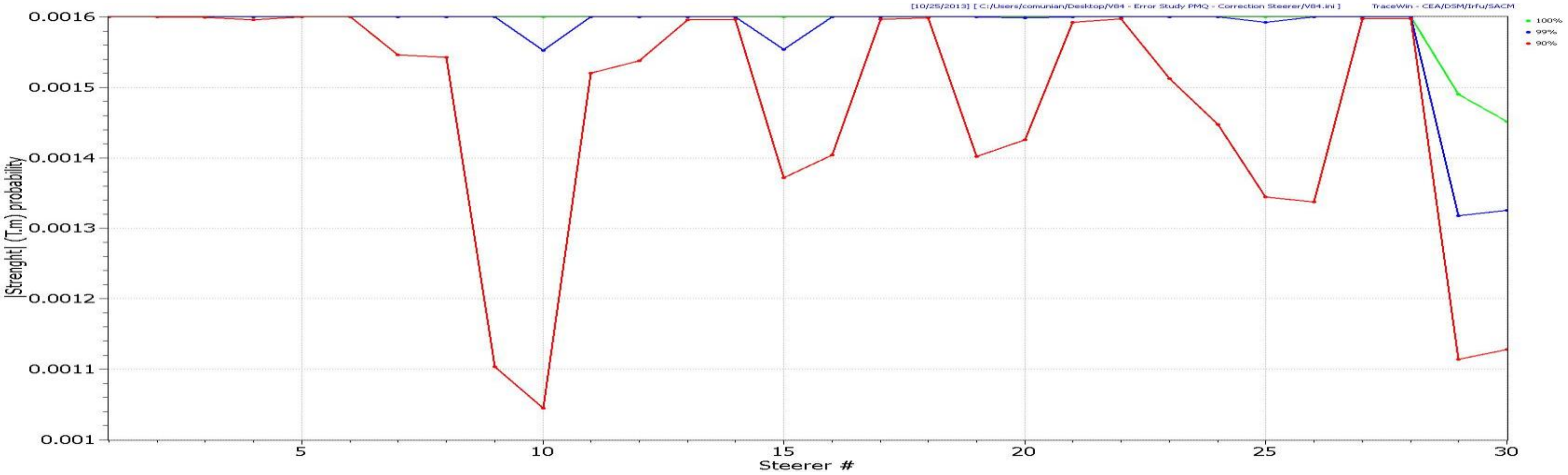
- Number of steps equal to 20 to sample the error range.
- Number of DTLs per step equal to 400.

- Error uniformly distributed in the error range.
- Error individually applied on each element.
- Included halo distribution, cut at 3σ, into input distribution.
- Number of the input particles equal to $\mathbf{5 \times 10^{5}}$ (~**0.5** W per particle at **90** MeV) with uniform distribution.
- 0.6% of the beam into the halo (~**1.3**KW in the halo).

Steerer

- Steerers placed in the empty space of the FODO lattice.
- 3 steerers per tank per plane.
- Max steerer strength equal to ± **1.6** mT m.
- 3 beam position monitors per tank with the accuracy equal to **0.1** mm.

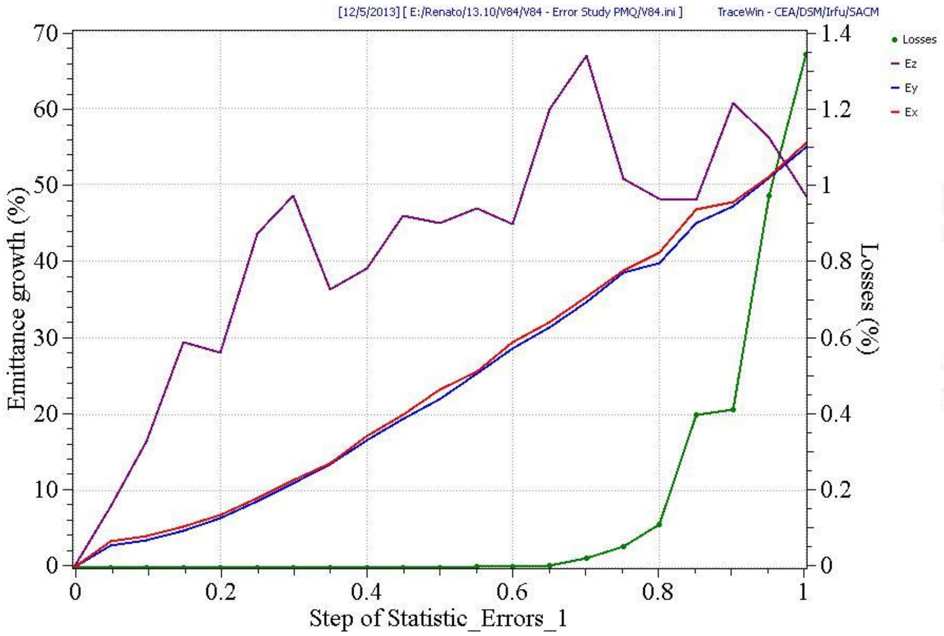
Element / Tank	T1	T1	T1	T2	T2	T2	T3	T3	T3	T4	T4	T4	T5	T5	T5
Steerer X [#]	6	20	36	75	85	95	119	127	135	157	163	169	192	198	204
Steerer Y [#]	9	23	39	78	88	98	122	130	138	160	166	172	195	201	207
BPM [#]	58	63	68	102	107	112	141	146	151	177	182	187	210	215	220



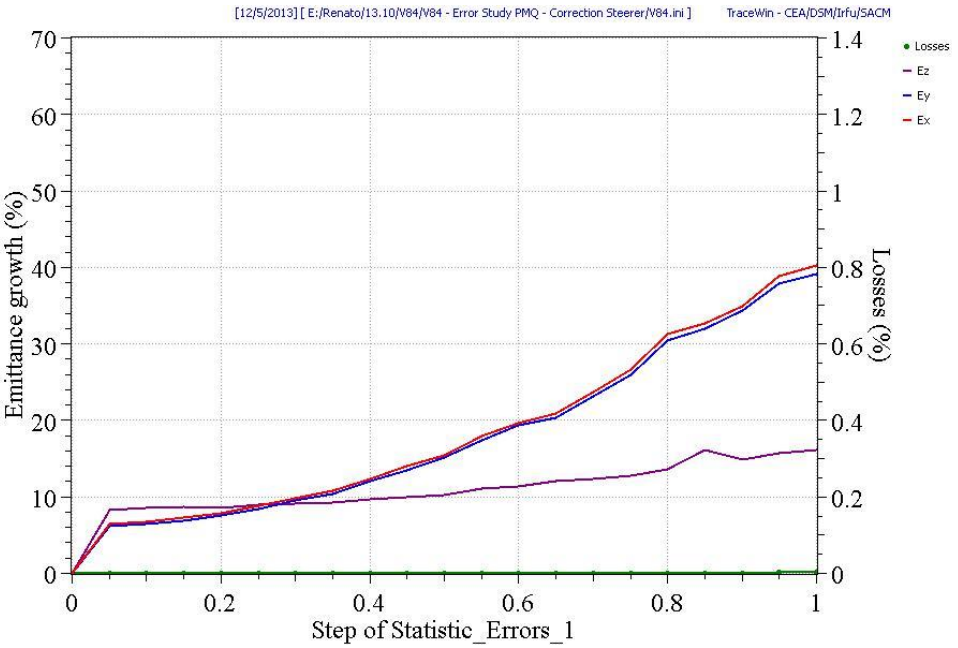
Error on PMQ position and gradient

Statistical errors on PMQ transverse displacement (1≡ ± **0.2** mm) and rotation (1≡ ±**1**°), longitudinal rotation (1≡ ±**1**°), gradient (1≡ ±**1**% of the gradient amplitude).

