Bunch Compressor for intense Proton Beams

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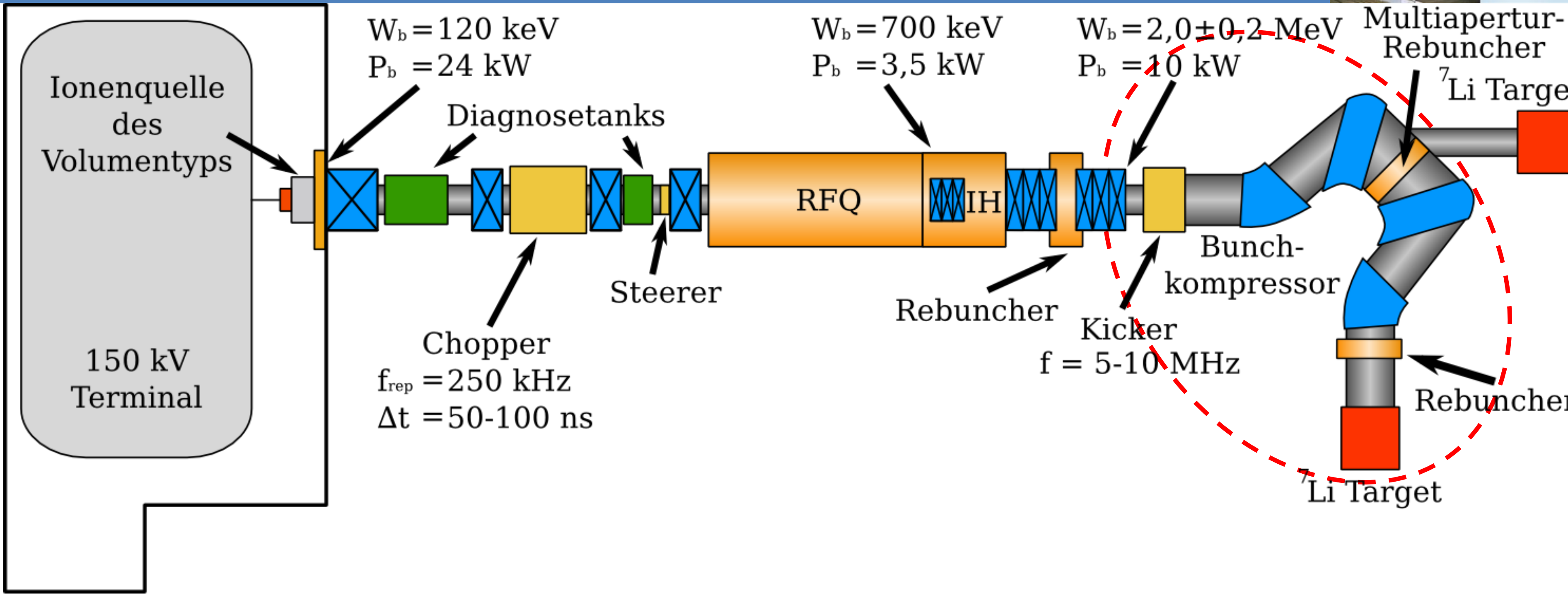
FRANZ: Requirement at the Target

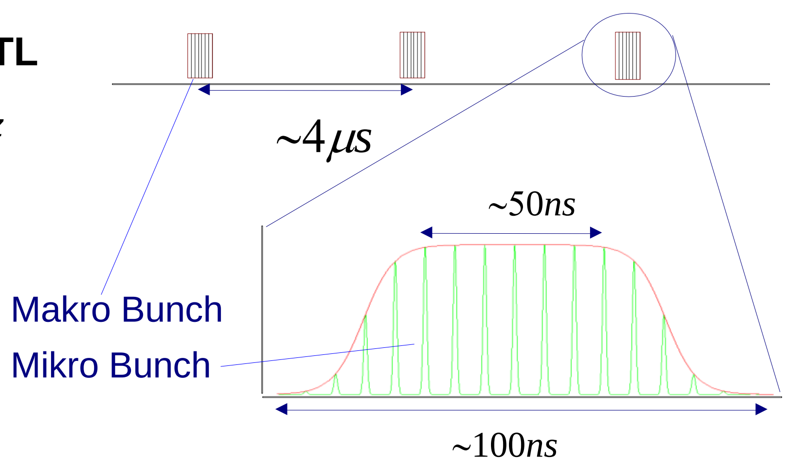


175*MHz*-DTL

rep.rate = 250*kHz*

E ~ 2.0*MeV*

I = 150*mA*



- N_{bunch} = 9
- ΔT = 50-100*ns* => $\Delta T_{rms} \approx 1ns$
- $A_{(beam\ at\ target)}$ < $3x3cm^2$
- $I_{(per\ pulse)}$ ≈ 8*A*
- ΔW < ± 5%

Beam size $r_0 \approx 1cm$

Average current over one RF-period: $I = 150mA$

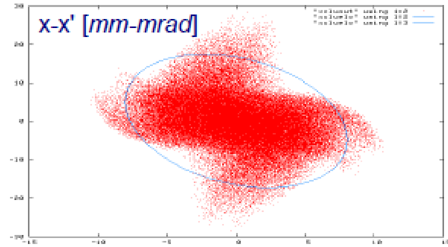
Center energy of the Bunch: $W = 2MeV$

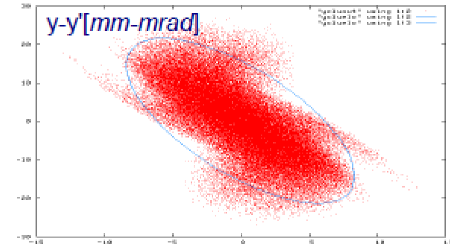
Velocity/speed of light : $\beta = 0.065$

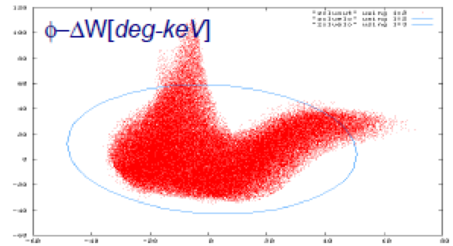
Charge per micro bunch: $Q_{bunch} = 0.85nC$

Number of protons per Bunch: $N_{proton} = 5.3\cdot10^9$

Path length(1. traj.) : $L \approx 4m$







LORASR (IH): $I = 150mA$

$\epsilon_x^{rms,n} = 1.42[\pi\cdot mm\cdot mrad]$

$\epsilon_y^{rms,n} = 1.44[\pi\cdot mm\cdot mrad]$

$\epsilon_\phi^{rms,n} = 423.99[\pi\cdot keV\cdot deg]$

Electric field on the surface of the bunch: $E_0 = 76.4kV/m$

Acceleration (proton on surface): $a = 7.4\cdot10^{15}m/s^2$

Potential Energy (proton on surface): $W_{pot}=763.9\ eV$

Max. velocity due to space charge forces: $v_{max}= 3.8\cdot10^5m/s$

=> max. Beam size after 4*m* drift: $r_1 \approx 5cm$

Significant
Space charge forces!

Transit time differences → Path length differences

Mobley-Buncher: (µA-Proton beams)

Kicker

→ Separation of the micro bunches

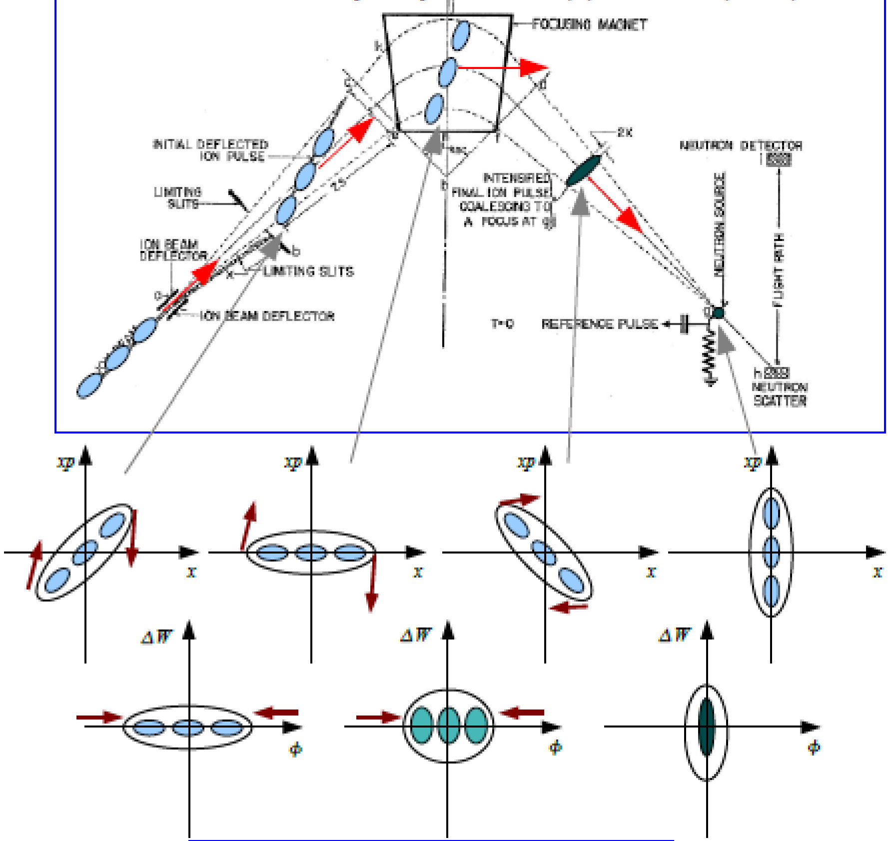
Bending system (1 Dipole)

→ “weak” focusing

→ path length differences

→ longitudinal compression

R.C. Mobley: Phys. Rev. **88**(2), 360-361 (1951)



Negligible energy spread (RF-deflector)

Mobley Type Bunch Compressor

Transit time differences → Path length differences

Mobley-Buncher: (µA-Proton beams)

