Towards High Compression Ratios

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Outlines:

- **Requirements**

- **Design / Optimization Cycles**
  - Geometry
  - 5MHz Kicker
  - Single Bunch Beam Dynamics
  - Merging Scenario
  - Magnet Design
  - Beam Dynamics with Realistic Field Distributions

- **Outlook**

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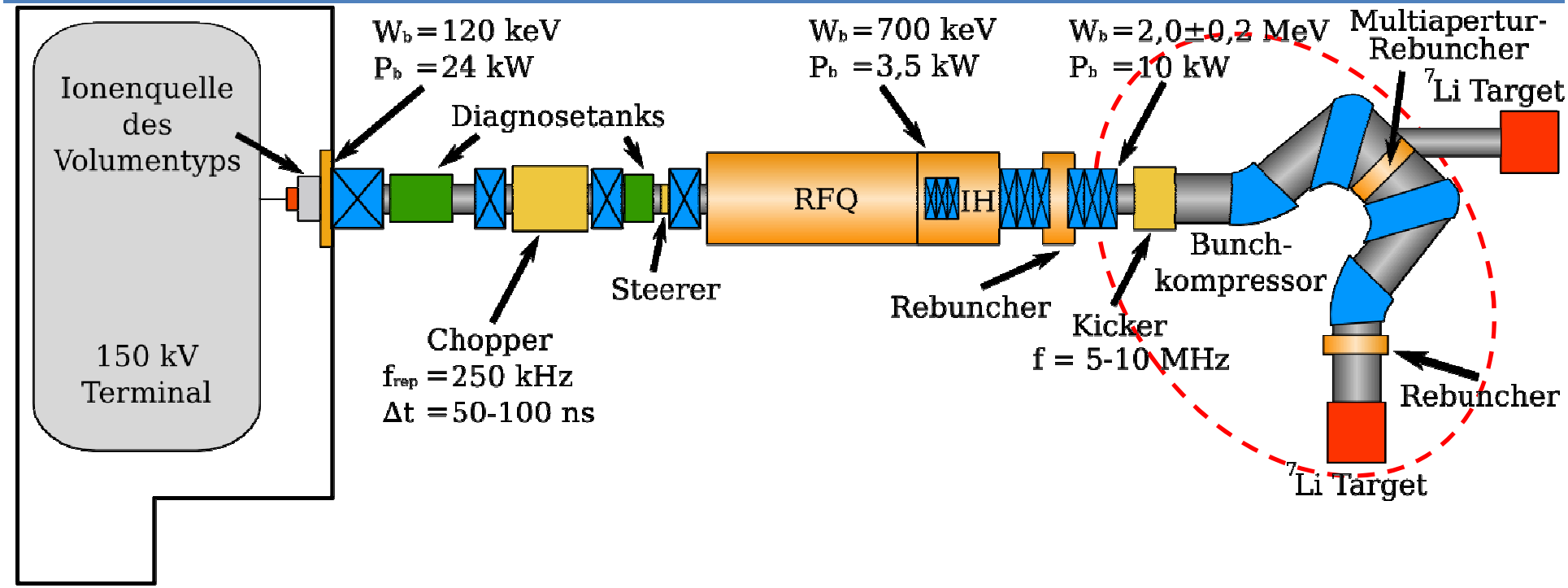
FRANZ: Bunch Compressor - Requirement

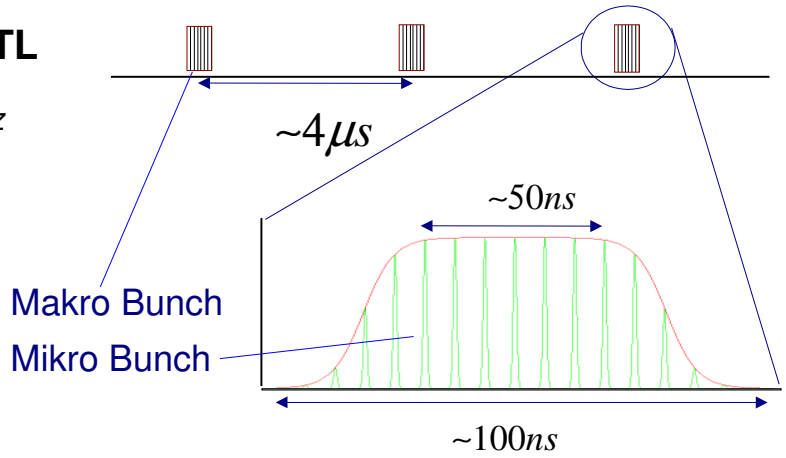


175*MHz*-DTL

rep.rate = 250*kHz*

E ~ 2.0*MeV*

I = 150*mA*



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

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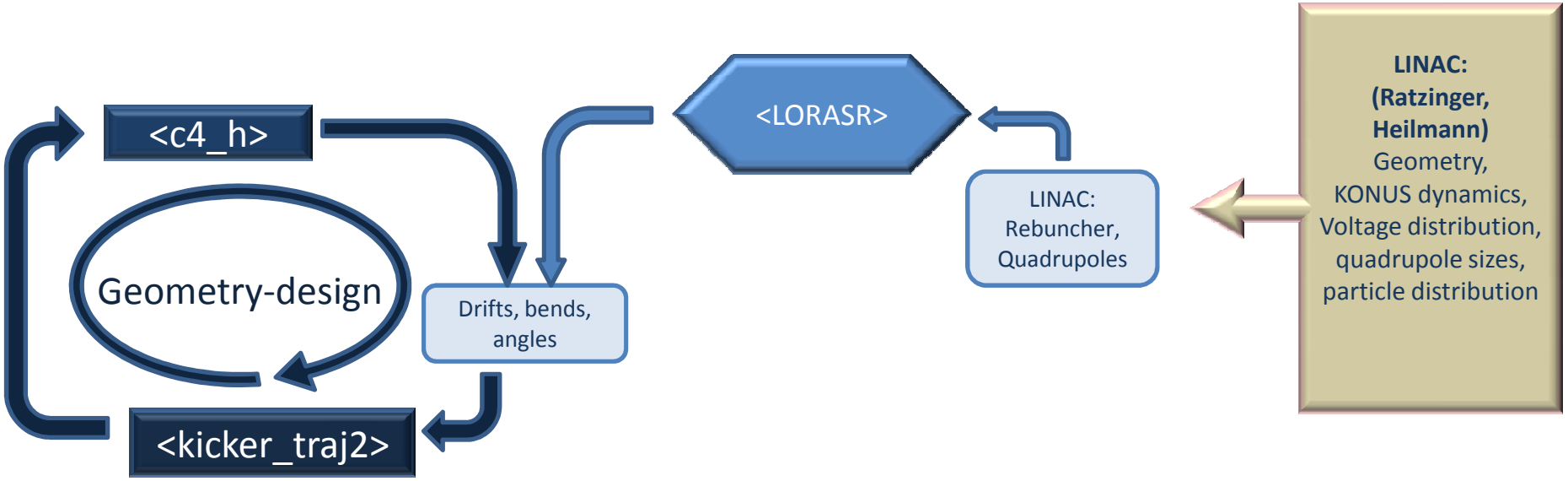

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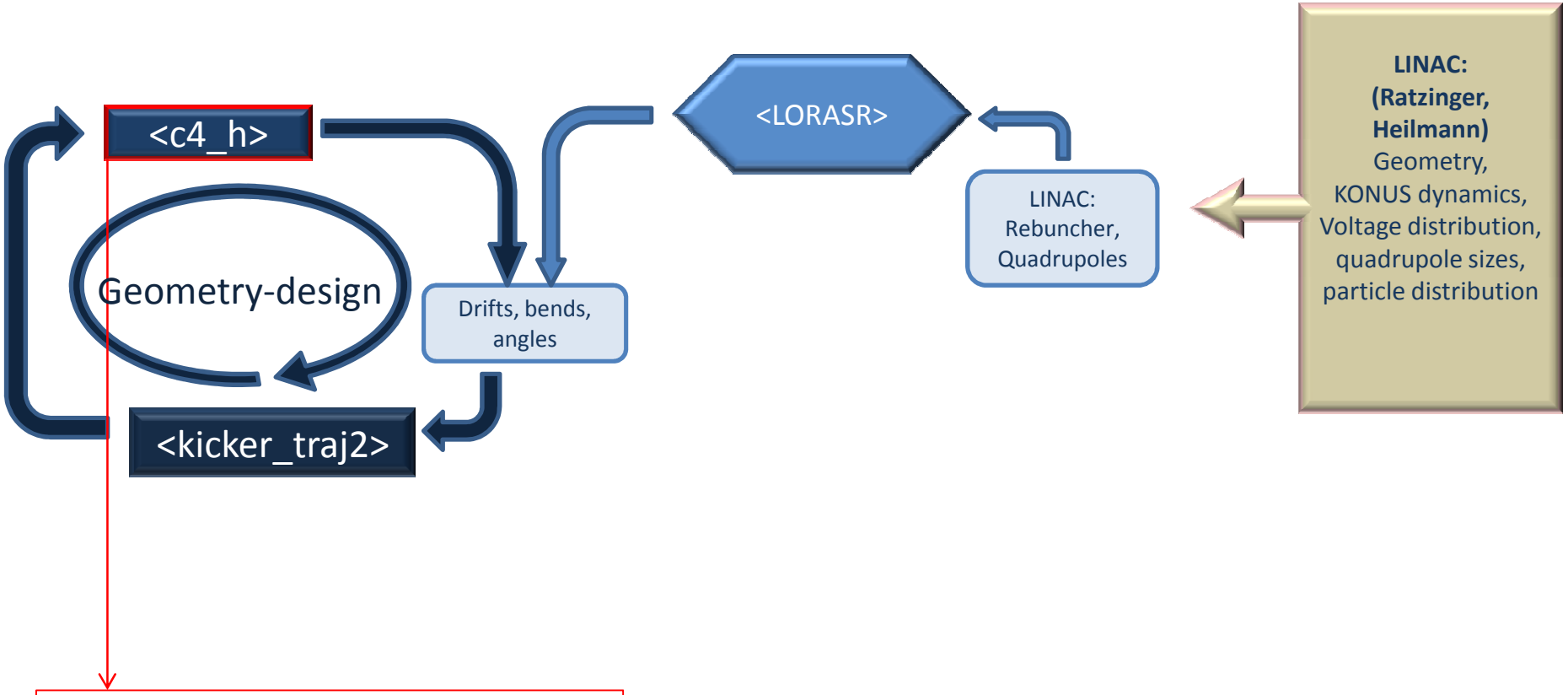