No steerer correction



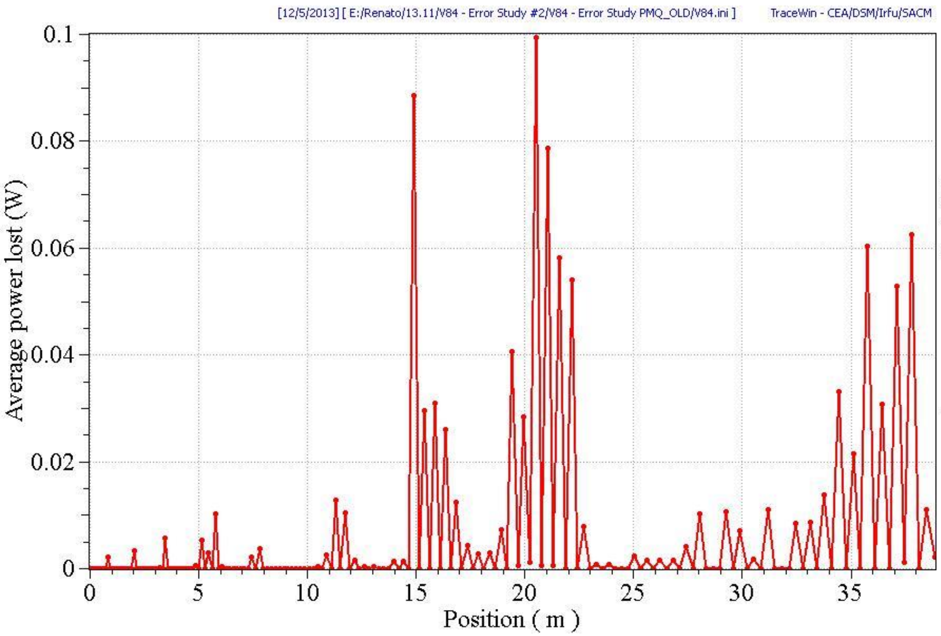
With steerer correction



Average Power Lost

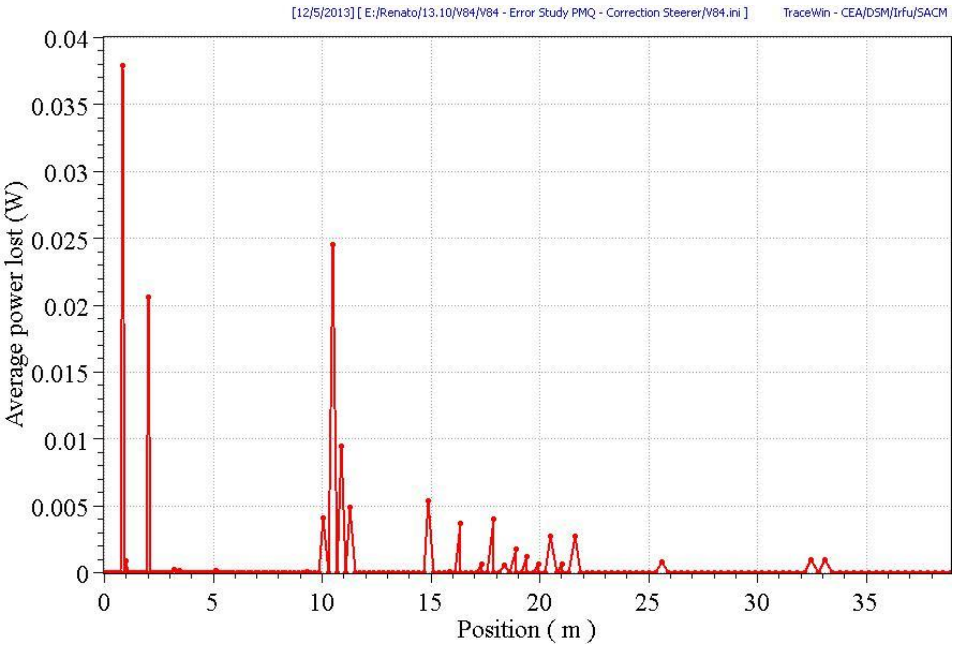
- Transverse PMQ displacement error (dx, dy) max **0.1** mm;
- PMQ rotation error (φ_x, φ_y, φ_z) max **0.5**°;
- PMQ gradient error (dg) max **0.5**% of the gradient amplitude.

No steerer correction



Total losses ~ **1.00** W
(over **30** MeV, after **11** m, total loss ~ **0.96** W).

With steerer correction

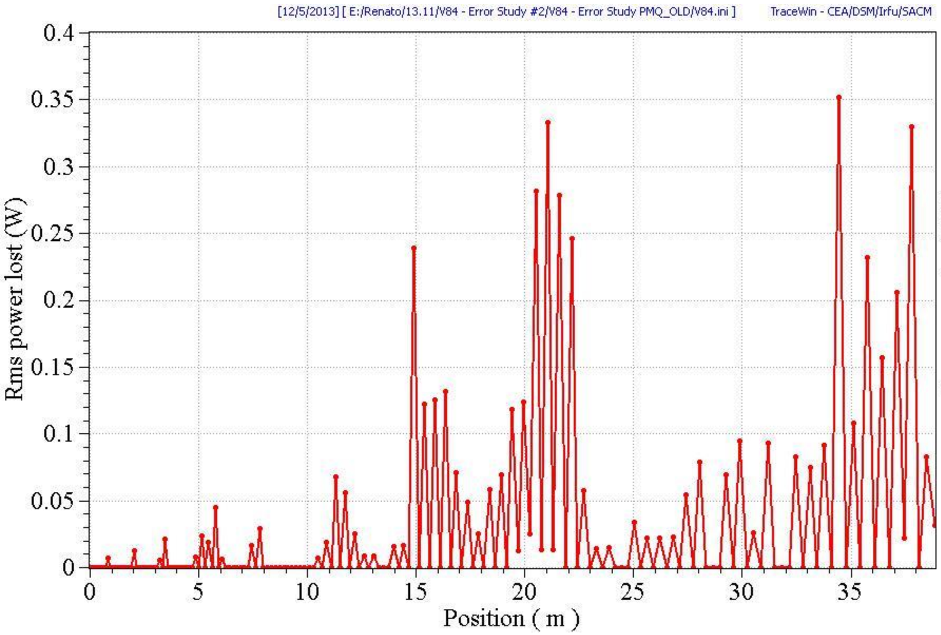


Total losses ~ **0.13** W
(over **30** MeV, after **11** m, total loss ~ **0.03** W).

RMS Power Lost

- Transverse PMQ displacement error (dx, dy) max **0.1** mm;
- PMQ rotation error (φ_x, φ_y, φ_z) max **0.5**°;
- PMQ gradient error (dg) max **0.5**% of the gradient amplitude.

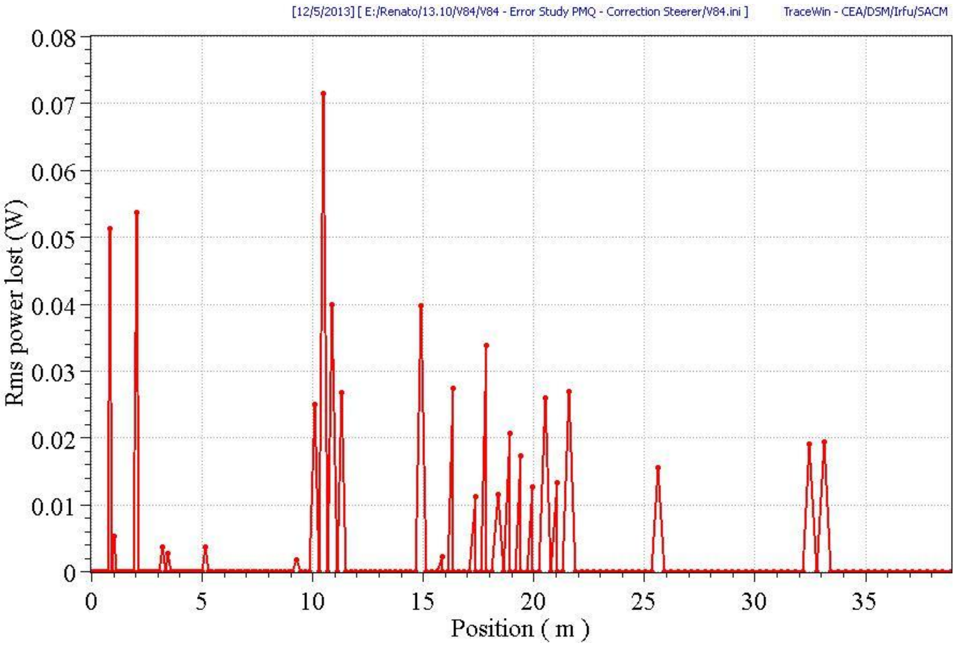
No steerer correction



Total losses ~ **5.1** W

(over **30** MeV, after **11** m, total loss ~ **4.7** W).

With steerer correction



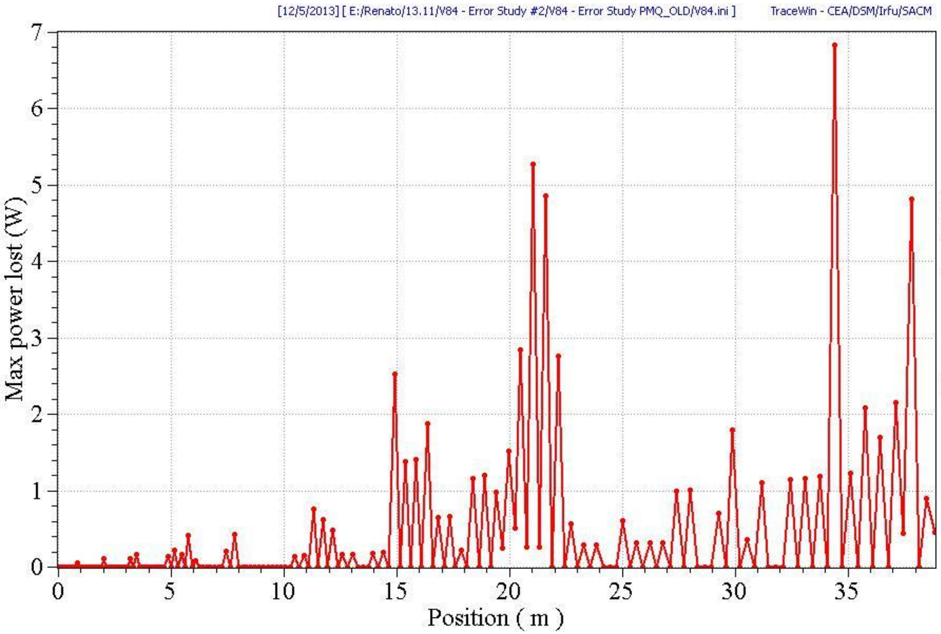
Total losses ~ **0.6** W

(over **30** MeV, after **11** m, total loss ~ **0.3** W).

Max Power Lost

- Transverse PMQ displacement error (dx, dy) max **0.1** mm;
- PMQ rotation error (φ_x, φ_y, φ_z) max **0.5**°;
- PMQ gradient error (dg) max **0.5**% of the gradient amplitude.

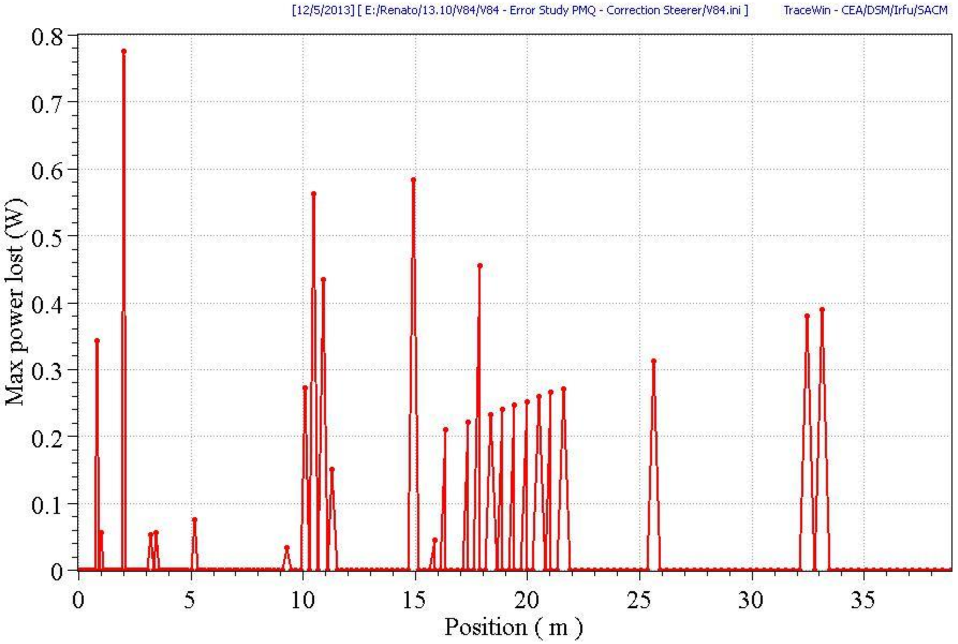
No steerer correction



Total losses ~ **68.4** W

(over **30** MeV, after **11** m, total loss ~ **66.0** W).