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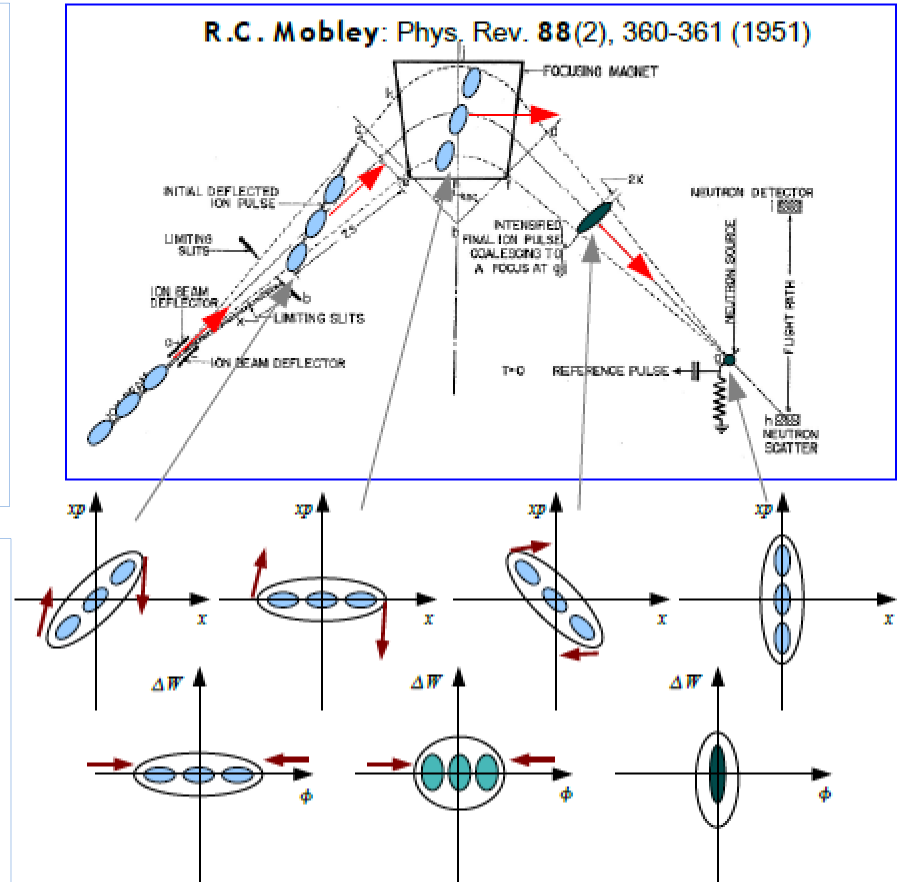


Improvements for 150mA Proton beams:

2 main dipoles (Gradient)

→ more parameters for beam dynamics

2 auxiliary dipoles (homogeneous)

→ linear separation of the trajectories

→ momentum exchange in trans. plane

2 rebuncher cavities

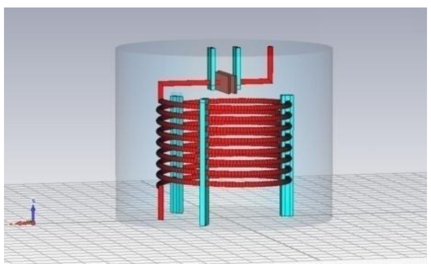
→ longitudinal Beam dynamics

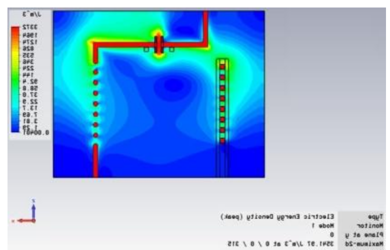
Negligible energy spread
(RF-deflector)

IAP

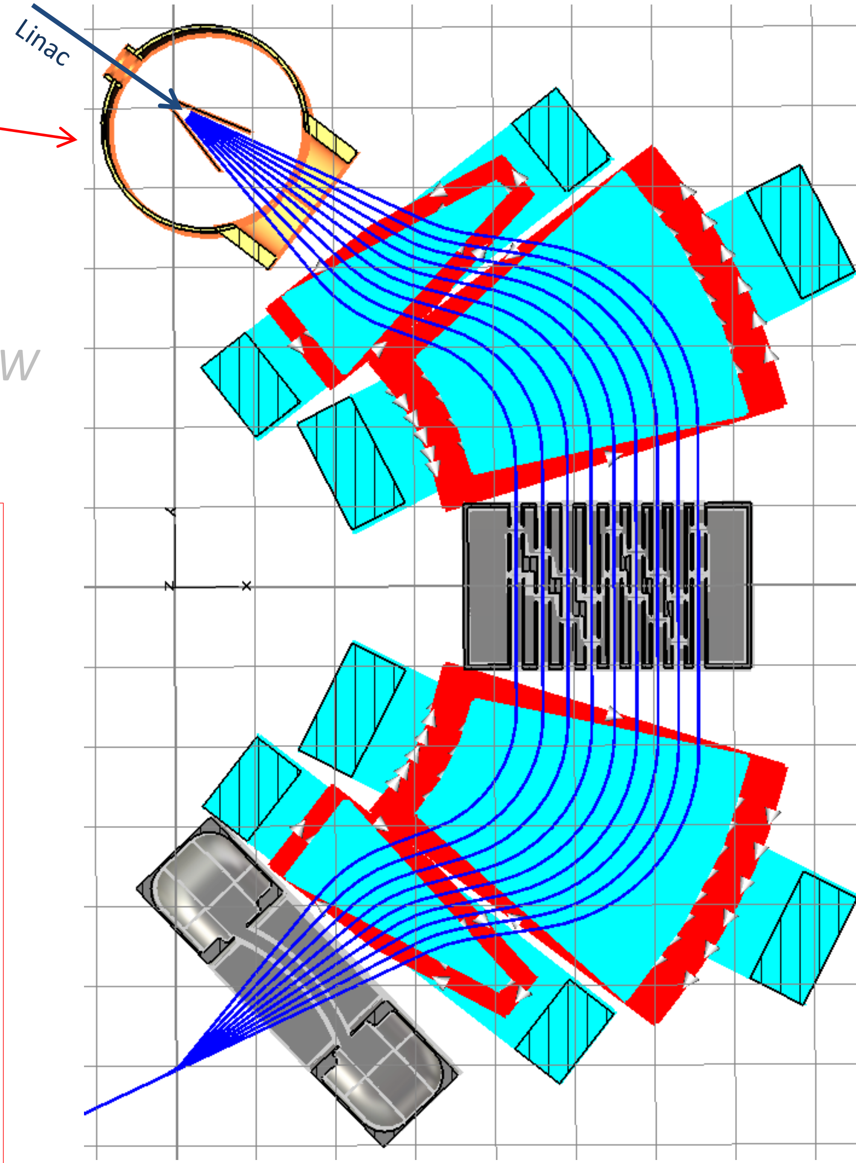
Components:

- Kicker: f = 5*MHz*, U_{max}=250*kV*; P ≈ 15*kW*
- Homogeneous dipoles: B_1 = -515.0*mT*
- Dipoles with gradient: B_2 = 551.9 ± 98.4*mT*
- Multi-Aperture-Rebuncher: U_{eff}= 100-140*kV*, P≈15*kW*
- Broad-Gap-Rebuncher: U_{eff}= 120*kV*, P≈10*kW*





THX @ Y.Nie & H. Podlech



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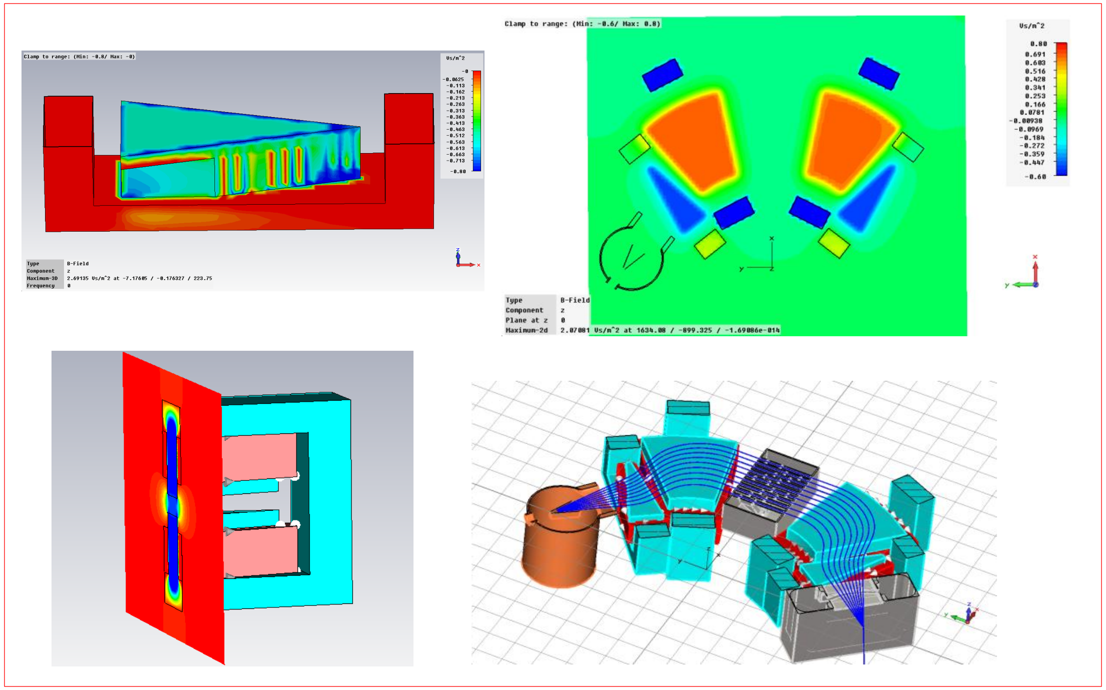