<c4_h>: Geometrical parameters

- trajectories, angles, distances
- magnetic fields, gradients
- shape of the dipoles

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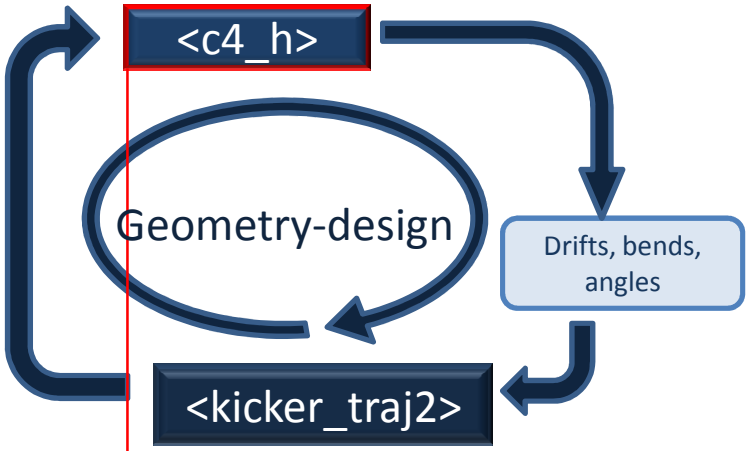

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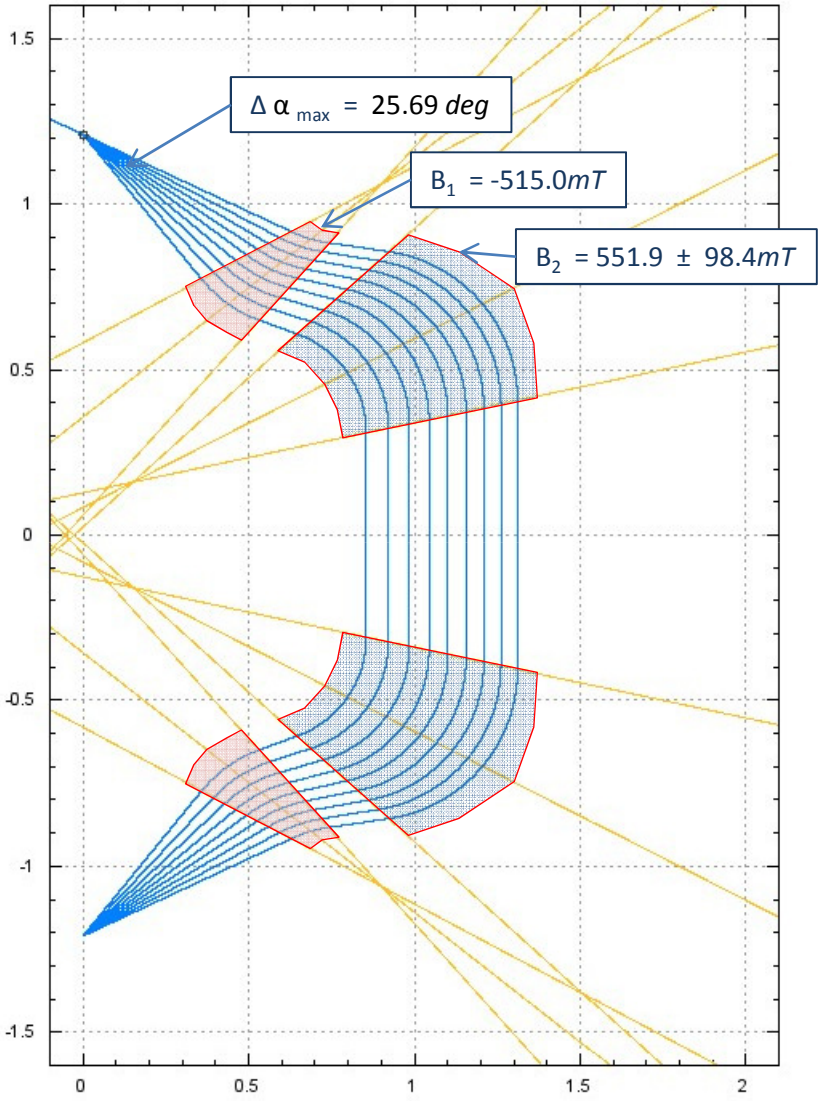
Geometry: g9_5x



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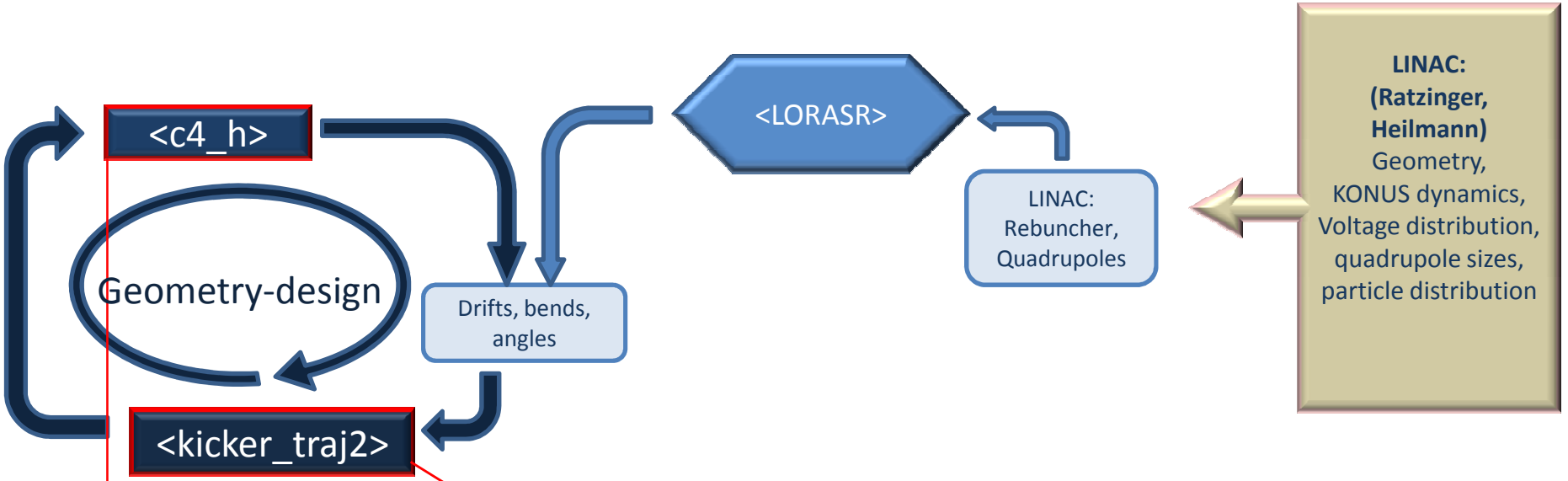

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- trajectories, angles, distances
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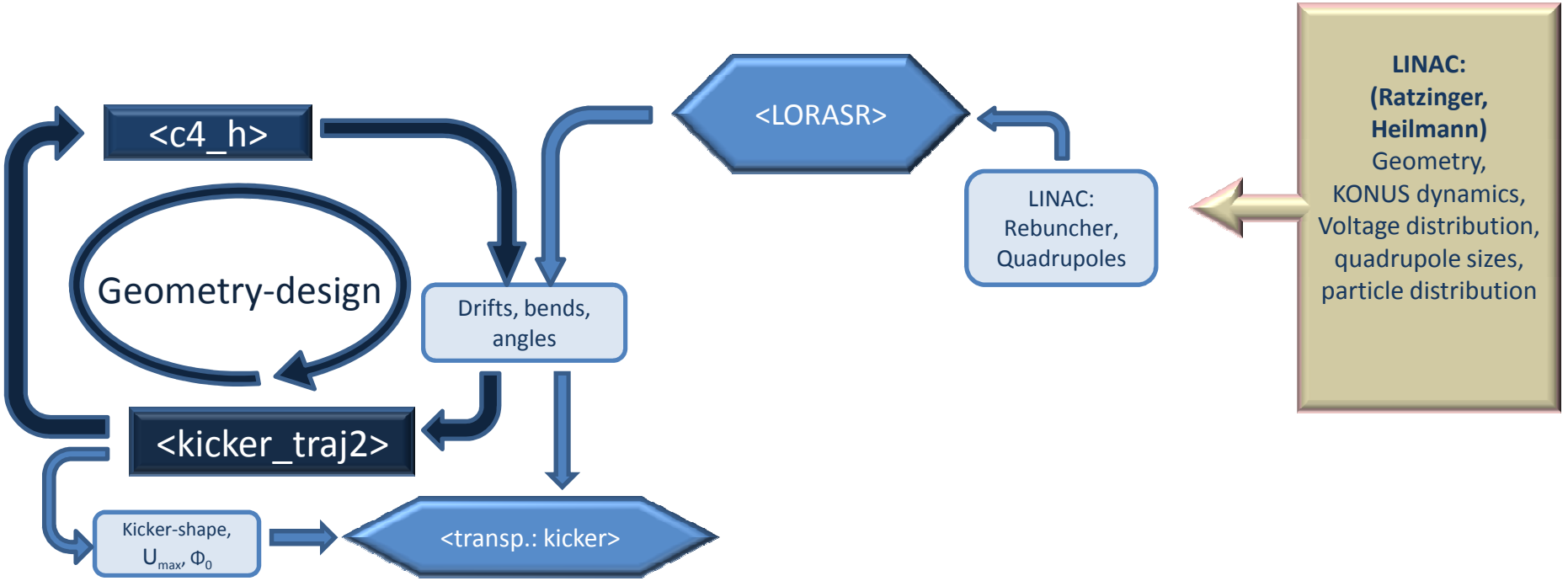
<kicker_traj2>: kicker properties
- max. deflection angles
- max. voltages
- shape of the plates