With steerer correction



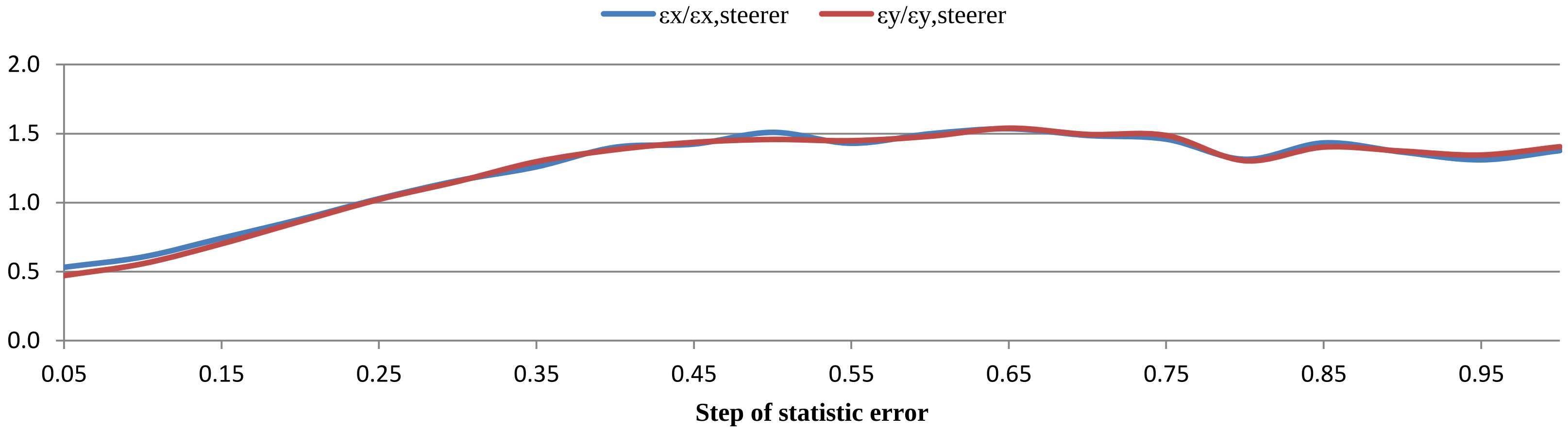
Total losses ~ **7.2** W

(over **30** MeV, after **11** m, total loss ~ **4.5** W).

Comparison WITH / WITHOUT Steerers

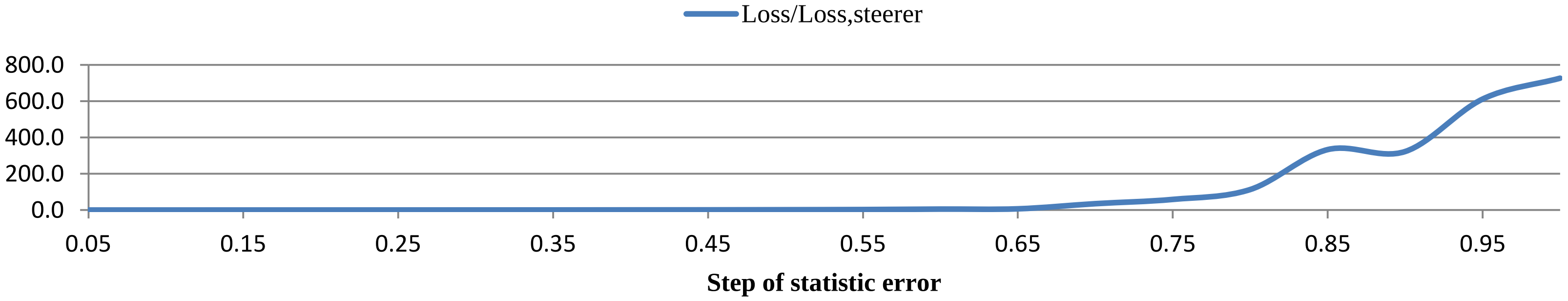
Total losses at half max errors **without** steeres ~ **68.4** W. Total losses at half max errors **with** steerers ~ **7.2** W.

ε-growth / ε-growth with steerers



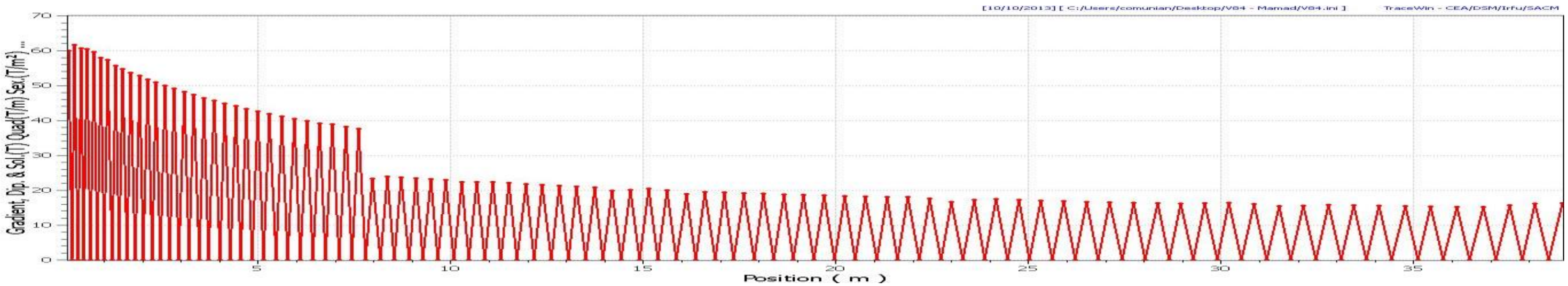
Losses / Losses with steerers

1≡max errors



3 Questions

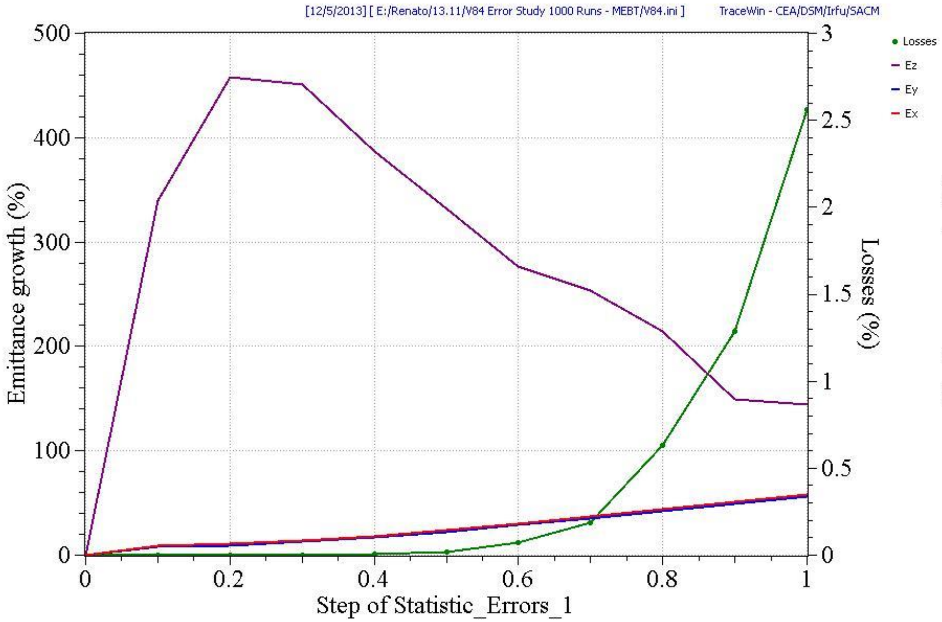
1. Is the DTL performance good even if there is a "realistic" (MEBT output as DTL input) particle distribution?
2. Is it useful to have larger beam apertures after the tank 1?
3. Is it possible to use "constant gradient" PMQ in the later tanks?



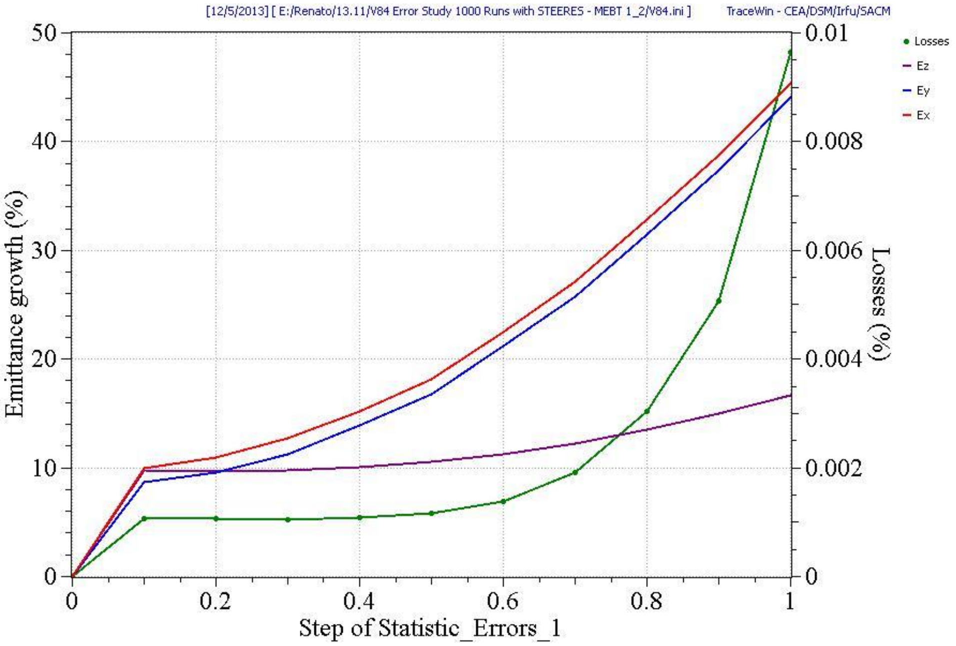
MEBT output as DTL input
Error on PMQ position and gradient

Statistical errors on PMQ transverse displacement (1≡ ± **0.2** mm) and rotation (1≡ ±**1**°), longitudinal rotation (1≡ ±**1**°), gradient (1≡ ±**1**% of the gradient amplitude).