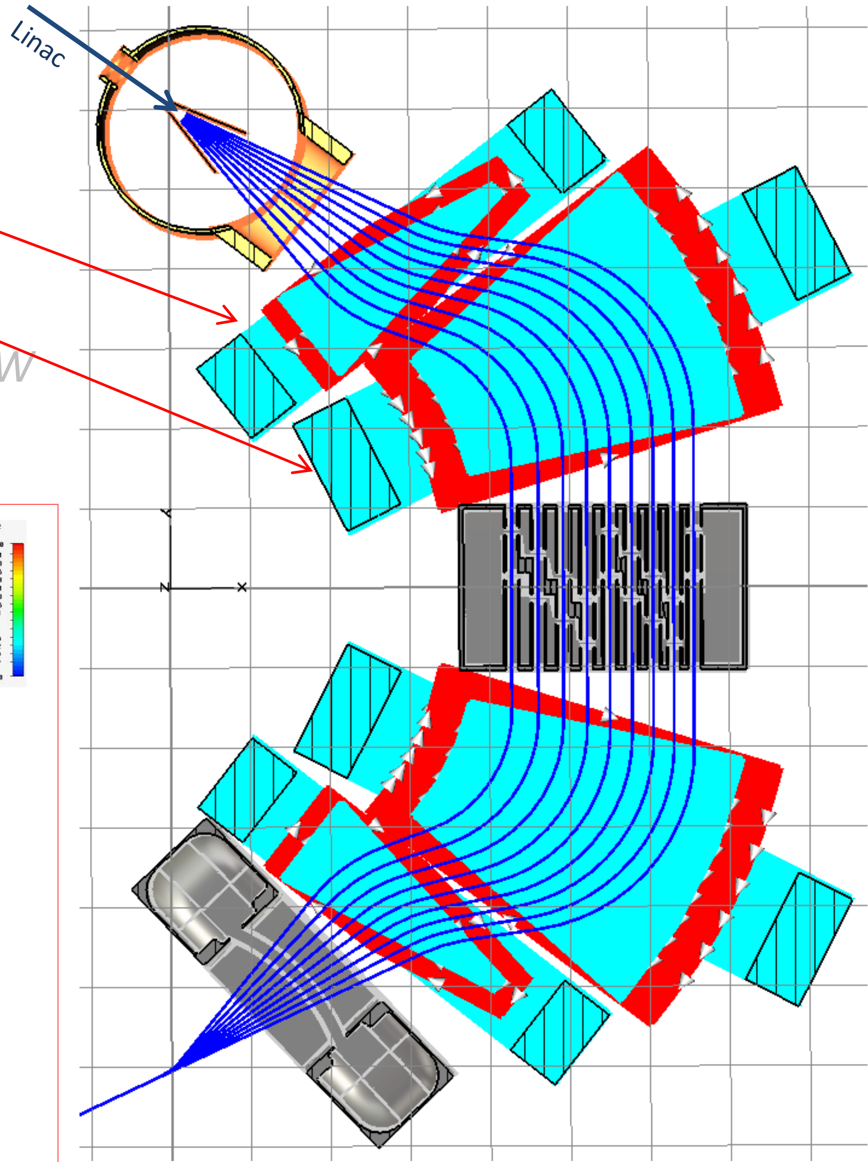

HIC for FAIR Helmholtz International Center
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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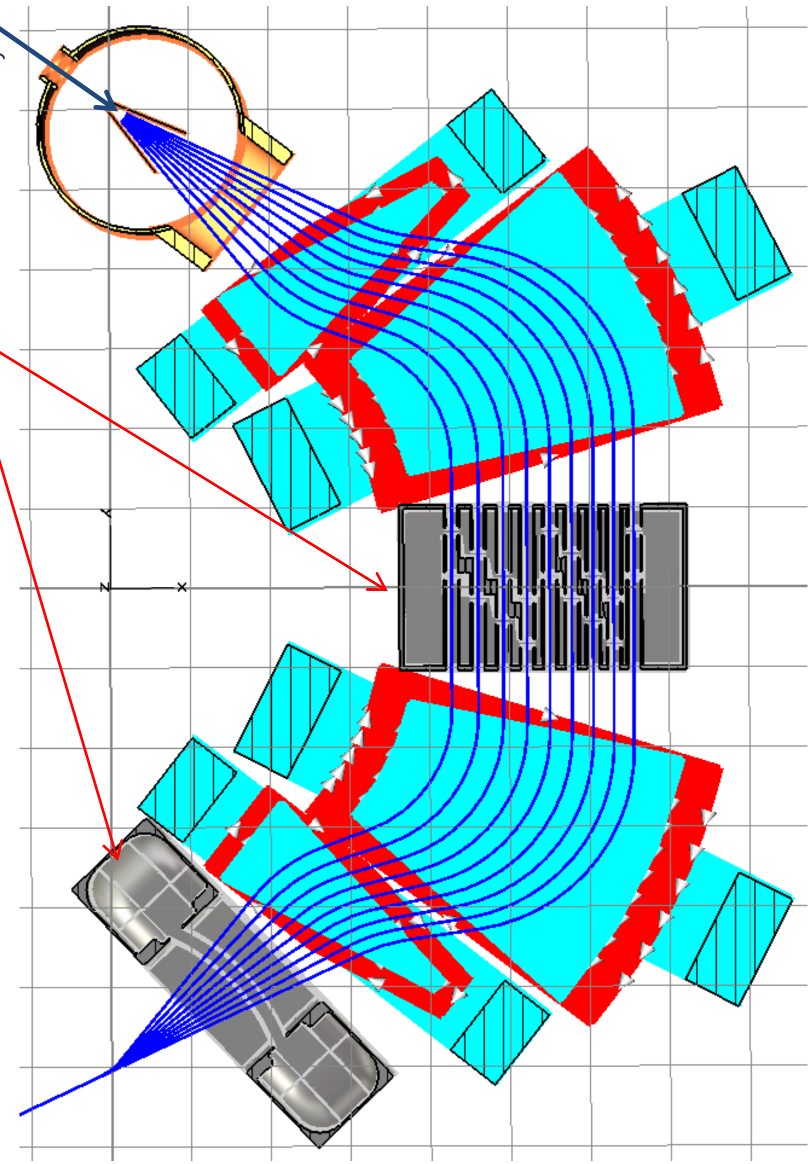
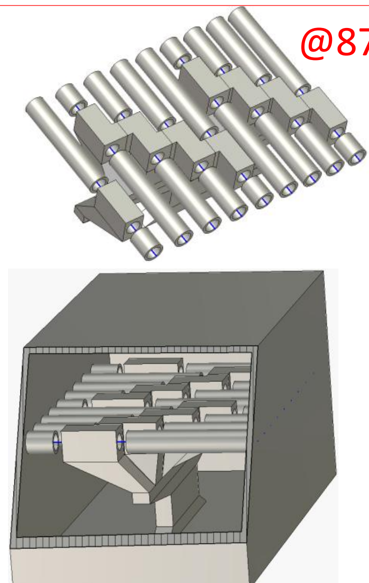


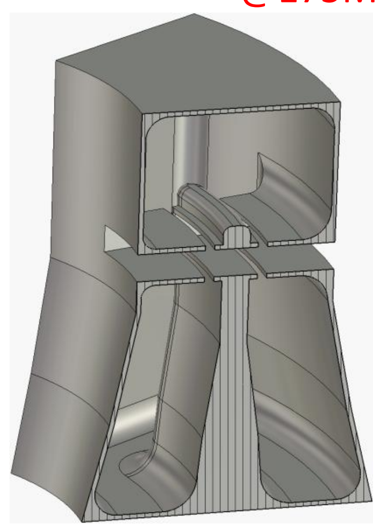
@87.5MHz



©D. Noll

Multi-Aperture-Rebuncher

@175MHz



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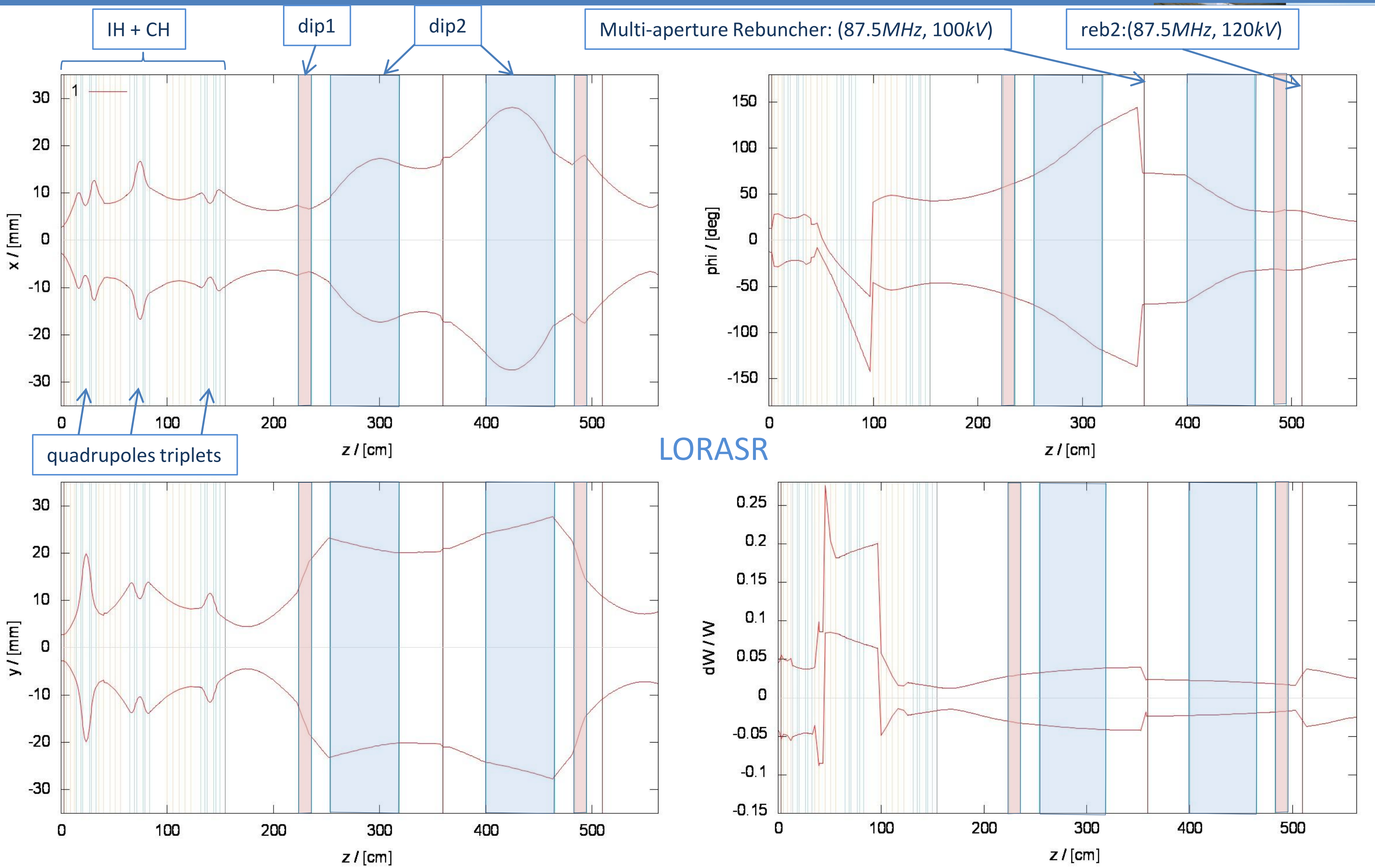
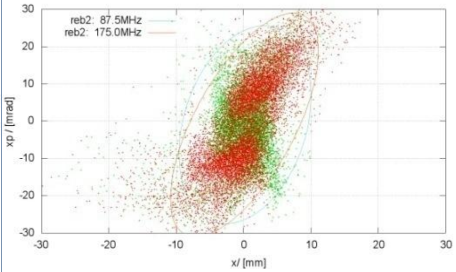
Broad-Gap-Rebuncher

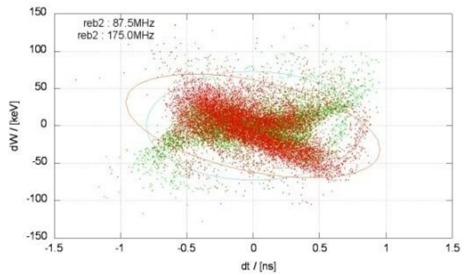
Bunch Compressor: Envelopes(95%) – bunch(1)

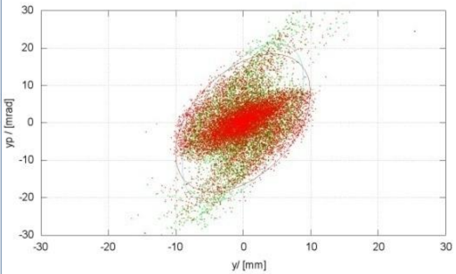


Bunch Compressor: projections at the target

Bunch(1)