Bunch Compressor: Design / Optimization Cycles



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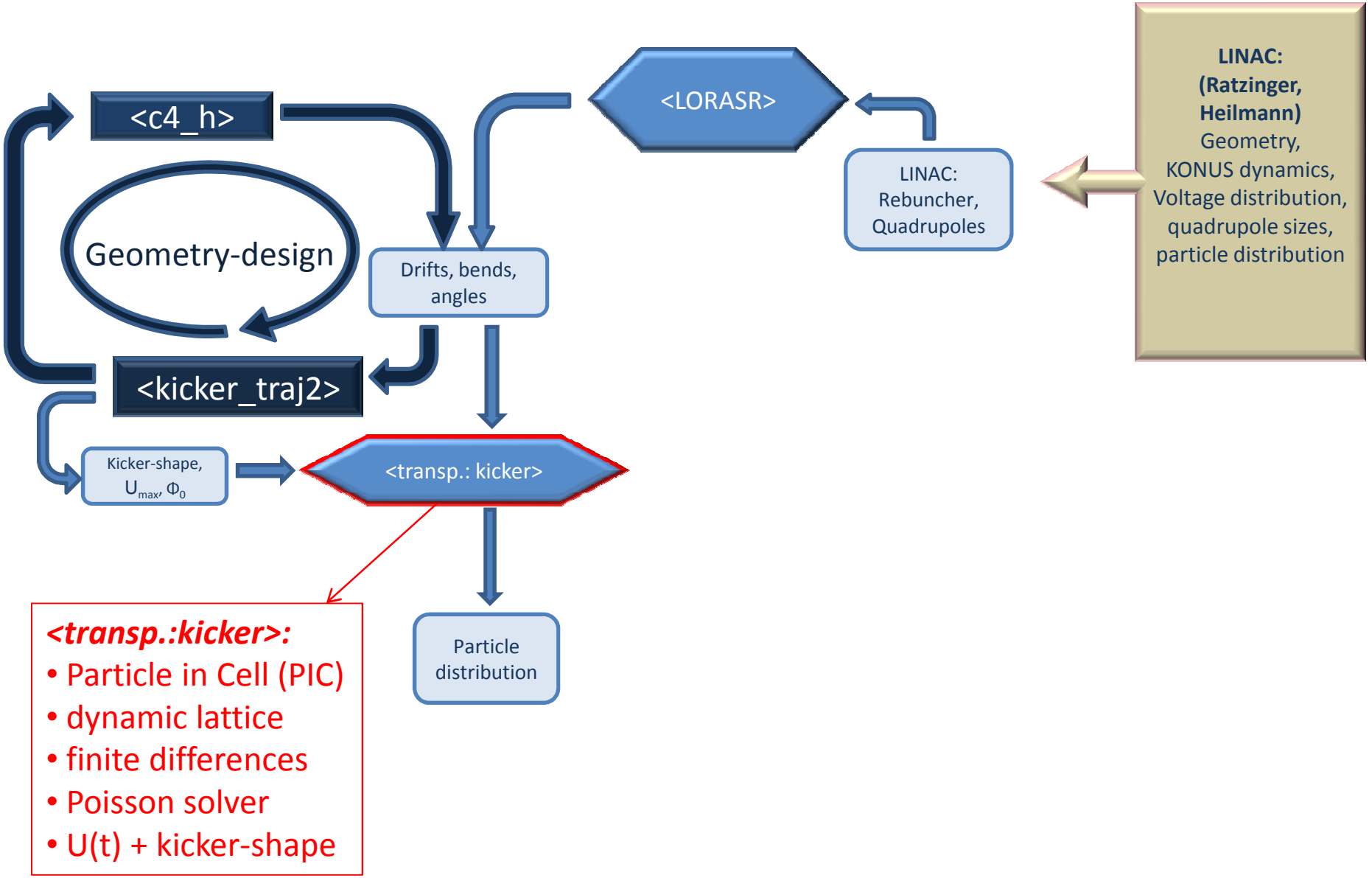

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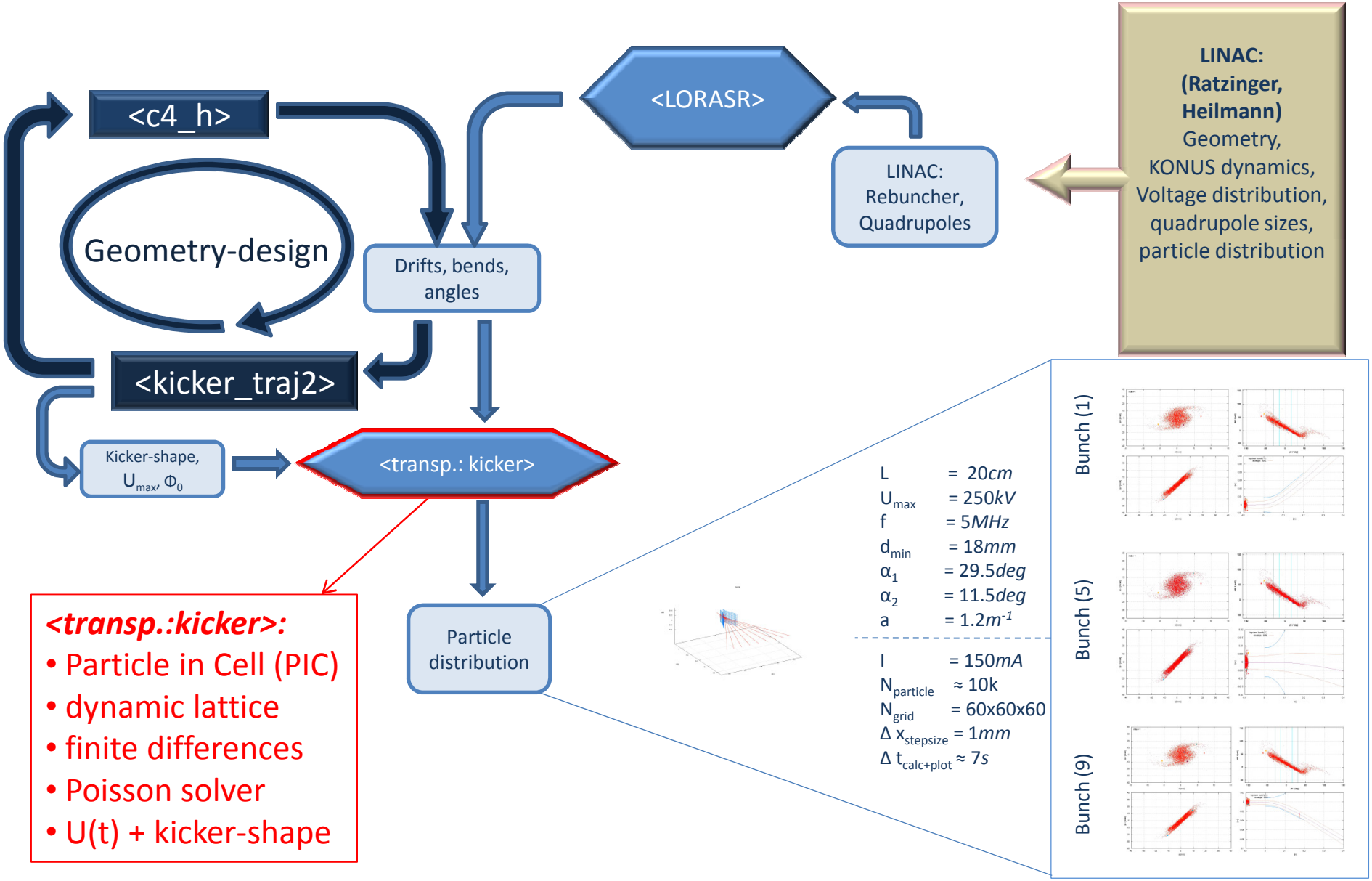

<transp.:kicker>:

- Particle in Cell (PIC)
- dynamic lattice
- finite differences
- Poisson solver
- U(t) + kicker-shape

Analytical estimations:

- RLC-Resonator
- Geometrical parameters:
  - diameter, lengths
  - coil geometry
  - number of windings
- Inductance L and Capacitance C
- RF-properties: f , Q_0, P