No steerer correction



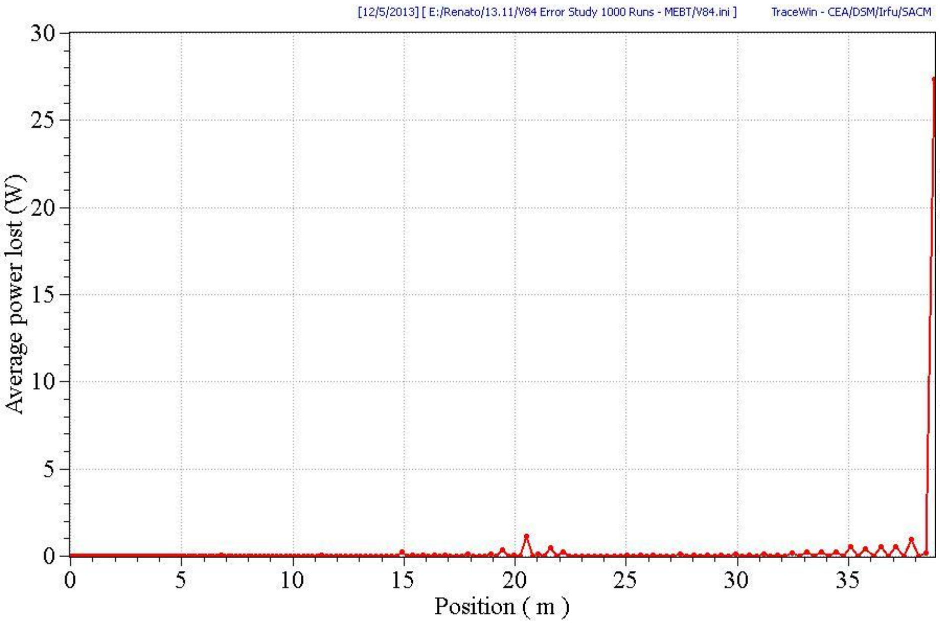
With steerer correction



MEBT output as DTL input
Average Power Lost

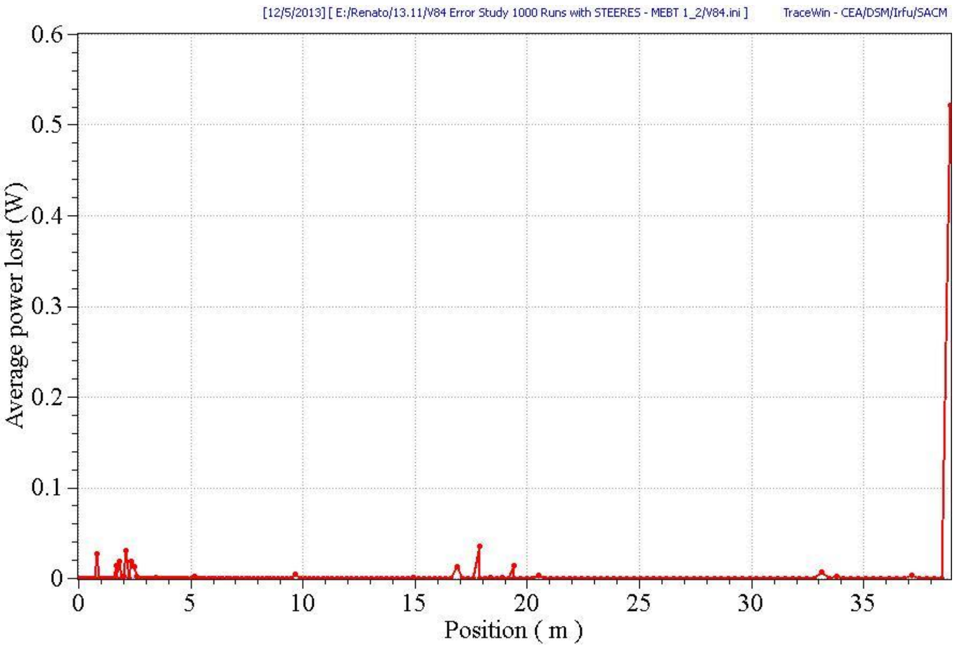
- Transverse PMQ displacement error (dx, dy) max **0.1** mm;
- PMQ rotation error (φ_x, φ_y, φ_z) max **0.5**°;
- PMQ gradient error (dg) max **0.5**% of the gradient amplitude.

No steerer correction



Total losses ~ **35.97** W
(over **30** MeV, after **11** m, ~ **35.77** W).

With steerer correction

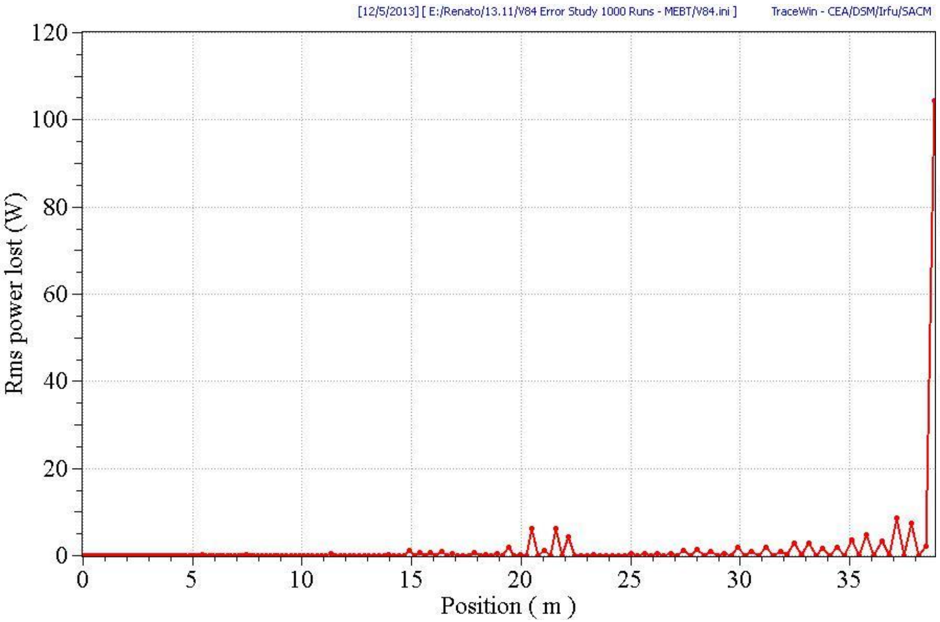


Total losses ~ **0.74** W
(over **30** MeV, after **11** m, ~ **0.61** W).

MEBT output as DTL input RMS Power Lost

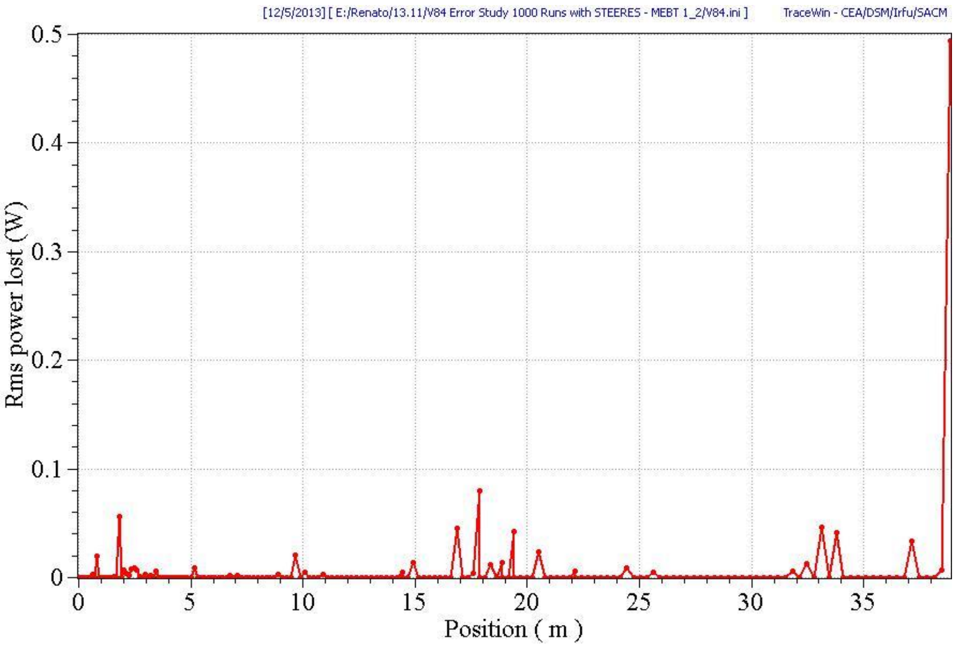
- Transverse PMQ displacement error (dx, dy) max **0.1** mm;
- PMQ rotation error (φ_x, φ_y, φ_z) max **0.5**°;
- PMQ gradient error (dg) max **0.5**% of the gradient amplitude.

No steerer correction



Total losses ~ **184.11** W
(over **30** MeV, after **11** m, ~ **183.01** W).