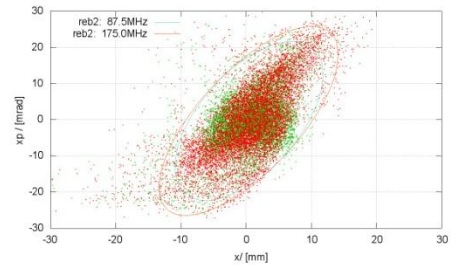


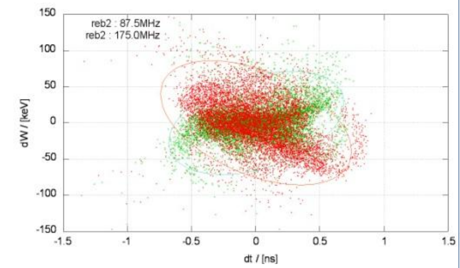


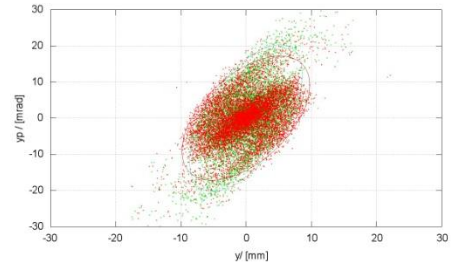
Rebuncher(2)

f/[MHz]	87.5	175.0	
U_{eff}/[kV]	120	60	
$\varepsilon_{x,rms}$/[π mm mrad]	2.354	2.932	+25%
$\varepsilon_{y,rms}$/[π mm mrad]	1.654	1.752	+6%
$\varepsilon_{z,rms}$/[π keV ns]	7.656	8.865	+16%

Bunch(5)



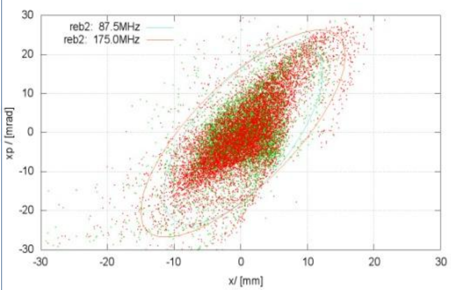


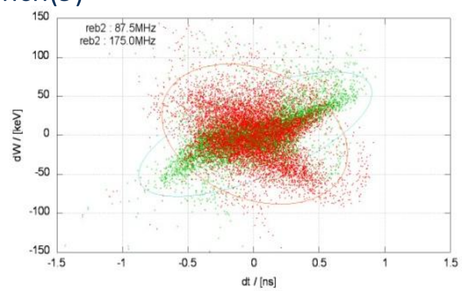


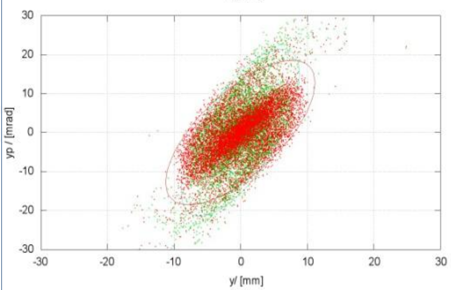
Rebuncher(2)

f/[MHz]	87.5	175.0	
U_{eff}/[kV]	120	60	
$\varepsilon_{x,rms}$/[π mm rad]	2.011	2.798	+39%
$\varepsilon_{y,rms}$/[π mm rad]	1.583	1.638	+3%
$\varepsilon_{z,rms}$/[π keV ns]	6.848	9.043	+32%

Bunch(9)







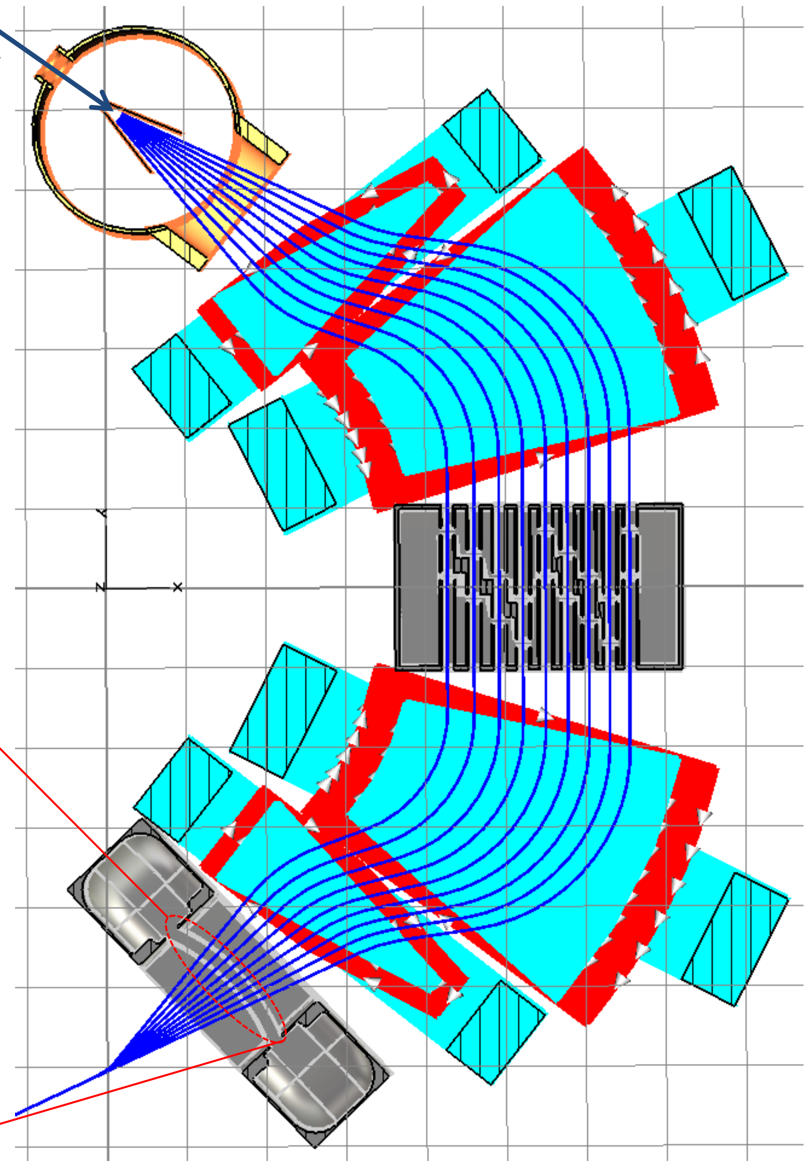
Rebuncher(2)

f/[MHz]	87.5	175.0	
U_{eff}/[kV]	120	60	
$\varepsilon_{x,rms}$/[π mm mrad]	1.917	2.577	+34%
$\varepsilon_{y,rms}$/[πmm mrad]	1.519	1.601	+5%
$\varepsilon_{z,rms}$/[π keV ns]	7.396	9.353	+27%

Single Bunch Beam Dynamics:

- ✓ N_{bunch} = 9
- ✓ ΔT = 50-100*ns* => $\Delta T \approx 1$*ns*
- ✓ $A_{(beam\ at\ target)}$ < $3x3cm^2$
- ✓ $I_{(per\ pulse)}$ ≈ 8*A*
- ✓ ΔW < ± 5%

- single bunch beam dynamics => realistic distributions
- Bunch-bunch-interaction in front of the target
- Particle in Cell : full space charge forces



L = 35*cm*

I = 9x150*mA*

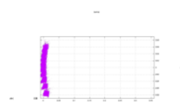
$N_{particle}$ ≈ 90k

N_{grid} = 100x100x100

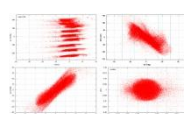
$\Delta x_{stepsize}$ = 1*mm*

$\Delta t_{calc+plot}$ ≈ 50*s*

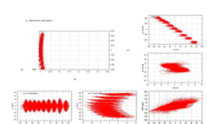
merge



Projections at target

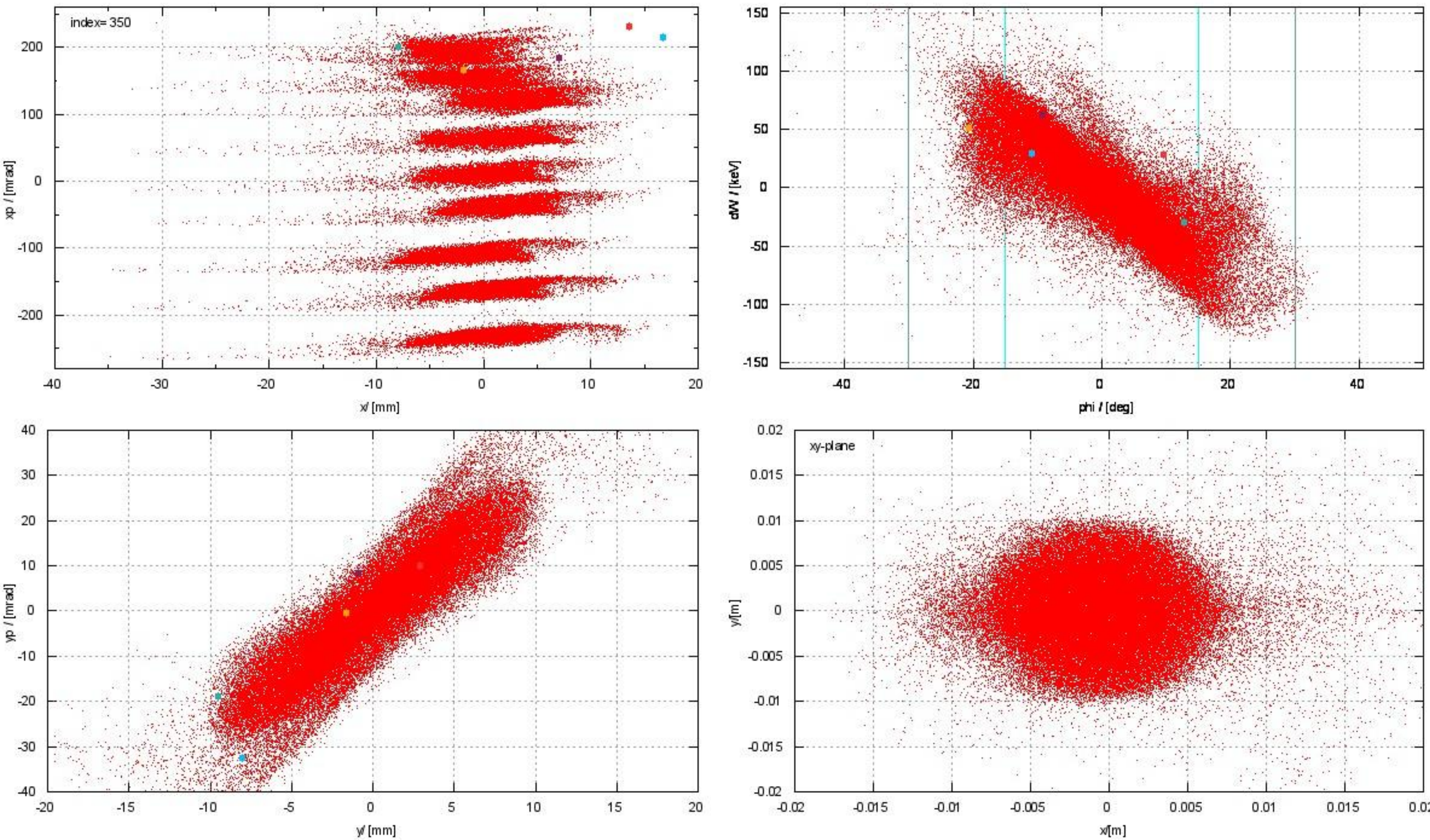


projections



<transp.:merge>:
- Particle in Cell (PIC)
- dynamic lattice
- finite differences
- Poisson solver