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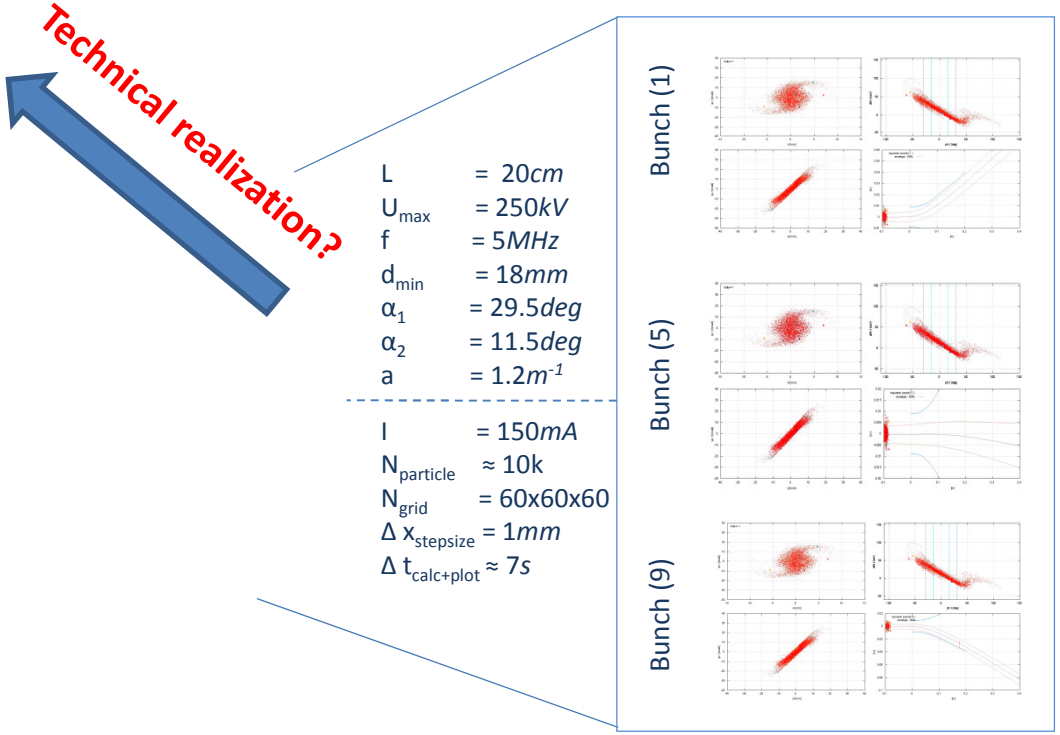
Visitor Scientist
Beijing University
(supervised by U. Ratzinger at FFM)



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Scaled Model (analytical):		
Number of turns	8	
Length of the coil	200	mm
Radius	150	mm
Effective Resistivity	0.246	Ω
Effective Inductance	12.9	µH
Effective Capacitance	28.8	pF
Frequency	**9.09**	**MHz**
Intrinsic Quality Factor	**2986**	
Shunt impedance	**4.4**	**MΩ**
Power losses @ 250kV	**14.8**	**kW**

Designs Studies for the 5MHz-Kicker

Analytical estimations:
- RLC-Resonator
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  - diameter, lengths
  - coil geometry
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- Inductance L and Capacitance C
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Numerical estimation:
- 3D Cavity designs with CST Studios

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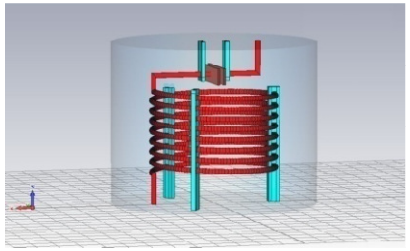

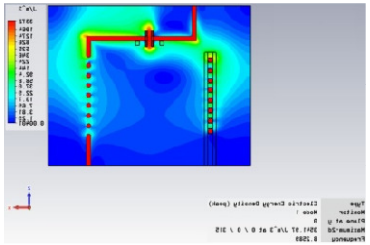

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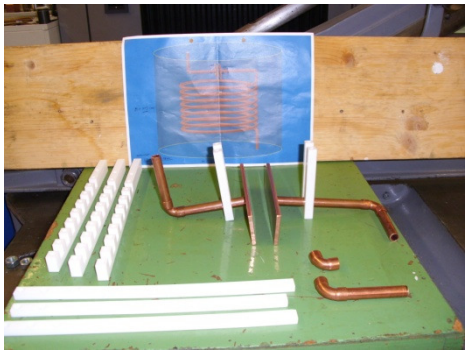
Construction and assembly at IAP- and IKF-workshop



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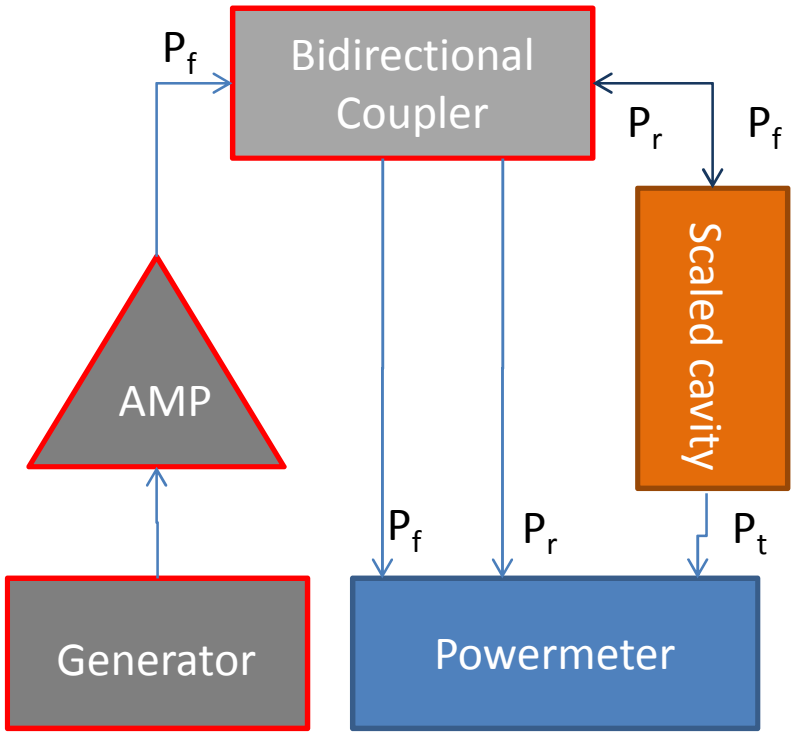
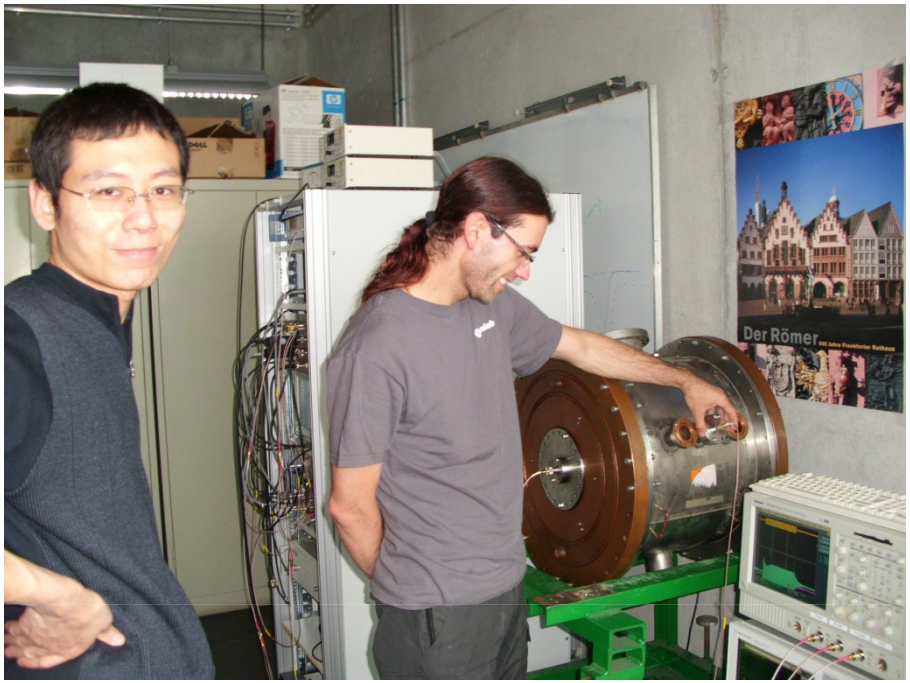
THANKS !!!
@Workshops
@A. Schempp

Measurements at scaled Model





THANKS to H. Podlech
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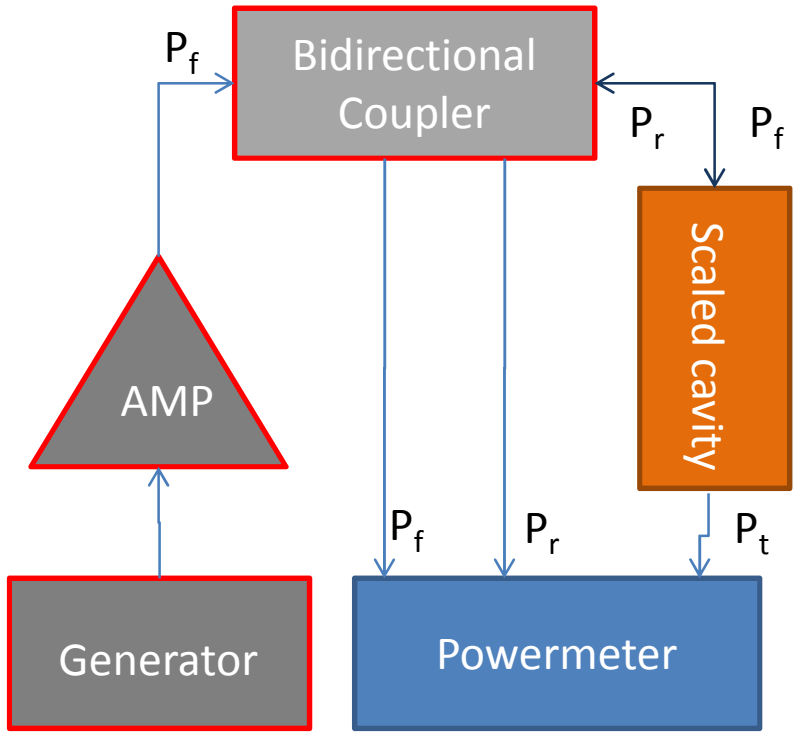