With steerer correction

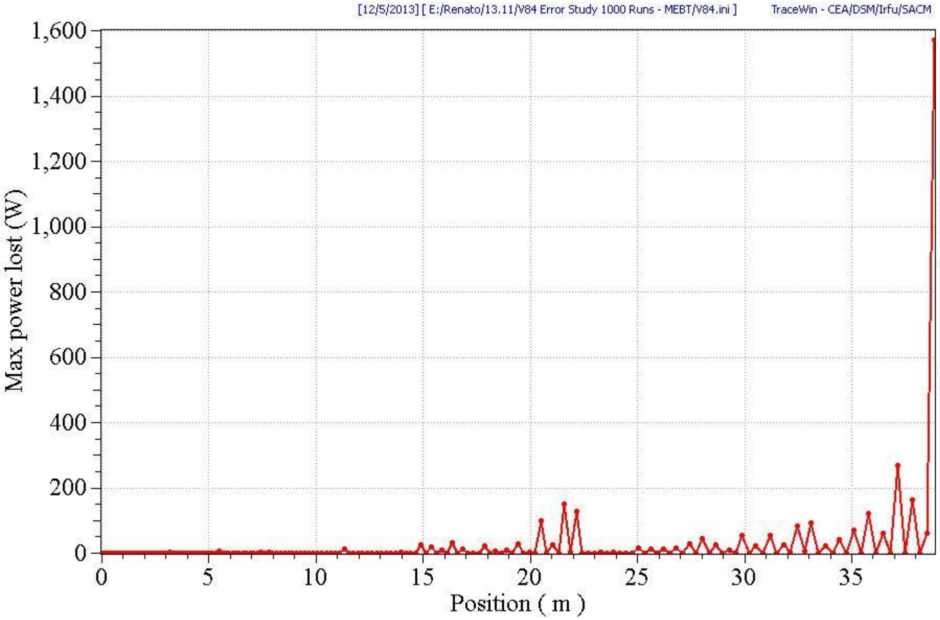


Total losses ~ **1.07** W
(over **30** MeV, after **11** m, ~ **0.90** W).

MEBT output as DTL input
Max Power Lost

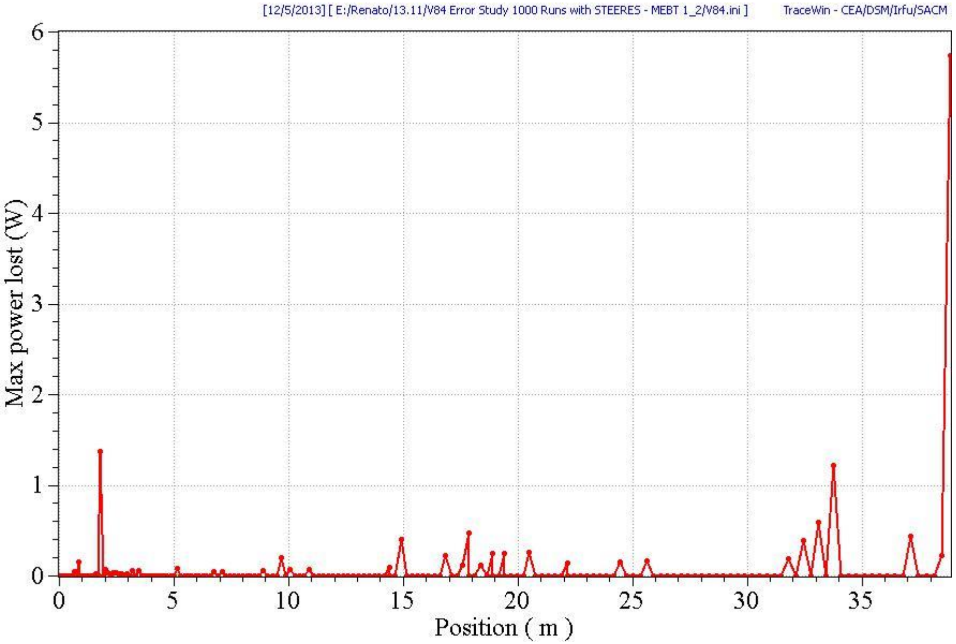
- Transverse PMQ displacement error (dx, dy) max **0.1** mm;
- PMQ rotation error (φ_x, φ_y, φ_z) max **0.5**°;
- PMQ gradient error (dg) max **0.5**% of the gradient amplitude.

No steerer correction



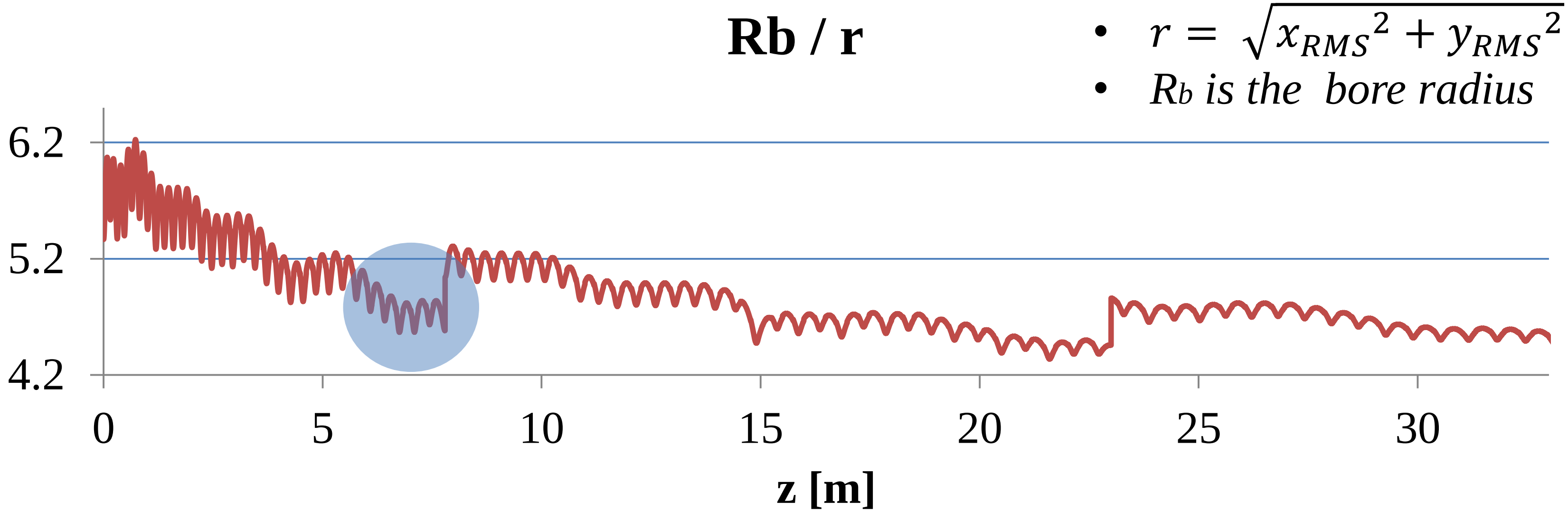
Total losses ~ **3520.02** W.

With steerer correction



Total losses ~ **14.01** W
(over **30** MeV, after **11** m, ~ **11.45** W).

Larger Beam Aperture after Tank 1



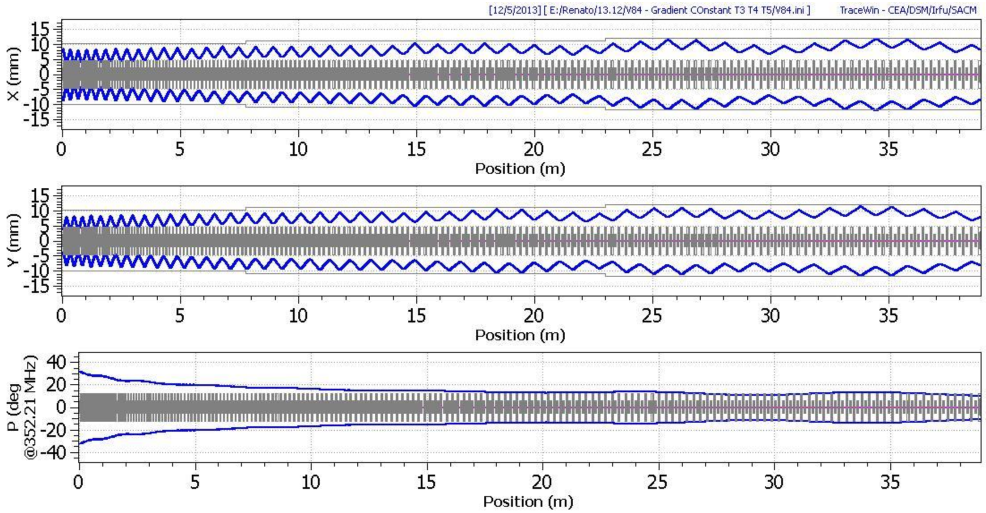
- $r = \sqrt{x_{RMS}^2 + y_{RMS}^2}$
- *R_b is the bore radius*

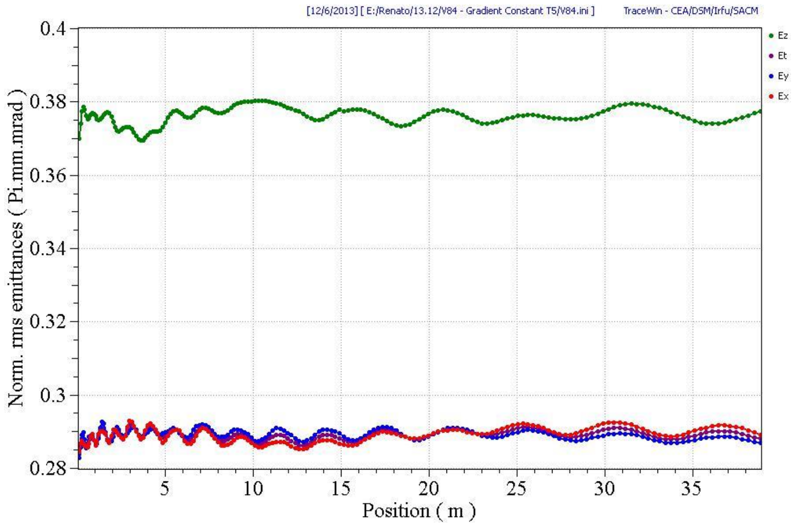
- In the tank 1 is not convenient to increase the bore radius to keep potential beam scraping (most of all at the end of the tank, blue circle);
- In the tank 2 it is not convenient to increase the bore radius, in fact:

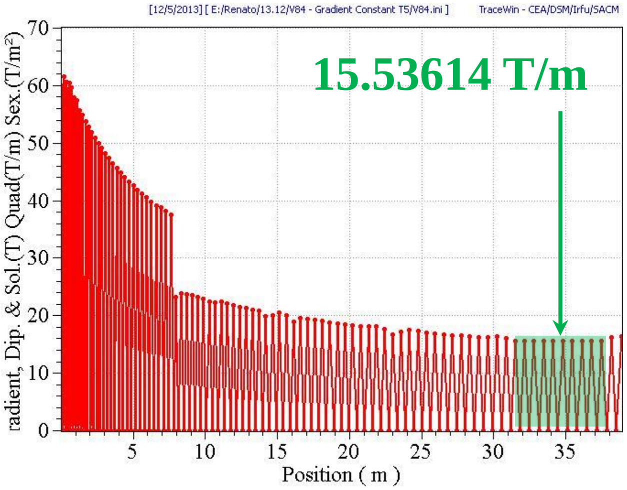
R_b [cm]	ΔZTT [%] respect to the nominal case (R_b = ***1.1** cm*)
1.2	**-0.63**
1.3	**-1.22**
1.4	**-1.45**

- In the tank 3,4 and 5 larger beam apertures don’t decrease the ZTT.