Bunch Compressor: Merging - Projections at the target



- Requirements: $(\Delta W/W)_{rms} < \pm 5\%$ ✓ $\Delta T_{rms} < 1ns$ ✓ $A < 3x3cm^2$ ✓

- Improvement of the **Mobley bunch compressor for high current applications**:
  Several μA beam current => 150mA per micro bunch
- Additional dipoles => transverse beam dynamics
- Rebuncher cavities => longitudinal beam dynamics
- Single **Bunch beam dynamics** + merging scenario => fulfills the requirements
- first step for technical realization of the bunch Compressor
- **Kicker:** design studies + numerical studies + **measurements at scaled model**
  => Results in good agreement with analytical and numerical estimations
- **Dipoles:** numerical studies with CST:EMS
  => Realistic field distributions <=> beam dynamics
  => Technical realization of the hardwares
- **Cavities:** feasible design with CST:MWS
  => optimization of the power consumptions

Thank you for your attention.

on behalf of:

M. Droba, O. Meusel, D. Noll, U. Ratzinger, C. Wiesner

IAP, Goethe University Frankfurt

acknowledgment:

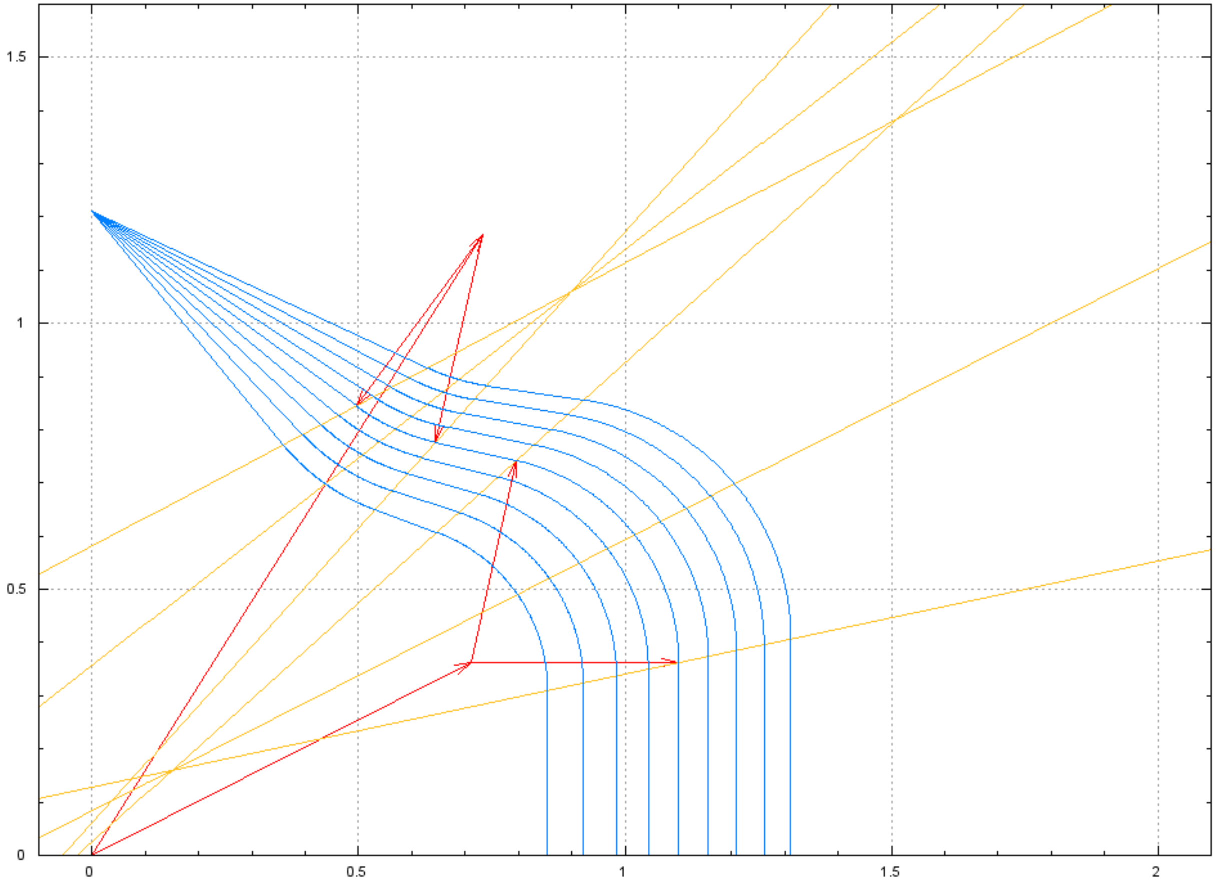
Y. Nie, H. Podlech, A. Schempp, S. Schmidt

IAP, Goethe University Frankfurt

LINAC-AG	http://linac.physik.uni-frankfurt.de
AG-Schempp	http://iaprfq.physik.uni-frankfurt.de
NNP-AG	http://nnp.physik.uni-frankfurt.de

DFG	http://www.dfg.de
HIC for FAIR	http://hicforfair.de

Bunch Compressor: geometrical parameters

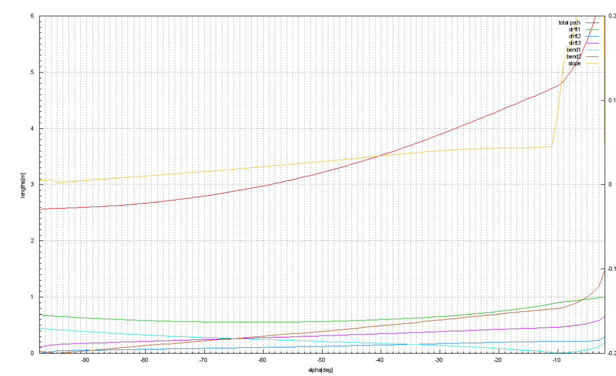


g9_5x

$B_1 = -0.51497[T]$

$\alpha_{max} = 25.69[deg]$

$< \alpha > = 3.21[deg]$



al [deg]	tp [m]	dr1 [m]	dr2 [m]	dr3 [m]	b1 [m]	b2 [m]	bet1 [deg]	bet2 [deg]	R2 [m]	B2 [T]	d_x1 [m]	d_x2 [m]	d_x3 [m]	d_x4 [m]	d_x5 [m]	d_a [deg]	d_x1p [m]	d_tp [m]	psi11 [deg]	psi12 [deg]	psi21 [deg]	psi22 [deg]
-25.000	4.0995	0.6949	0.1845	0.4069	0.1162	0.6472	16.645	-81.645	0.4542	0.4535	0.0397	0.0352	0.0412	0.0515	0.0504	2.702	0.0328	-0.1125	37.0000	33.6455	39.6455	12.0000
-27.702	3.9870	0.6718	0.1777	0.3962	0.1296	0.6182	18.560	-80.857	0.4381	0.4702	0.0382	0.0353	0.0419	0.0529	0.0518	2.781	0.0326	-0.1125	34.2979	32.8575	38.8575	12.0000
-30.483	3.8745	0.6510	0.1707	0.3852	0.1421	0.5884	20.349	-79.866	0.4221	0.4880	0.0374	0.0359	0.0429	0.0545	0.0533	2.887	0.0328	-0.1125	31.5167	31.8661	37.8661	12.0000
-33.370	3.7620	0.6323	0.1633	0.3738	0.1540	0.5576	22.052	-78.682	0.4061	0.5073	0.0370	0.0369	0.0442	0.0563	0.0551	3.023	0.0334	-0.1125	28.6298	30.6819	36.6819	12.0000
-36.393	3.6495	0.6154	0.1558	0.3621	0.1655	0.5259	23.703	-77.310	0.3898	0.5285	0.0371	0.0385	0.0461	0.0584	0.0571	3.194	0.0343	-0.1125	25.6071	29.3105	35.3105	12.0000
-39.587	3.5370	0.6003	0.1480	0.3500	0.1769	0.4932	25.339	-75.753	0.3731	0.5522	0.0377	0.0407	0.0485	0.0610	0.0596	3.409	0.0358	-0.1125	22.4131	27.7526	33.7526	12.0000
-42.995	3.4245	0.5870	0.1401	0.3373	0.1885	0.4593	27.001	-74.005	0.3556	0.5793	0.0390	0.0437	0.0516	0.0641	0.0627	3.677	0.0377	-0.1125	19.0046	26.0054	32.0054	12.0000
-46.672	3.3120	0.5754	0.1320	0.3240	0.2006	0.4239	28.735	-72.063	0.3370	0.6112	0.0411	0.0477	0.0557	0.0681	0.0666	4.017	0.0404	-0.1125	15.3277	24.0631	30.0631	12.0000
-50.689	3.1995	0.5660	0.1237	0.3098	0.2137	0.3866	30.607	-69.918	0.3168	0.6502	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000	11.3105	21.9176	27.9176	12.0000

Components:

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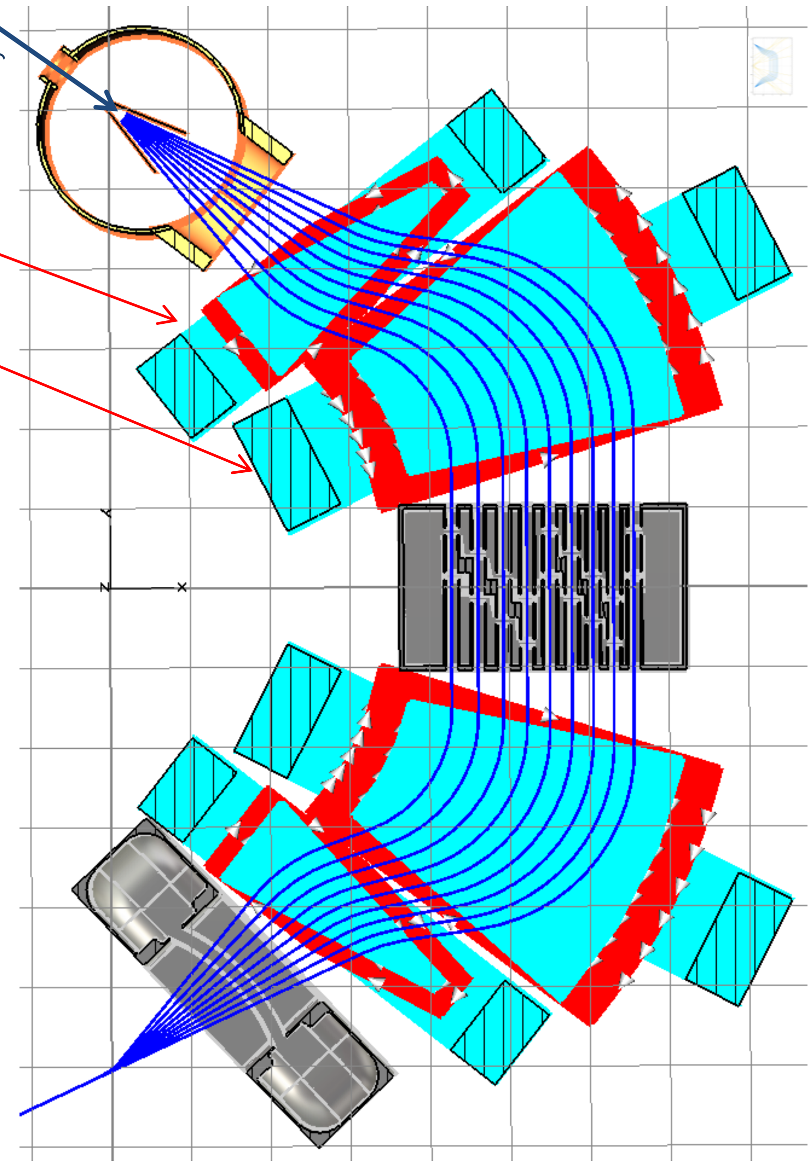
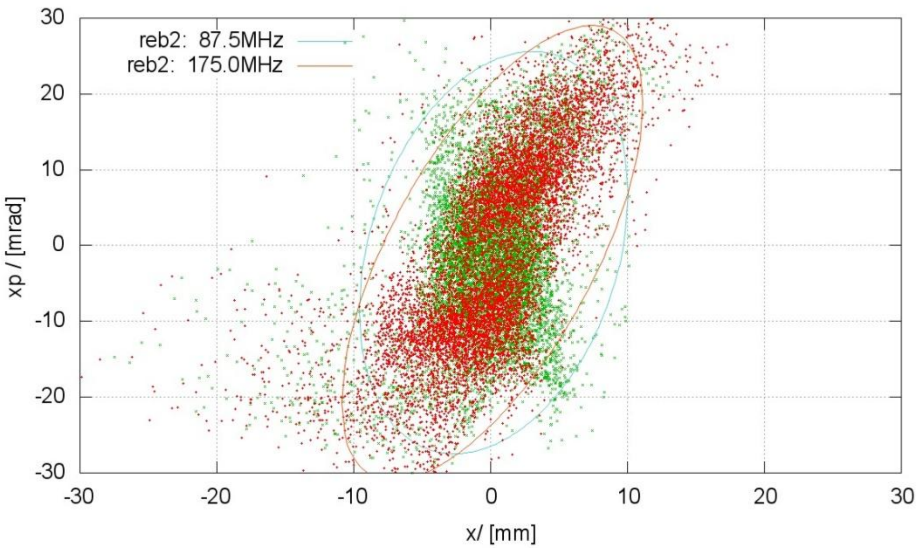
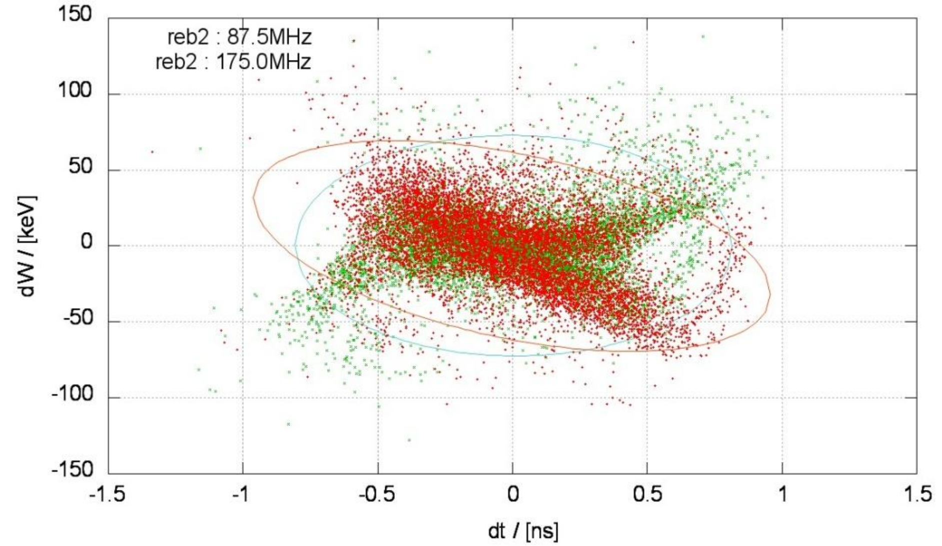


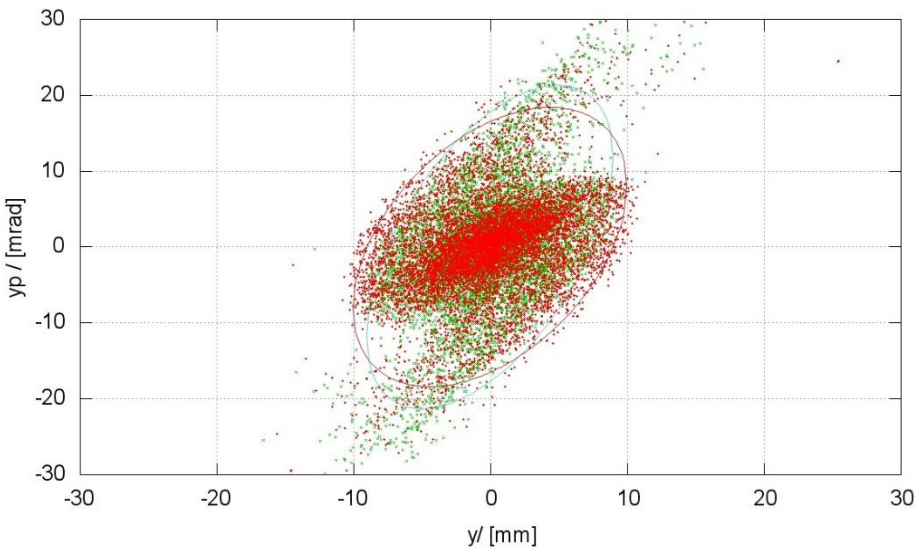
Dipole(1)	
B_1/[mT]	515
g/[mm]	60
N·I/[A]	10420
A_{coil}/[mm^2]	50×150
A_{wind}/[mm^2]	7×7
N	153
I/[A]	68

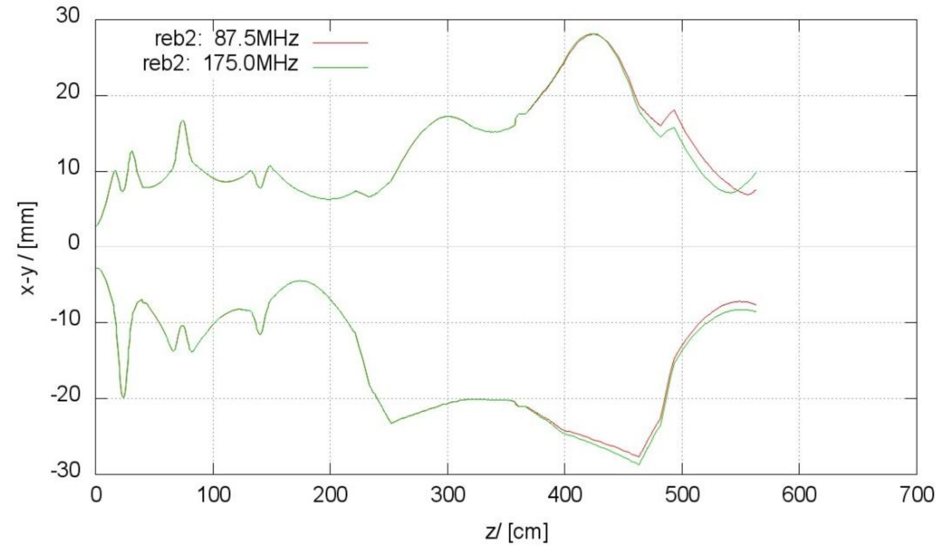
Dipole(2)	
B_2/[mT]	650
g/[mm]	60
N·I/[A]	60476
A_{coil}/[mm^2]	100×200
A_{wind}/[mm^2]	7×7
N	408
I/[A]	148

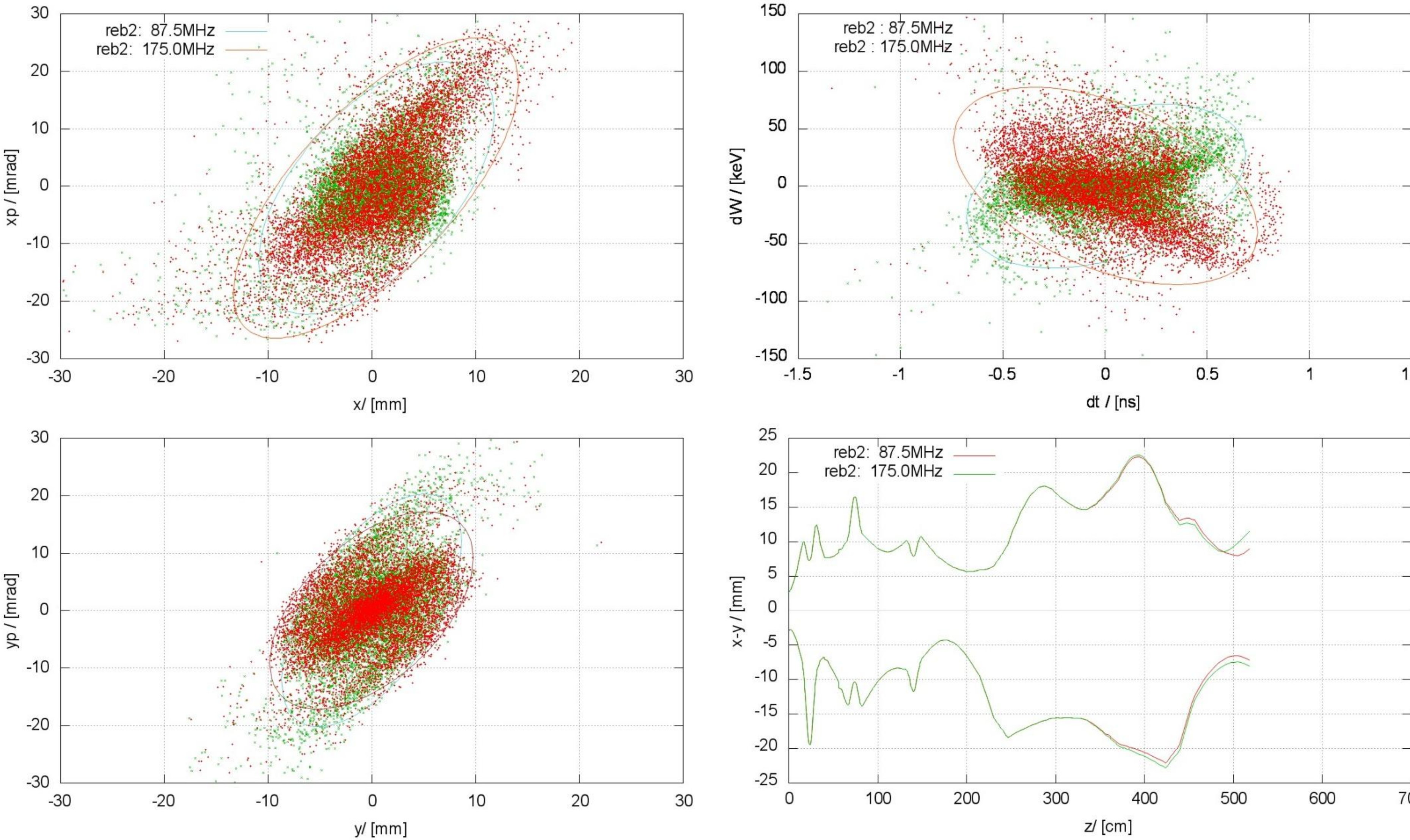
Bunch Compressor: Bunch(1) at the target