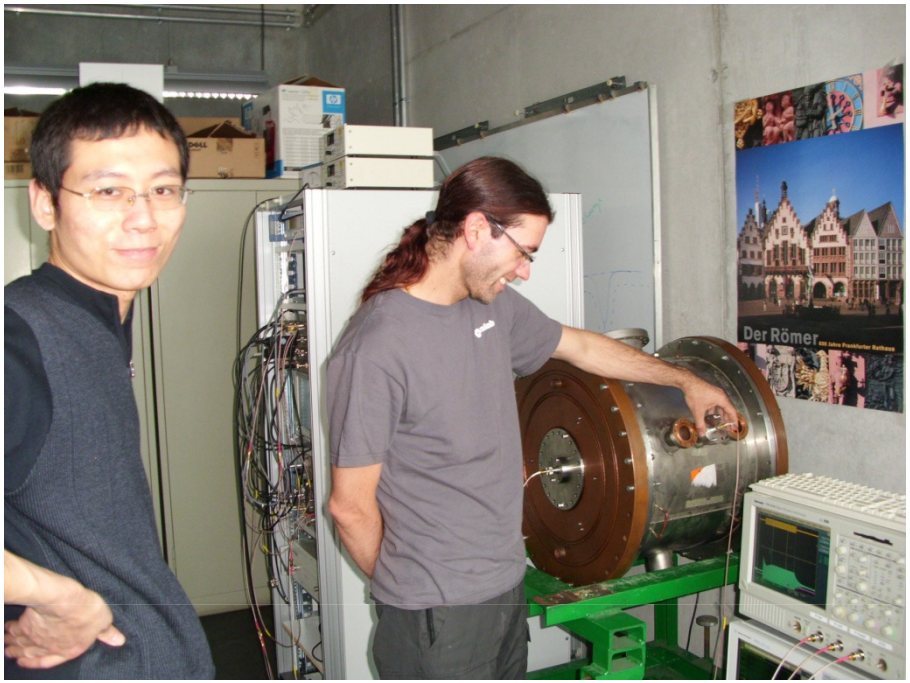

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P_t : $U(t) = U_0 \cdot \exp(-t/\tau) \sim E(t)$

$W(t) \sim E(t)^2 \Rightarrow \tau = 2\,\tau_L$

τ_L : decay time of the stored energy in the cavity

$\Rightarrow Q_L = \omega \cdot \tau_L$: loaded quality factor

$\Rightarrow Q_0 = Q_L \cdot (1+\beta)$: intrinsic quality factor

$\Rightarrow P_r^{on} = P_r^{off} \Leftrightarrow \beta=1$ (critical coupling) $\Rightarrow Q_0=2Q_L$

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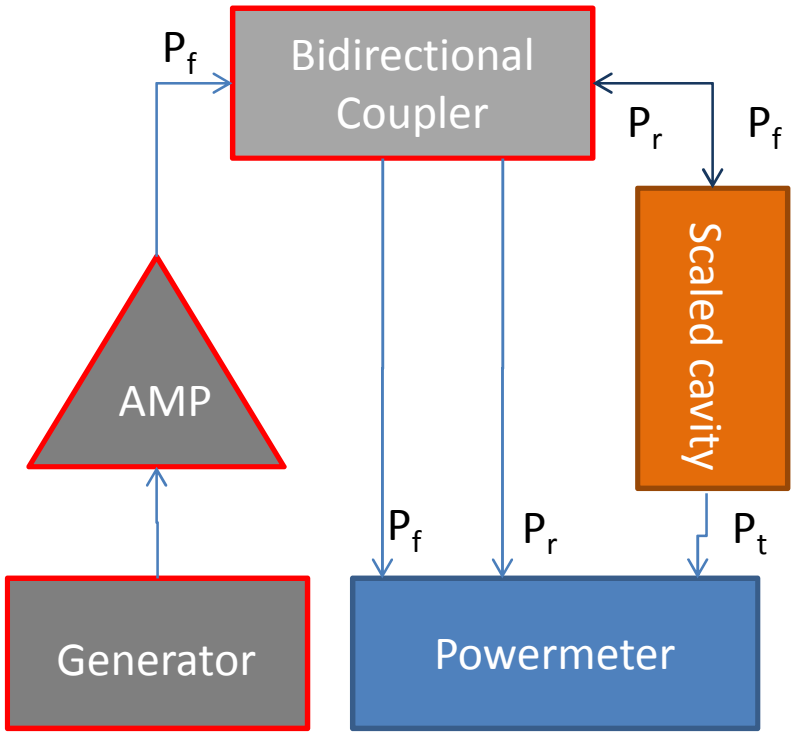

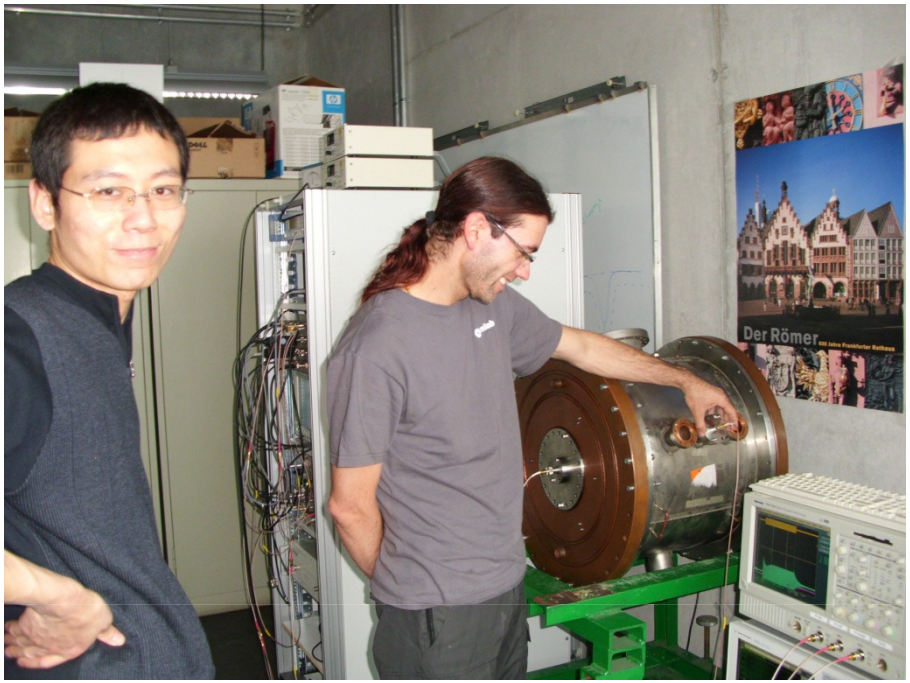

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Perturbation Capacitor method
=> shunt impedance

$$f_{per} = \frac{1}{2\pi\sqrt{L(C+\Delta C)}} \Leftrightarrow C = \frac{\Delta C}{(f/f_{per})^2 - 1}$$

$$R_p = \frac{U^2}{P} = \frac{2Q_0}{\omega C}$$

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 (~ 120×62mm^2) are needed for critical coupling

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

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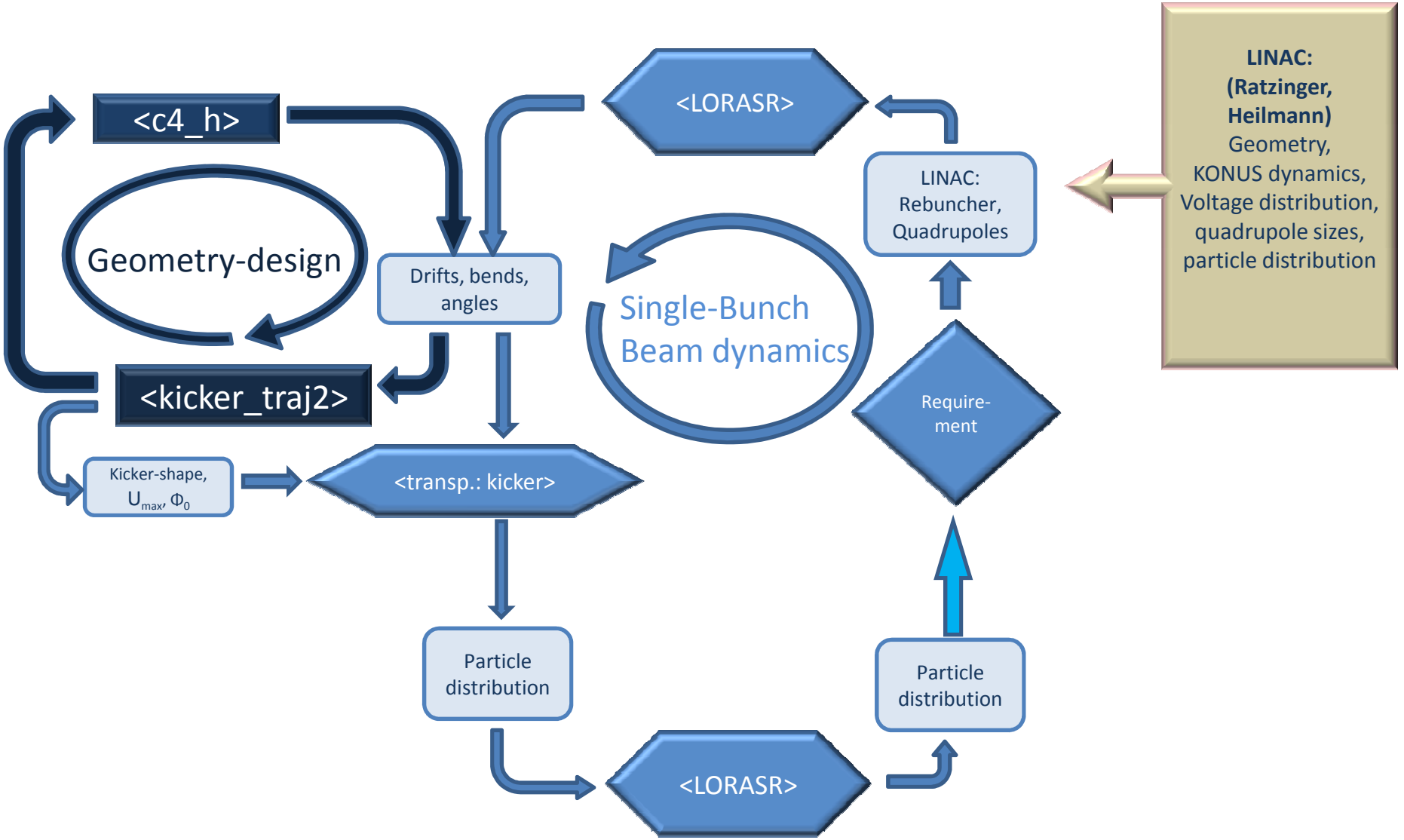