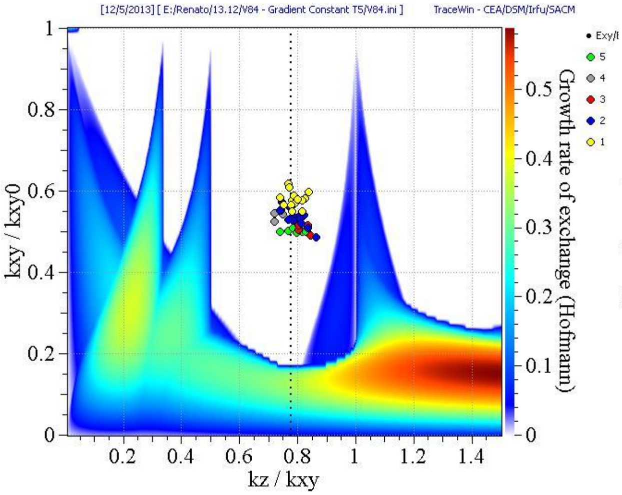
PMQ Constant Gradient Tank 5

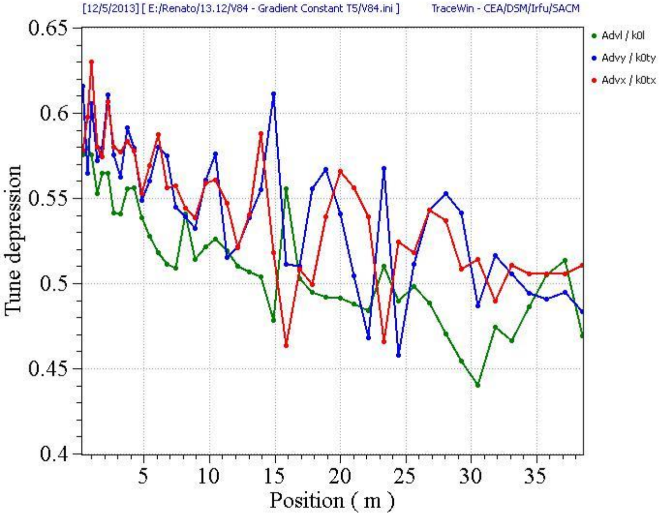

[12/5/2013] [E:/Renato/13.12/V84 - Gradient COnstant T3 T4 T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM


[12/6/2013] [E:/Renato/13.12/V84 - Gradient Constant T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM

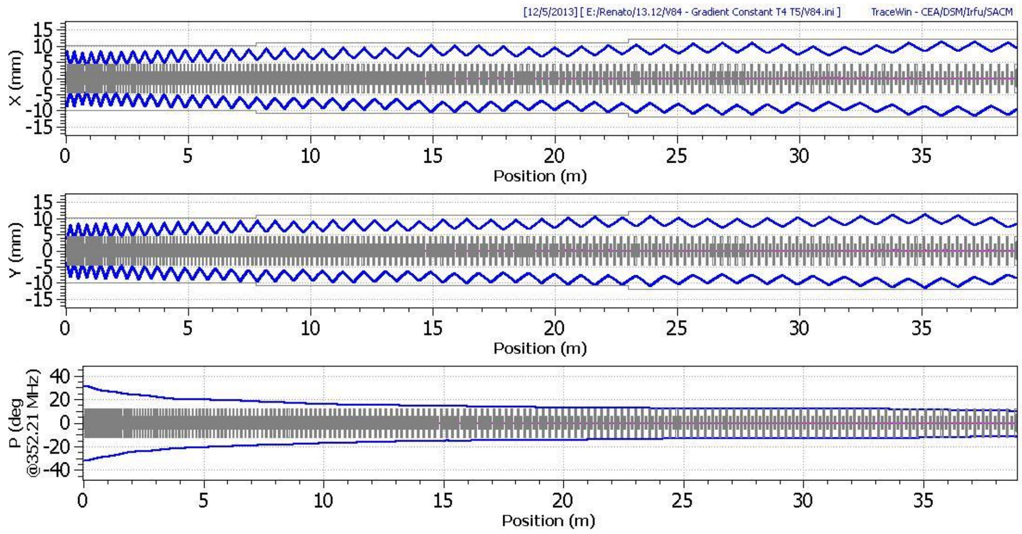

[12/5/2013] [E:/Renato/13.12/V84 - Gradient Constant T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM

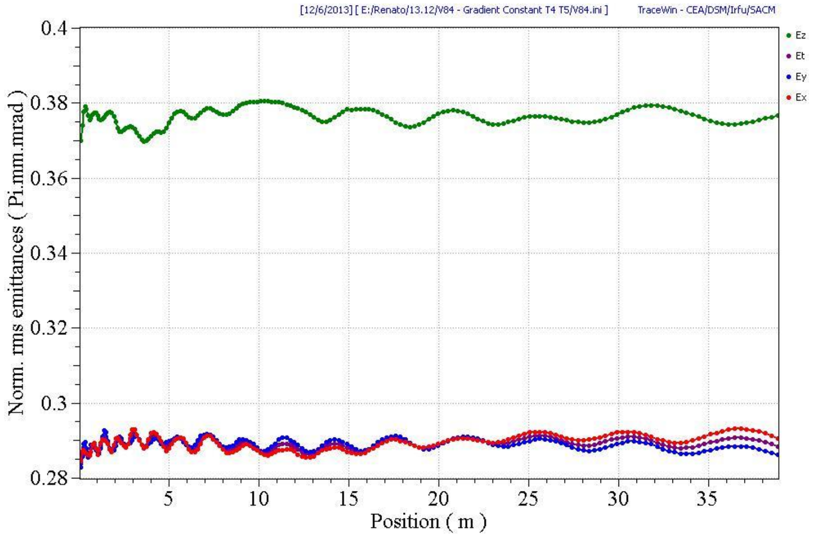
15.53614 T/m

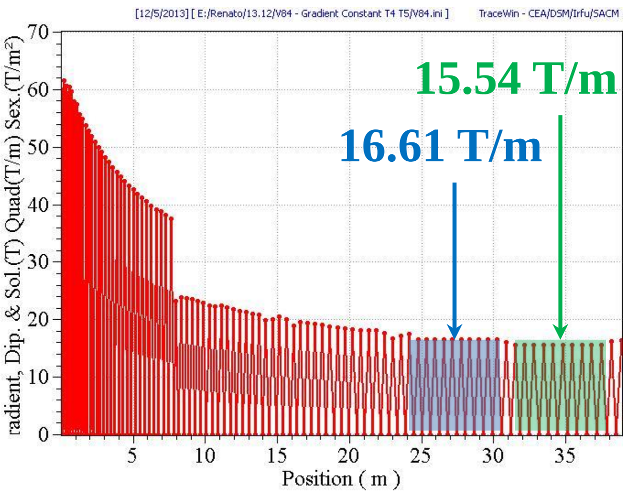

[12/5/2013] [E:/Renato/13.12/V84 - Gradient Constant T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM


[12/5/2013] [E:/Renato/13.12/V84 - Gradient Constant T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM