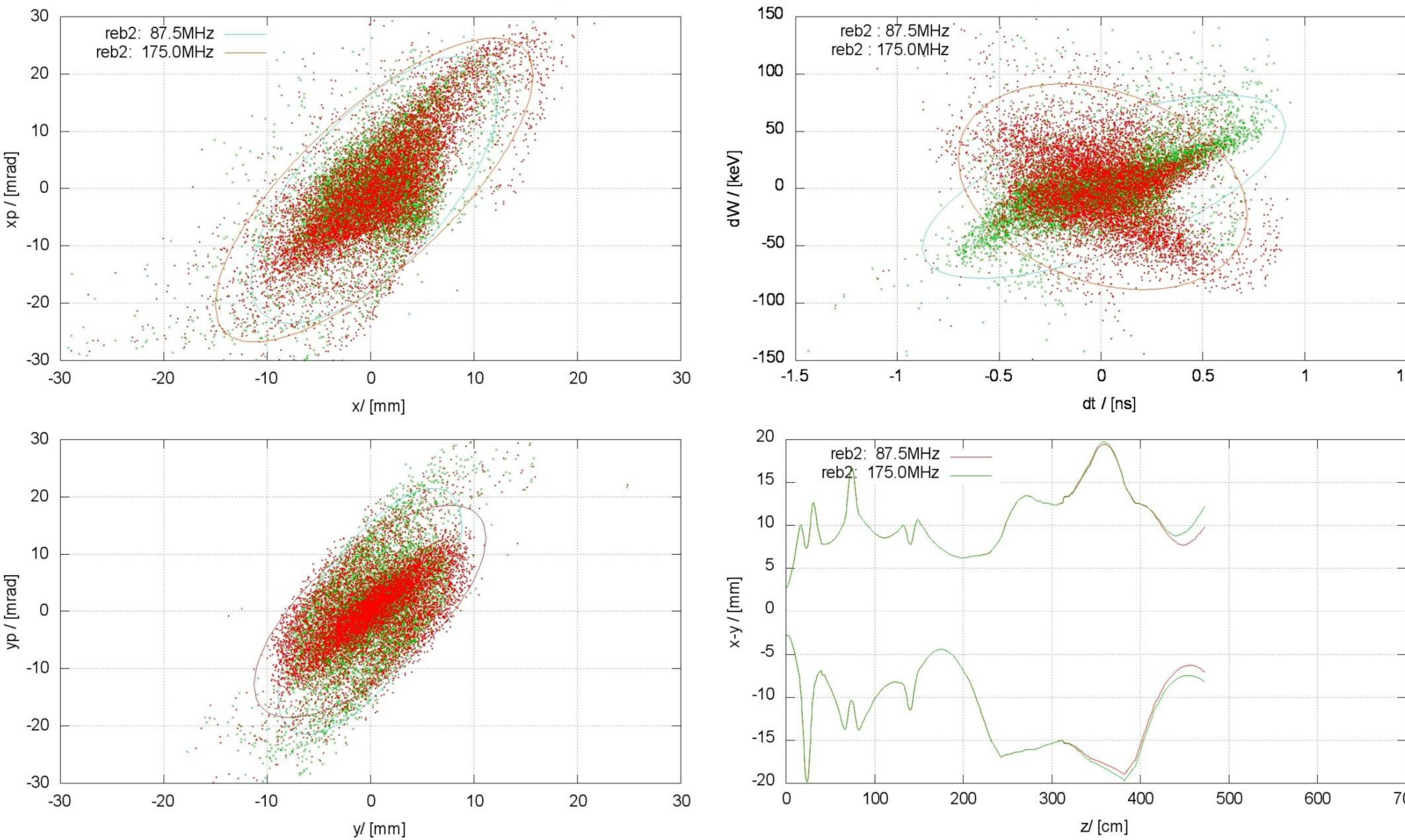




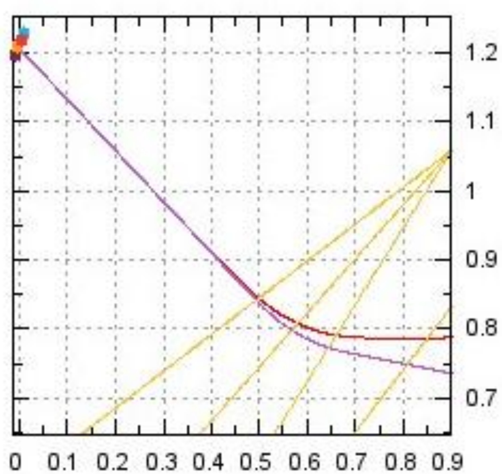


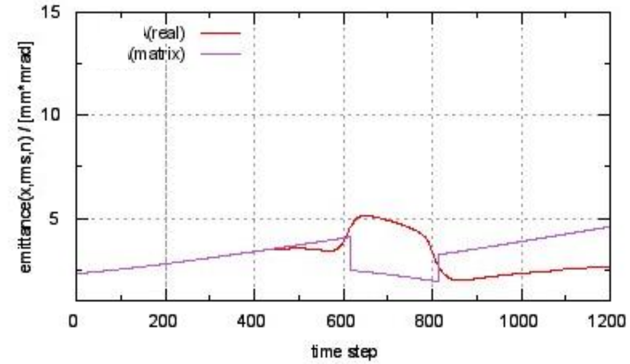

reb2: 87.5MHz
reb2: 175.0MHz
xp / [mrad]
x/ [mm]
reb2 : 87.5MHz
reb2 : 175.0MHz
dW / [keV]
dt / [ns]
yp / [mrad]
y/ [mm]
reb2: 87.5MHz
reb2: 175.0MHz
x-y / [mm]
z/ [cm]

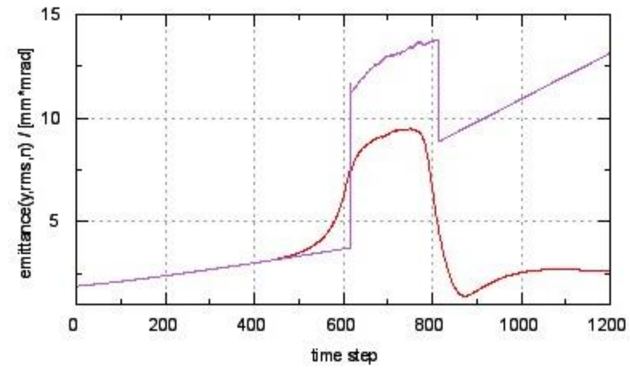
Bunch Compressor: Bunch(9) at the target

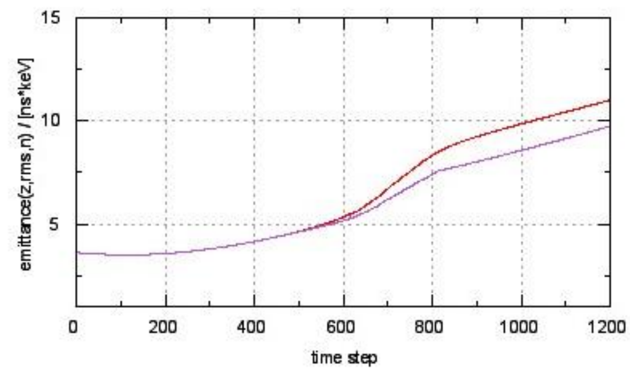


- Center motion significantly changed by large fringing field.
- paraxial approach over estimate the emittance growth
  in transverse plane.
- bigger emittance growth in long. plane with realistic fields.
- field enhancement nearby the edges due to saturation
  Insufficiently described by first order matrix formalism.