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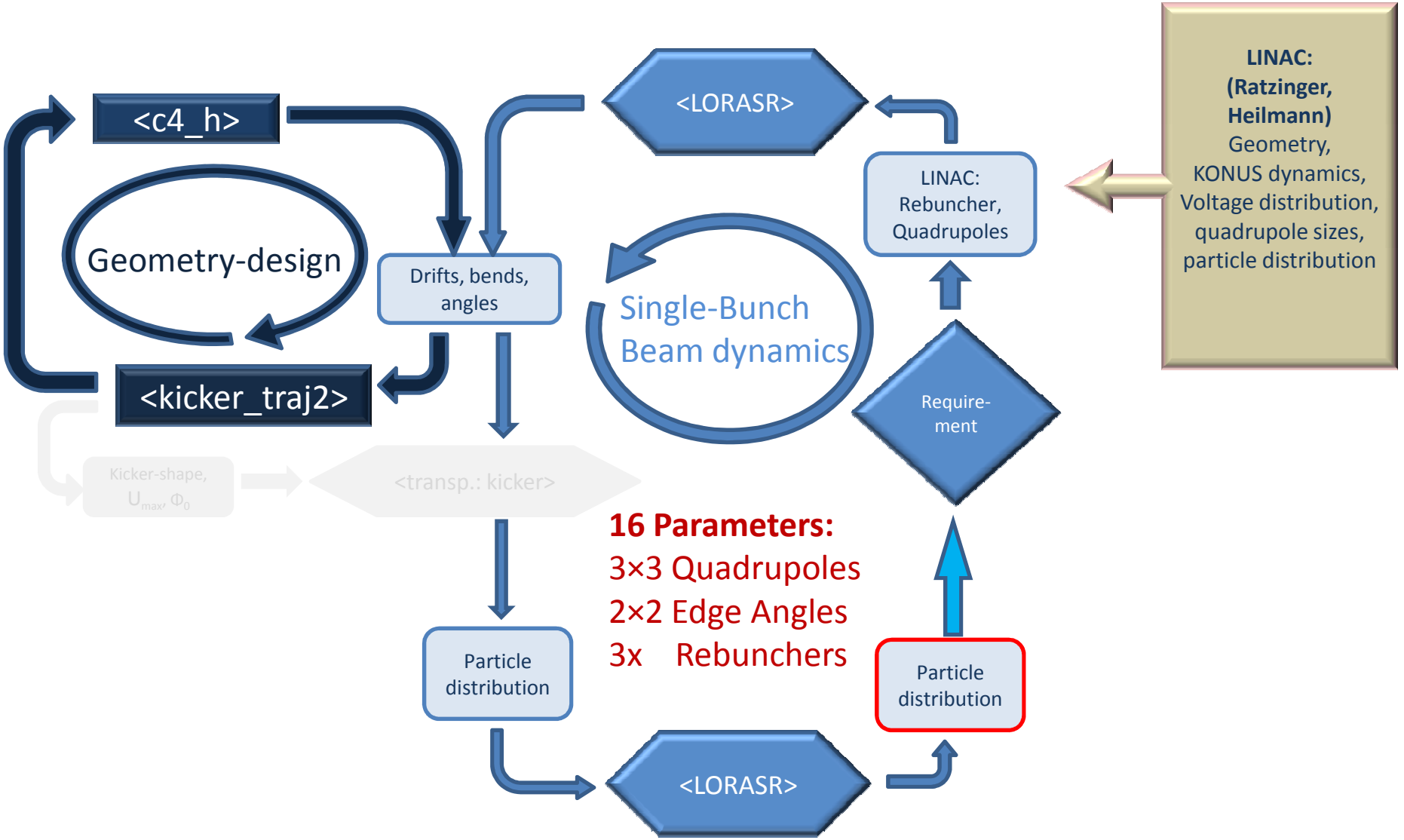
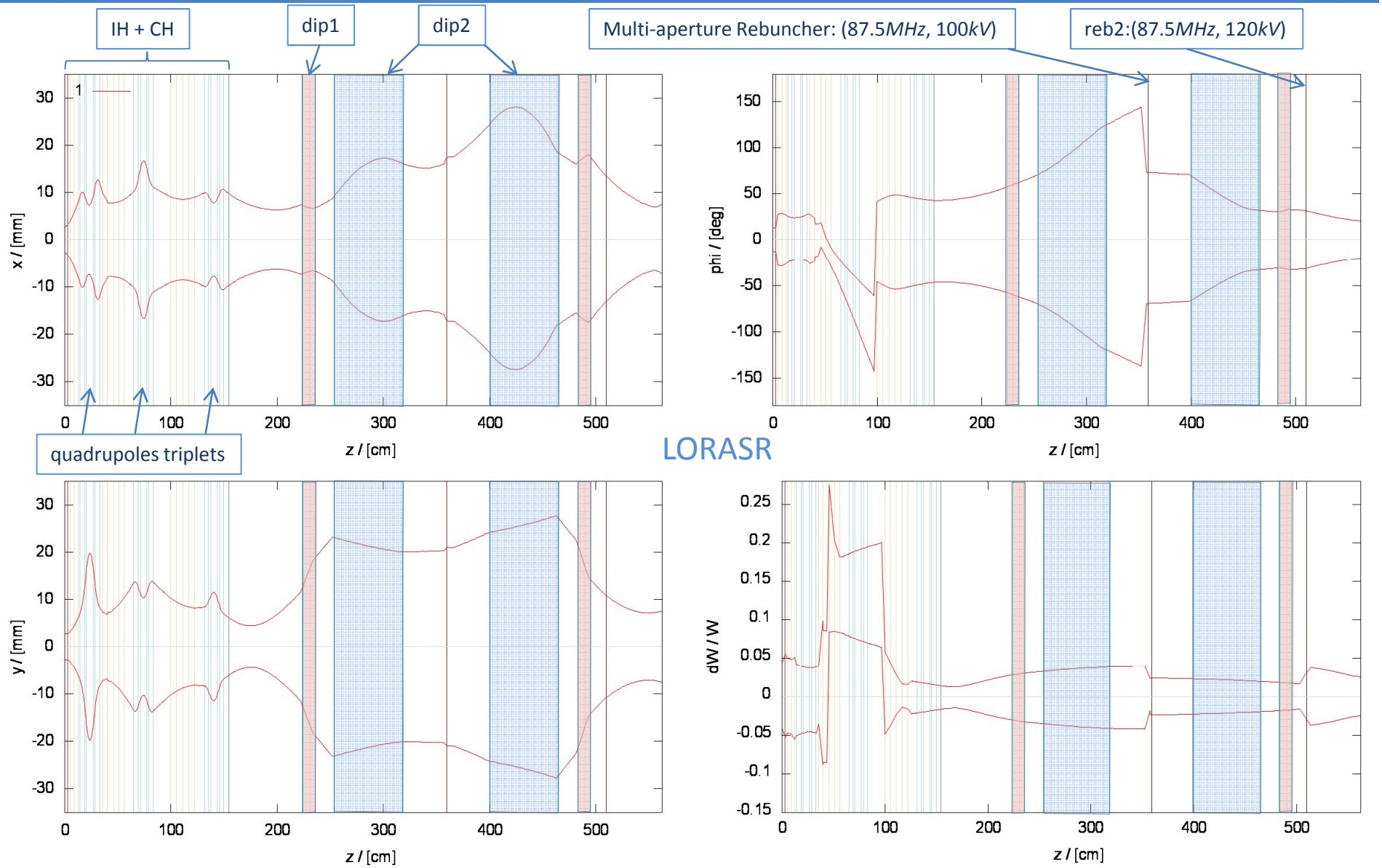
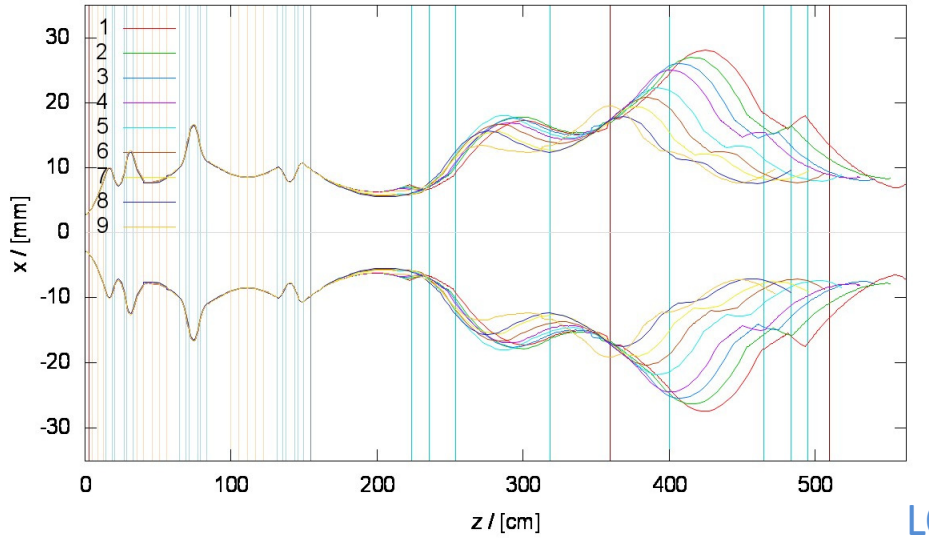
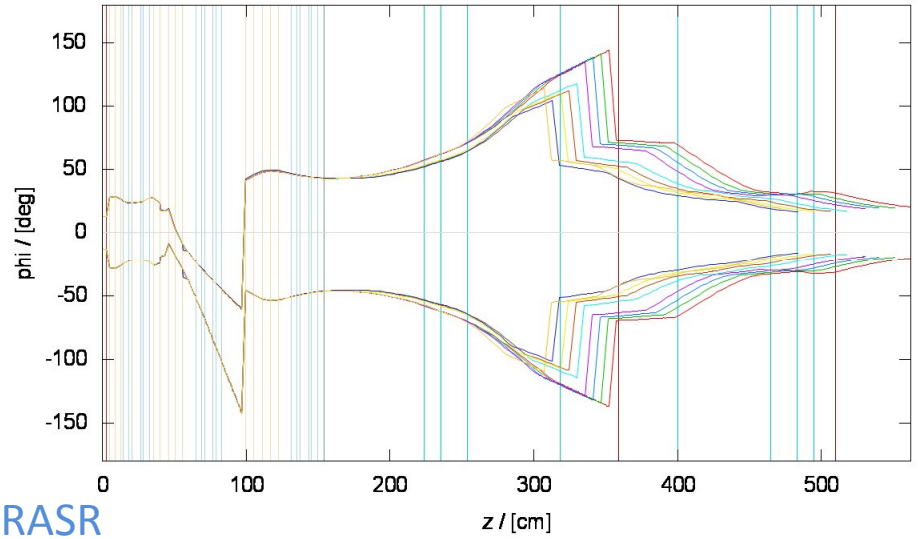