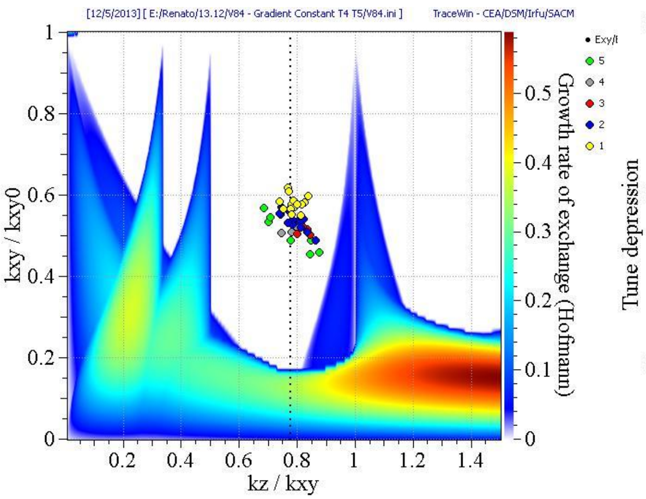
PMQ Constant Gradient Tank 4, 5

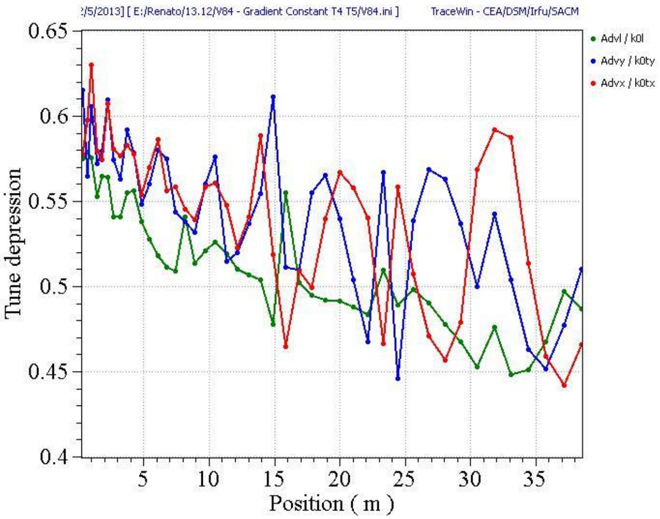




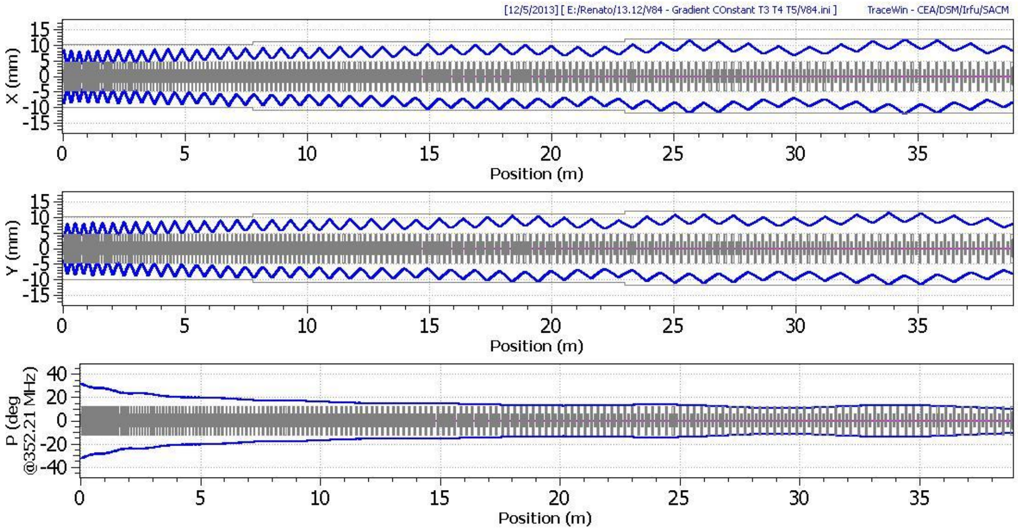

15.54 T/m

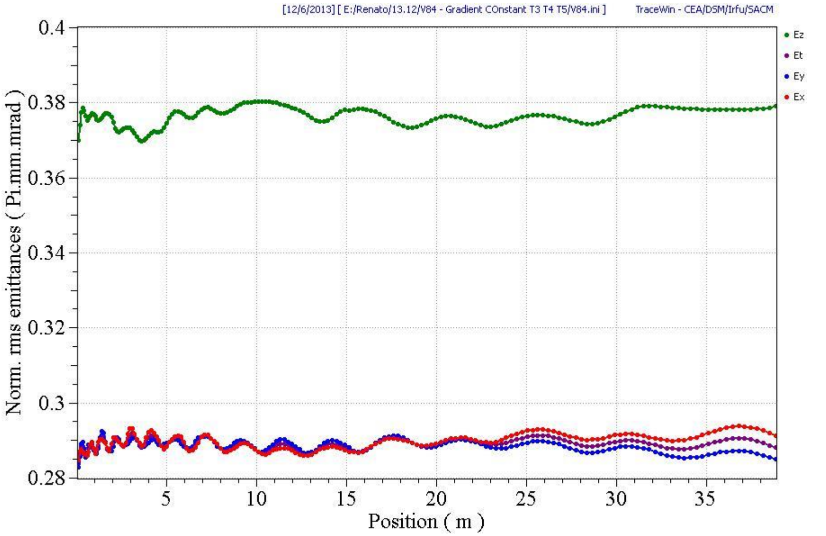
16.61 T/m





PMQ Constant Gradient Tank 3, 4, 5


[12/5/2013] [E:/Renato/13.12/V84 - Gradient COnstant T3 T4 T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM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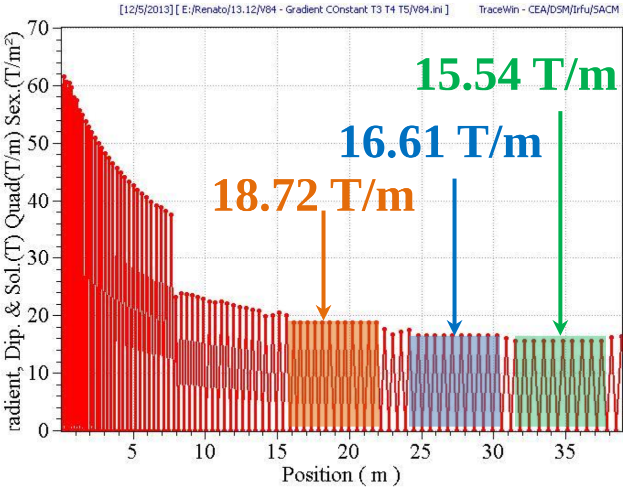
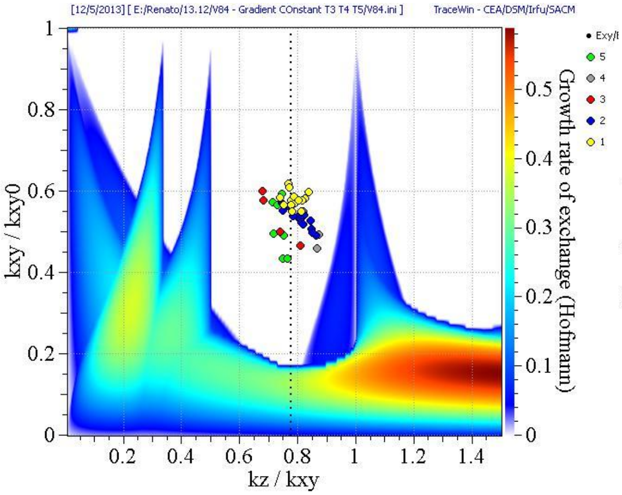

[12/5/2013] [E:/Renato/13.12/V84 - Gradient COnstant T3 T4 T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM

15.54 T/m

16.61 T/m

18.72 T/m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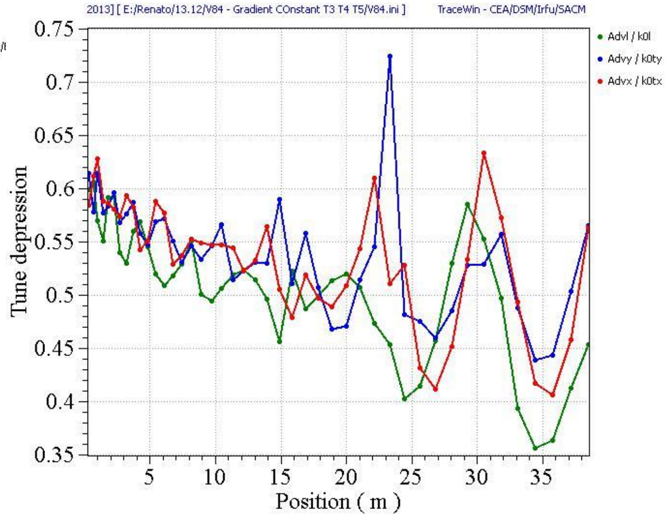
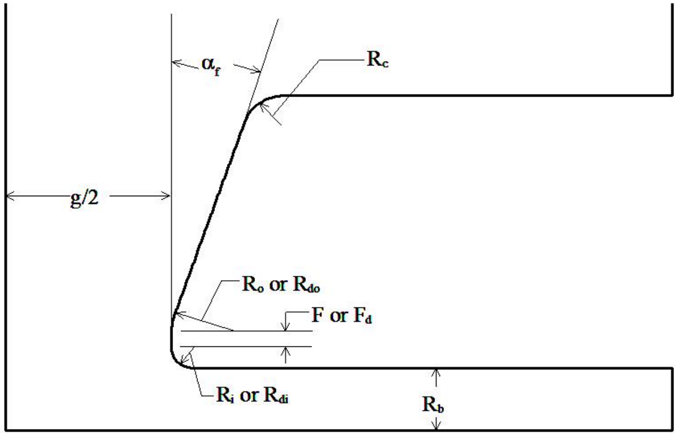

2013] [E:/Renato/13.12/V84 - Gradient COnstant T3 T4 T5/V84.ini] TraceWin - CEA/DSM/Irfu/SACM

Geometrical Parameters

Fixed Parameters

Parameter [cm] / Tank	1	2	3	4	5
R_o	0.8	0.8	0.8	0.8	0.8
R_b	1.0	1.1	1.1	1.2	1.2
R_c	0.5	0.5	0.5	0.5	0.5
R_i	0.3	0.3	0.3	0.3	0.3
F	0.3	0.3	0.3	0.3	0.3
D_{DT}	9.0	9.0	9.0	9.0	9.0
D_T	52.0	52.0	52.0	52.0	52.0



Design Parameters

Every cell is designed by defining cell length, gap length and face angle in order:

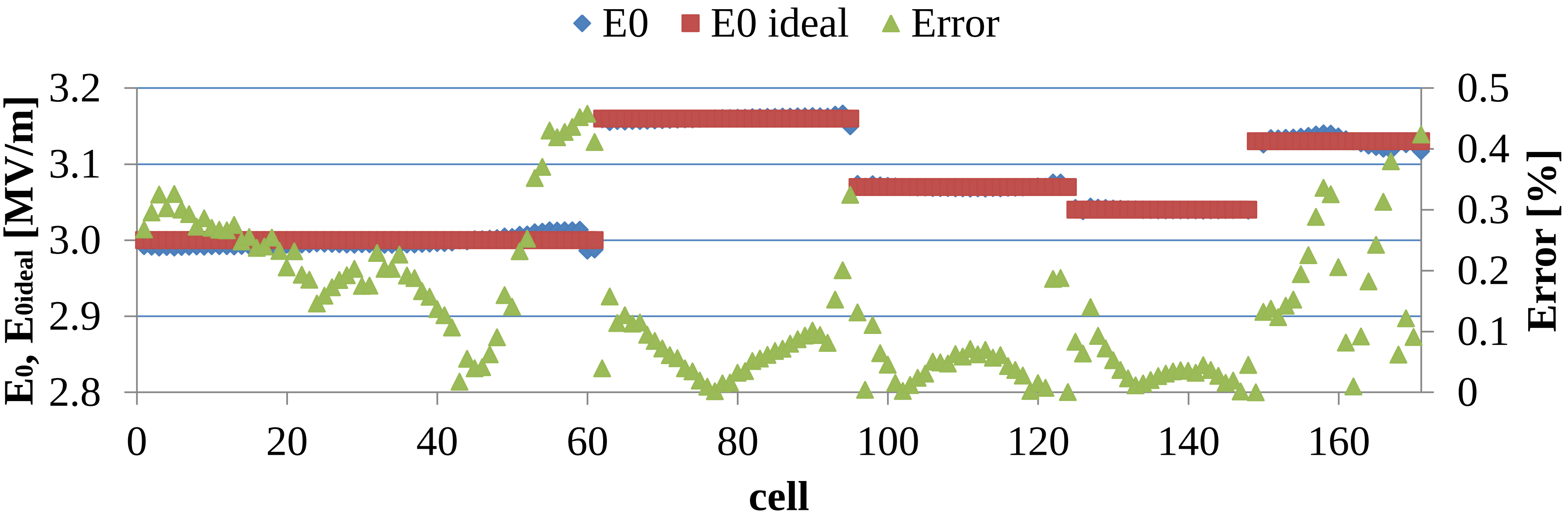
- to reach the desired resonance frequency and to be consistent with the RF phase;
- to maximize the shunt impedance;
- to maintain the level of the maximum surface electric field below the design threshold.

Every tank is designed by defining its length such that:

- $P_{copper} \times 1.25 + P_{beam}$ (I_{beam} = 62.5 mA, 1.25 is margin on MDTfish computation) < **2.20MW**.

Fine Tuning on E_0

- Even if the cells, different in length, have the same pulsation, the accelerating field is not constant because there is NOT a perfect mode matching between the adjacent cells built individually. The mismatch produces a natural tilt of the accelerating field that must be compensated.
- The phase variation implies a cell length variation.
- The tilt that results from a cell length variation, that varies (less or more) linearly, can be compensated by end walls.
- The tilt that results from a cell length variation, *that doesn't vary linearly*, can be compensated by end walls and fine tuning (cell by cell tuning).



* For more information read: **R. De Prisco** et al. "**ESS DTL RF MODELIZATION: FIELD TUNING AND STABILIZATION**", IPAC'13, Shanghai, THPWO070.

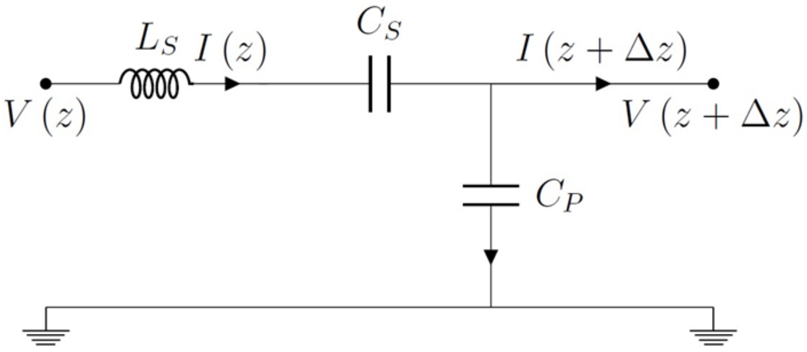
Stabilization (1/2)

- PCs can be introduced as series of inductance, L_{PC}, and capacitance, C_{PC}, in parallel with the capacitance C_P positioned in the longitudinal center of the drift tubes.

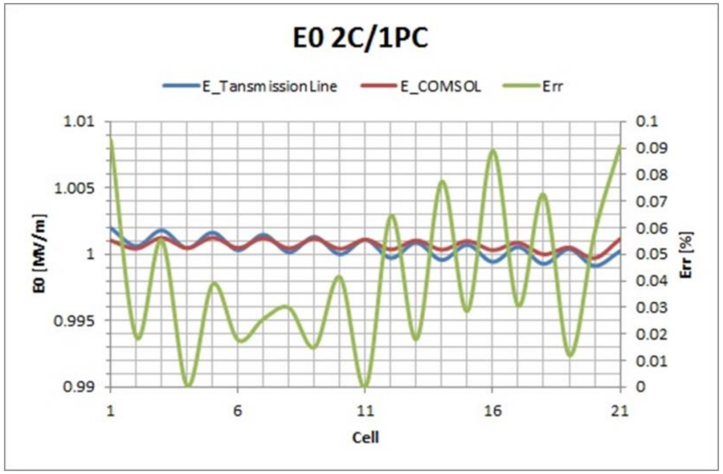
- The values of L_{PC} and C_{PC} must be chosen in order to stabilize the accelerating field. It is possible to outdistance the PCs until the E_0 is within the **1**% of the desired value.

- Fixed the number of PCs the post length are then adjusted such that the frequency of the PC 0-mode is close to the operation frequency of **352.21** MHz (confluence).

- Fixed the perturbations of the end cells to simulate the worst case (maximum machining error), the stabilization (by assuming that PCs are inserted with their optimum length) depends essentially from the distance between two consecutive PCs. *This length in the case of ESS DTL is around **33** cm to have an error of 1% on E_0 respect to the nominal case.*



The results are confirmed by COMSOL 3D-simulations.



* For more information read: **R. De Prisco** et al. "**ESS DTL RF MODELIZATION: FIELD TUNING AND STABILIZATION**", IPAC'13, Shanghai, THPWO070.

Stabilization (2/2)

Parameter / Tank	**1**	**2**	**3**	**4**	**5**
Cells per cavity	61	34	29	26	23
PC distance [m]	0.35	0.33	0.35	0.32	0.33
N PCs	23	22	28	25	22
N PCs / N cells	First 12 cells: 1/4 Second 18 cells: 1/3 Others: 1/2	First 20 cells: 1/2 Others: 1/1	1/1	1/1	1/1
Detuning [MHz]	0.17	0.17	0.20	0.17	0.17
Power [MW]	0.031	0.036	0.044	0.031	0.031

Manufacturing Error

The first cell of the first tank (smallest cell) is the most sensitive to errors.

Cell 1 of the tank 1	Nominal [mm]	Sensitivity [KHz/mm]	Tolerance [mm]	Static Error [KHz]
GAP_Length	13.13	5187.65	±0.025	±129.691
FACE_Angle		6684.35	±0.025	±167.109
DT_Diameter	90	-1191.20	±0.025	∓29.780
TANK_Diameter	520	-450.96	±0.100	∓45.096
STEM_Diameter	28	131.84	±0.025	±3.296

$\sum|\cdot|$

Static error in the worst case is equal to: **374.97** KHz.

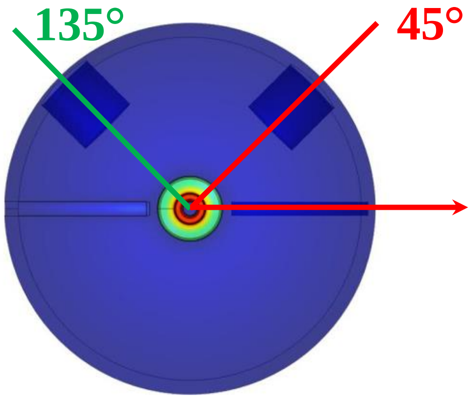
- The static tuners compensate manufacturing errors.
- The movable tuners compensate thermal expansion.

Static Tuners

- Tuner diameter equal to **90** mm.
- Distributed uniformly every **30** cm along the tank.
- Located at +**45**° and +**135**° with respect to the post coupler axis in order not to influence the frequency of the PC 0-mode by tuner penetration.
- The tuner sensitivity is **6.02** (kHz/mm)×m, linear around **20**mm of penetration.
- Static tuners must compensate the static error that in the worst case (+**20**% margin also) is equal to **450** KHz.
- *Frequency shift of stems and post couplers are compensated by the face angles.*
- The Superfish frequency target is: **352.21** MHz – **0.45** MHz = **351.71** MHz.

Example for the first tank

First tank length [m]	**7.53**
Tuner sensitivity [(MHz/mm) × m]	**0.00602**
Tuners per meter [1/m]	**3**
Tuner number	**23**
Nominal penetration [mm]	**25.0**



Beam Loading

- Each tank is composed by cells with different lengths, L_i, accelerating field integral, E_{0i}, transit time factor, T_i, and different synchronous phase, ϕ_i. It is necessary an equivalent definition of ϕ_{tank} for the tank:

$$tan\phi_{tank} = \frac{\sum_i E_{0i} L_i T_i sin\phi_i}{\sum_i E_{0i} L_i T_i cos\phi_i}$$

- To minimize the generator power with respect to waveguide-to-cavity coupling parameter, β_0, it is necessary that:

$$\beta_0 = 1 + \frac{P_{beam}}{P_{Cu}} \qquad f_0 = \frac{f_{RF}}{\frac{(\beta_0-1)tan\phi_{tank}}{2Q_L(\beta_0+1)} + 1} \qquad f_{RF} = 352.21\ MHz$$

Parameter / tank	**1**	**2**	**3**	**4**	**5**
Pcu* [MW]	1088	1078	1090	1126	1190
Pbeam [MW]	1104	1114	1106	1064	1005
Q0* = $Q_L\ (\beta_0 + 1)$	42524	44455	44344	43804	43413
Optimum Detuning = $f_0 - f_{RF}$ [KHz]	2.69	2.20	2.18	2.07	1.98
3dB Bandwidth = $f_0 / (2Q_L)$ [KHz]	12.49	12.02	11.97	11.84	11.54
Cavity time constant = $Q_L / (\pi f_0)$ [μsec]	12.74	13.24	13.29	13.44	13.79

* *including **1.25** factor as margin.*