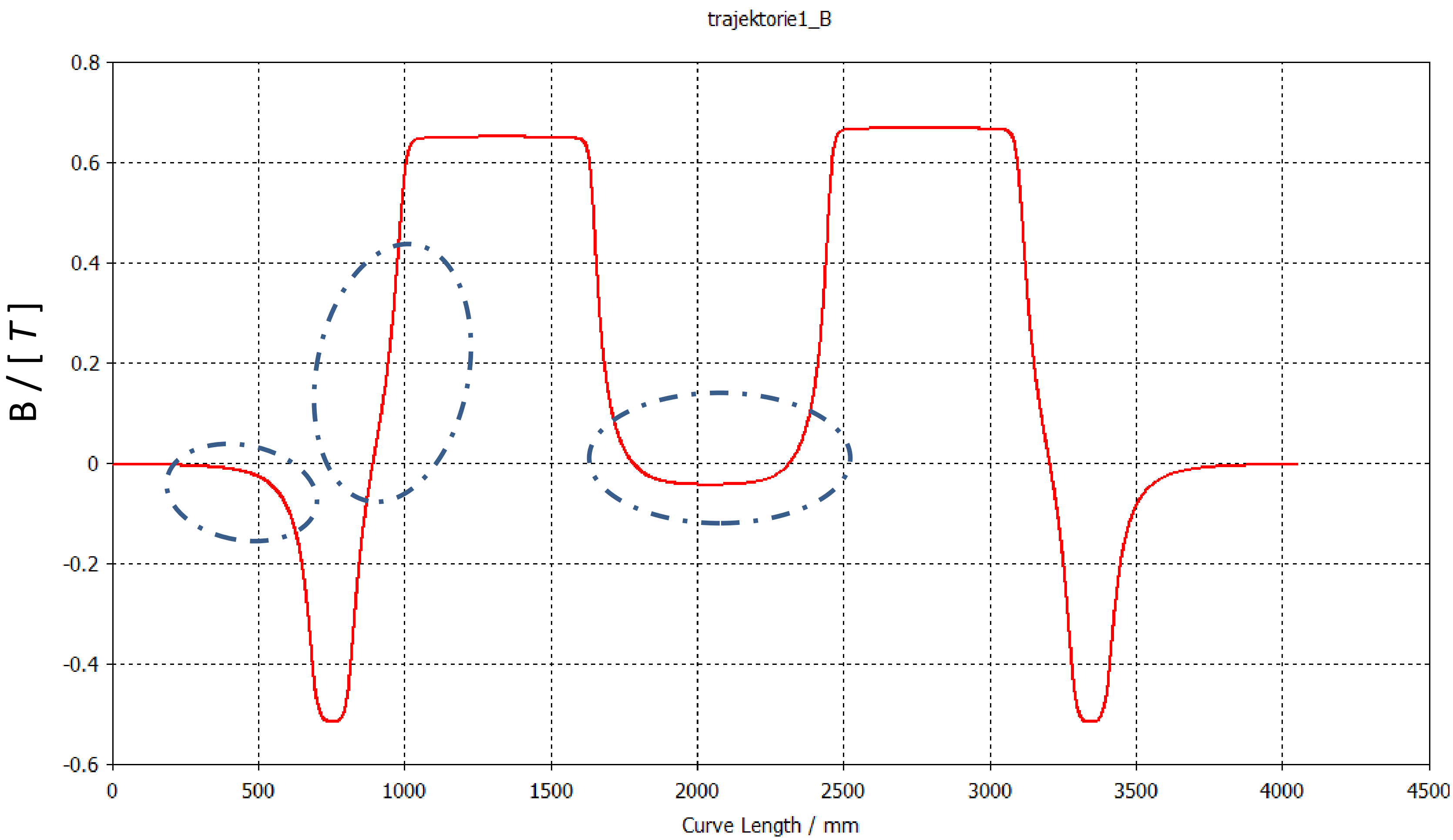
Measurements at scaled Model

		Analytical	MWS	Measured (Powermeter)
Effective Inductance	µH	12.9	12.3	12.5
Effective Capacitance	pF	23.8	31.1	28.8
Frequency	MHz	9.09	8.26	8.37
Intrinsic Quality Factor		2986	3058	1772
Shunt impedance	MΩ	4.4	3.9	2.8

- Good agreement for the Inductance
- Stray Capacitance underestimated => higher frequency
- ~ 60% of the calculated intrinsic quality factor can be reached
- Measurements with network analyzer give comparable results
- Analytic formulas are good enough for “first shot” estimations
- big loops (~ $120 \times 62 mm^2$) are needed for critical coupling

  => mechanical problems + RF-properties of the loop
- alternative coupling methods (capacitive, galvanic) have to be investigated

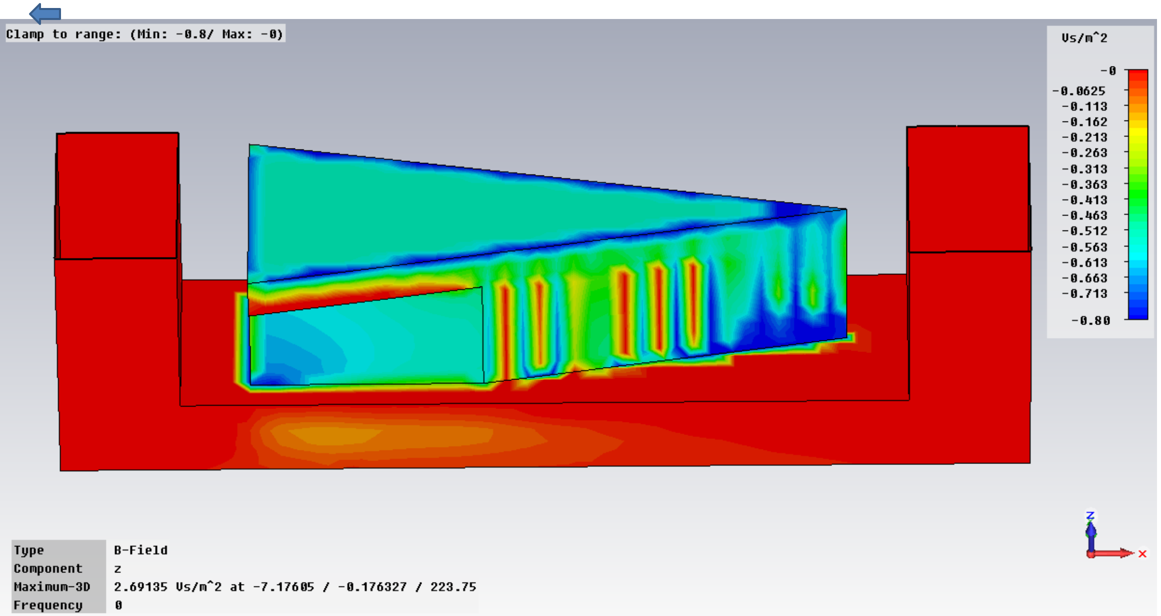
Bunch Compressor: field along the first trajectory at preliminary dipole design

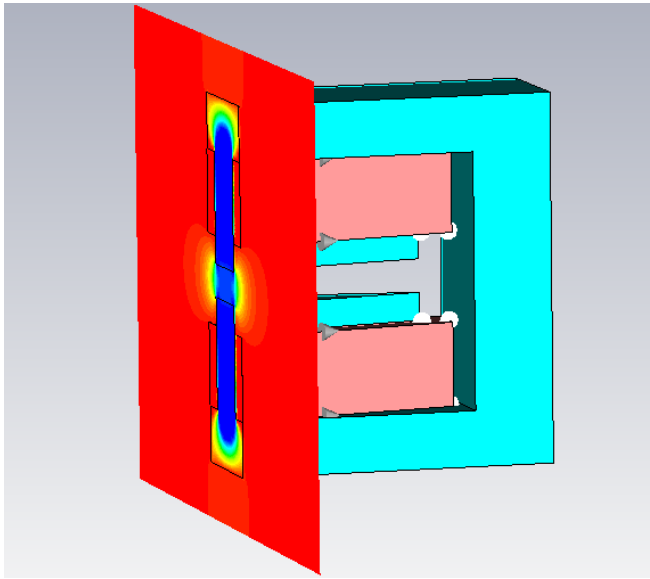


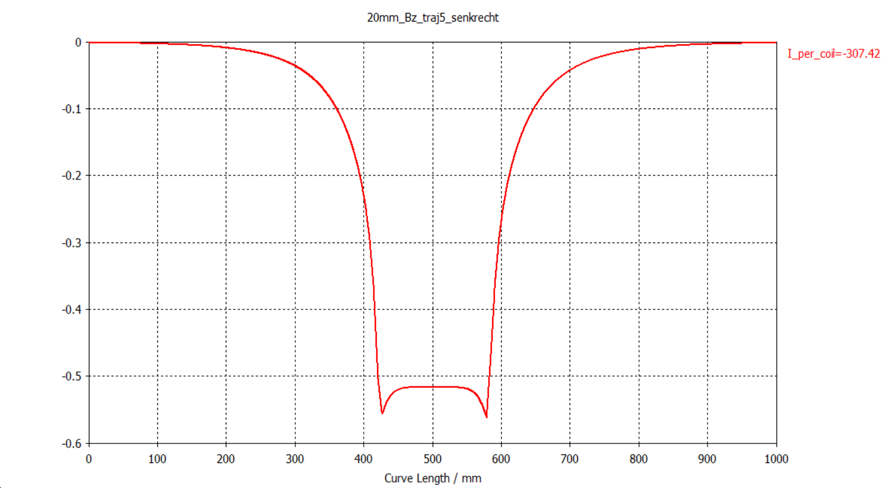
- large fringing field
- Connected fringing field region

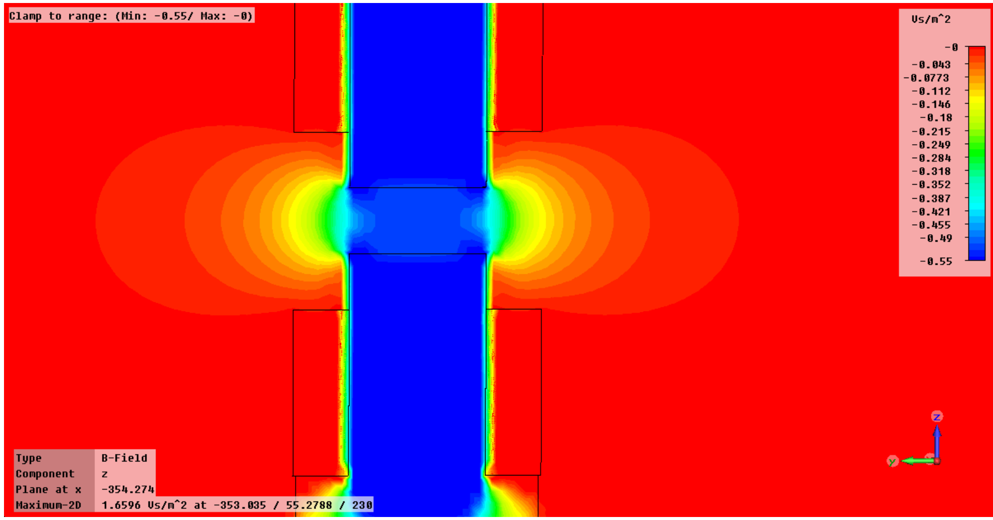
=> Effects of fringing fields on beam dynamics?

field enhancement at the edges due to saturation effects







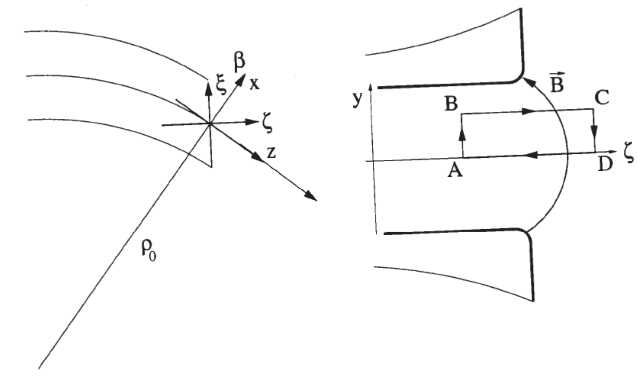


Beam dynamics with realistic field distribution

The complete effect of the fringing field is applied in one instantaneous kick in the transverse planes:

$$x' = x'_0 + \underbrace{\boxed{k_x(\phi, \rho_0)\cdot x_0}}_{\Delta x'}$$

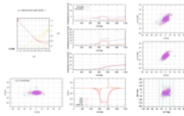
$$y' = y'_0 + \underbrace{\boxed{k_y\left(\phi, \frac{g}{\rho_0}, K\right)\cdot y_0}}_{\Delta y'}$$



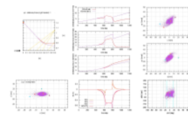
Parameters of the first dipole:

Fringing field Integral	K	=	1.034	
Edge angle	$\phi_{entrance}$	=	-25.01	[deg]
Edge angle	ϕ_{exit}	=	29.31	[deg]
Magnetic field	B_0	=	515.0	[mT]
Gap	g	=	60.0	[mm]

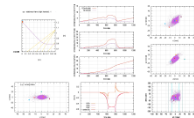
Comparison with realistic field distribution:



0mA: real field dist. vs. matrix



150mA: real field dist. vs. matrix



real field dist.: 0mA vs. 150mA