Bunch Compressor: Envelopes(95%) – bunch(1)

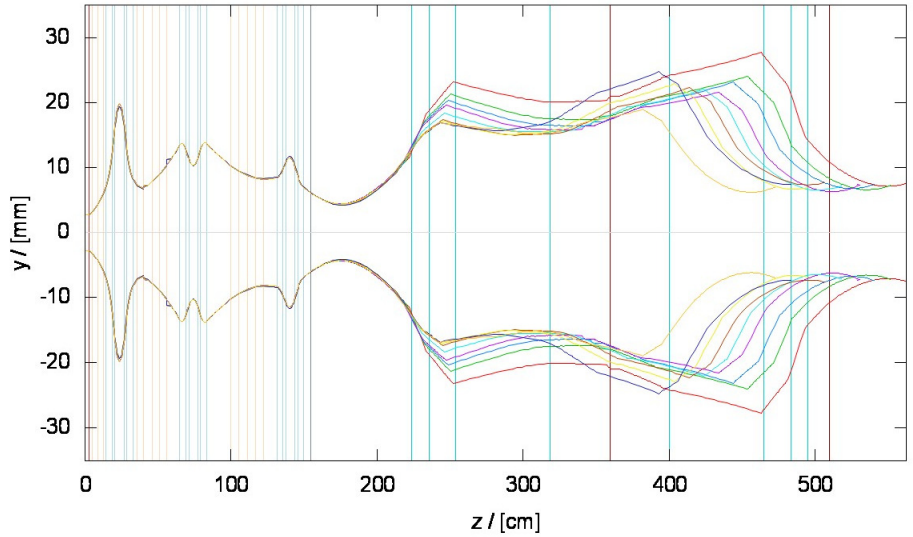


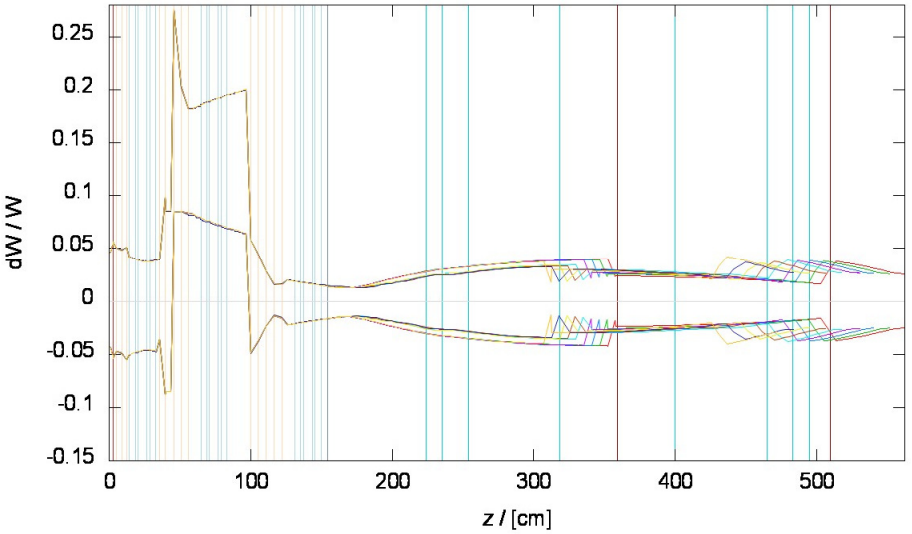
Bunch Compressor: Envelopes(95%) – bunch(all)





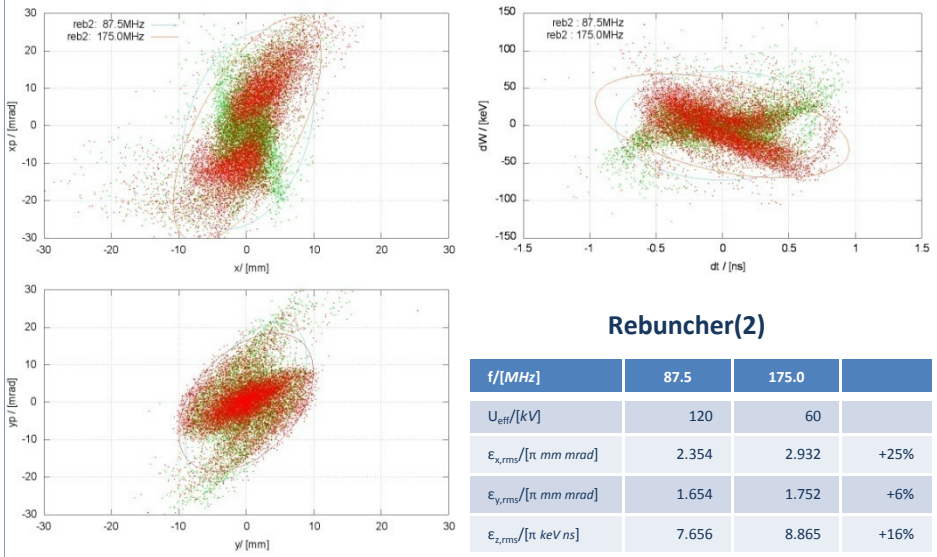
LORASR





Bunch Compressor: projections at the target

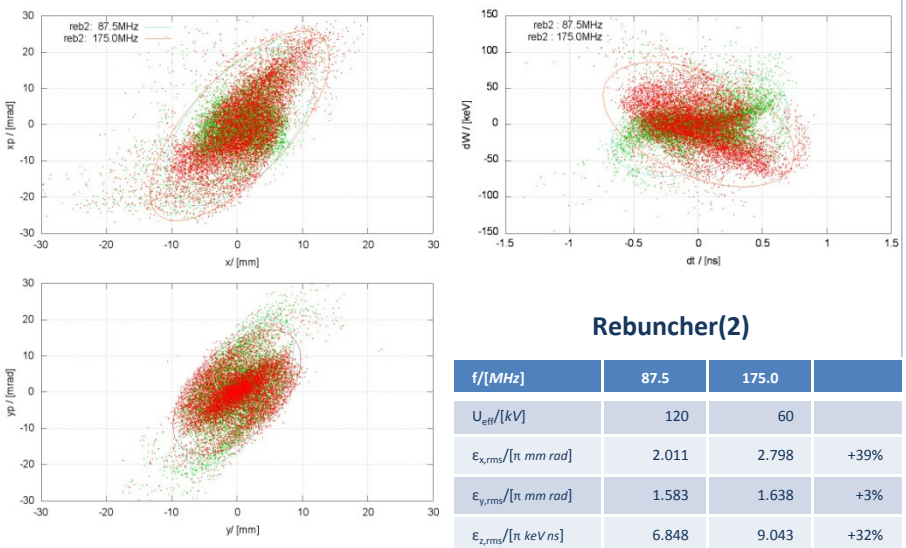
Bunch(1)



Rebuncher(2)

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

Bunch(5)



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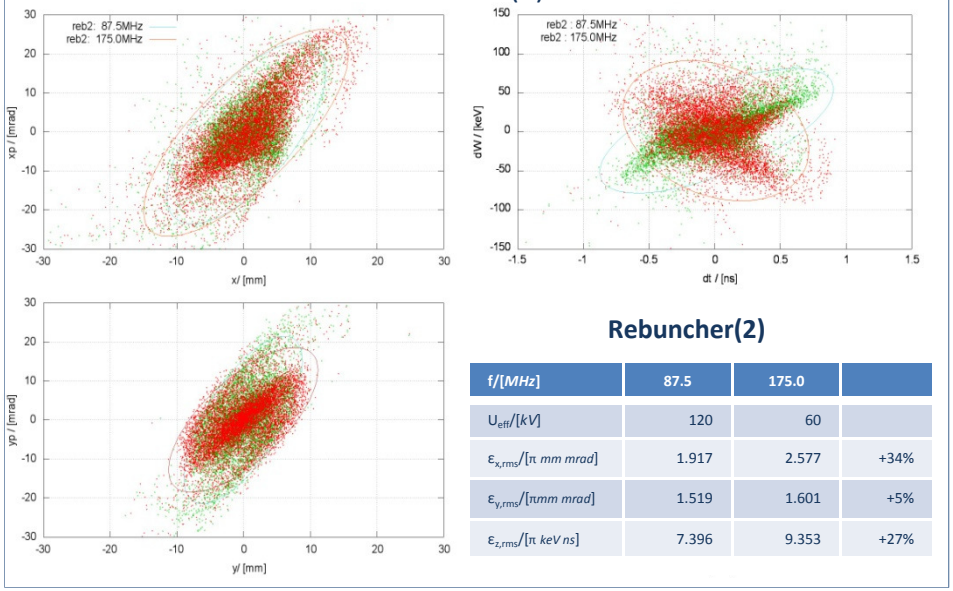

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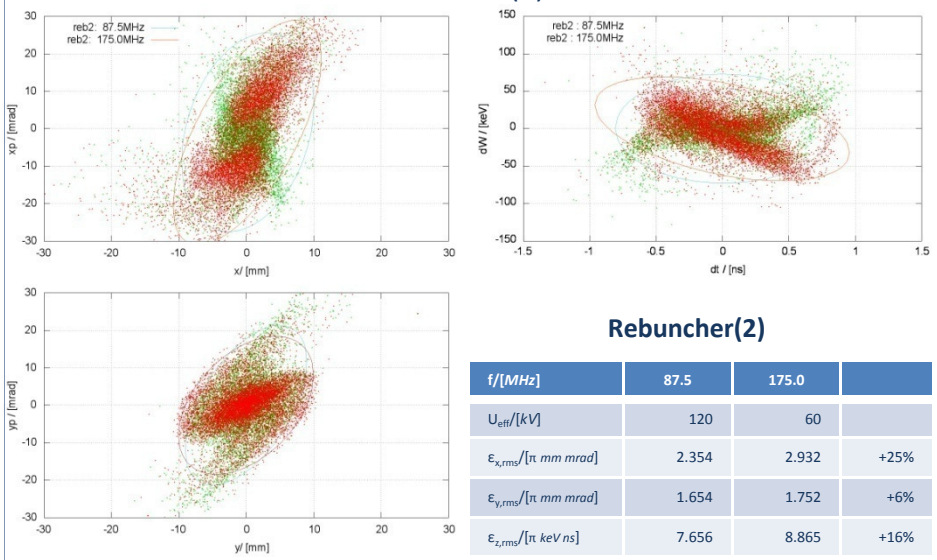

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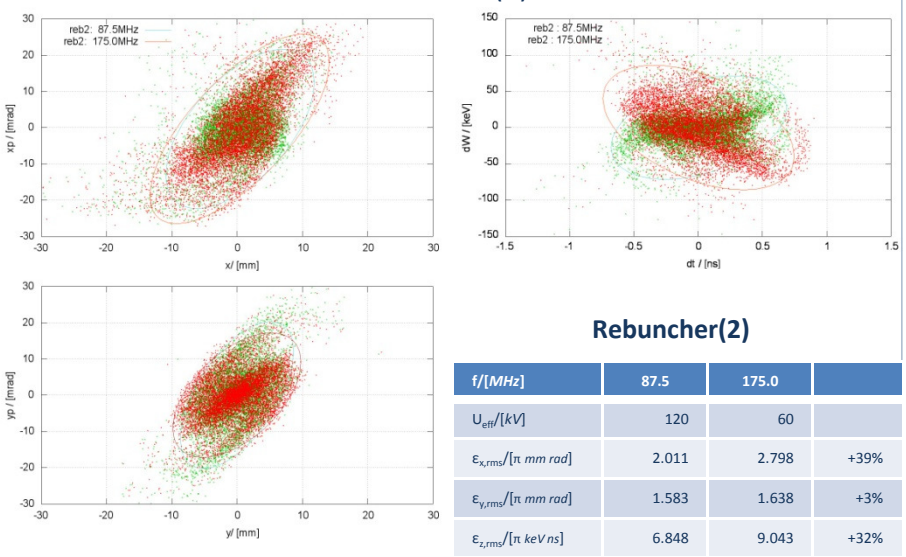

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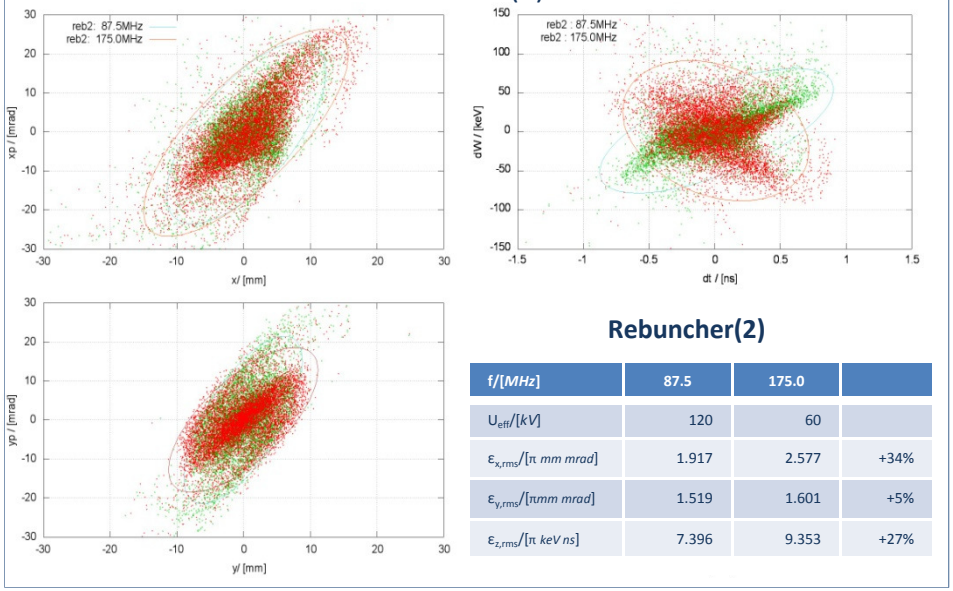

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Single Bunch Beam Dynamics:

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

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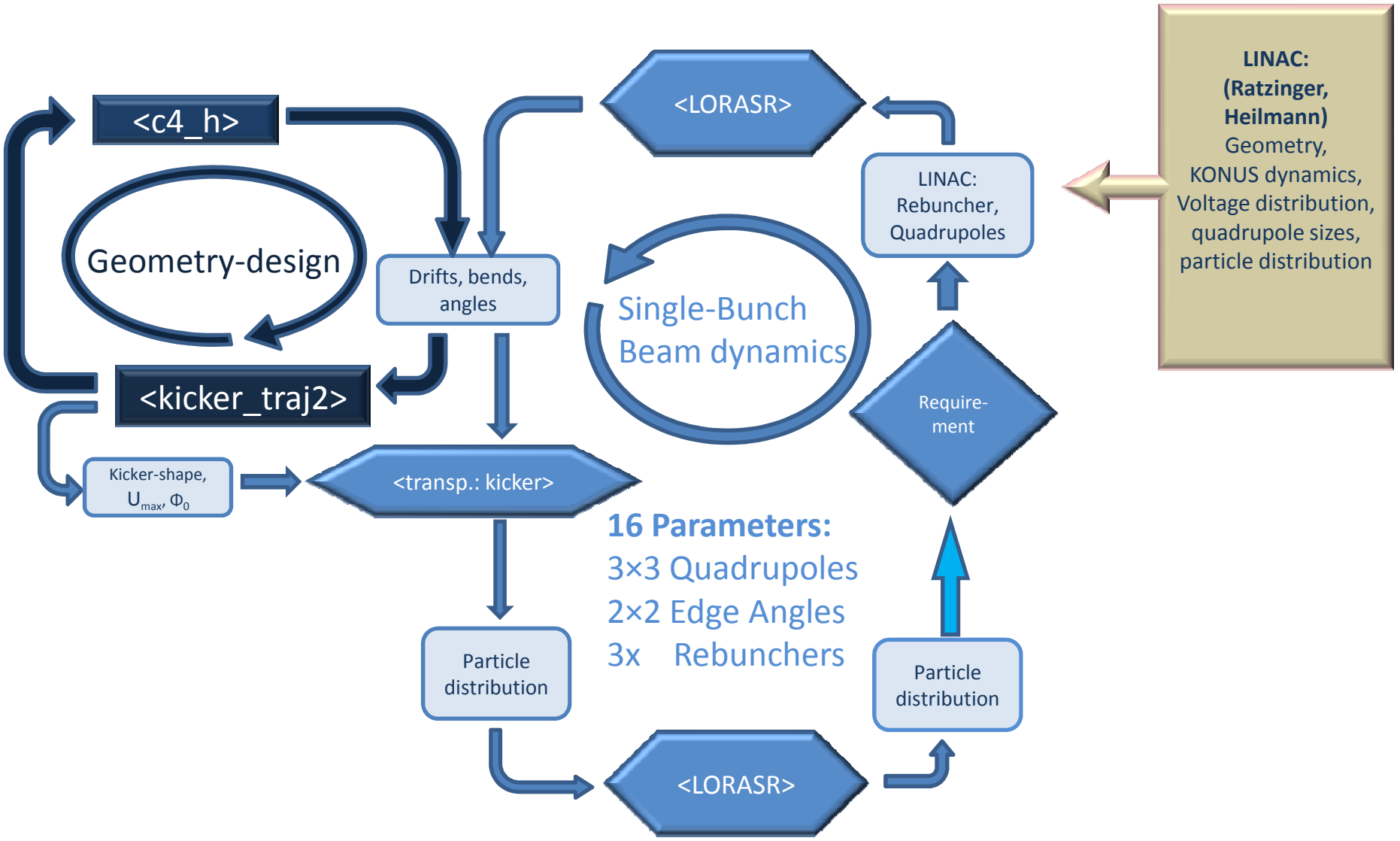

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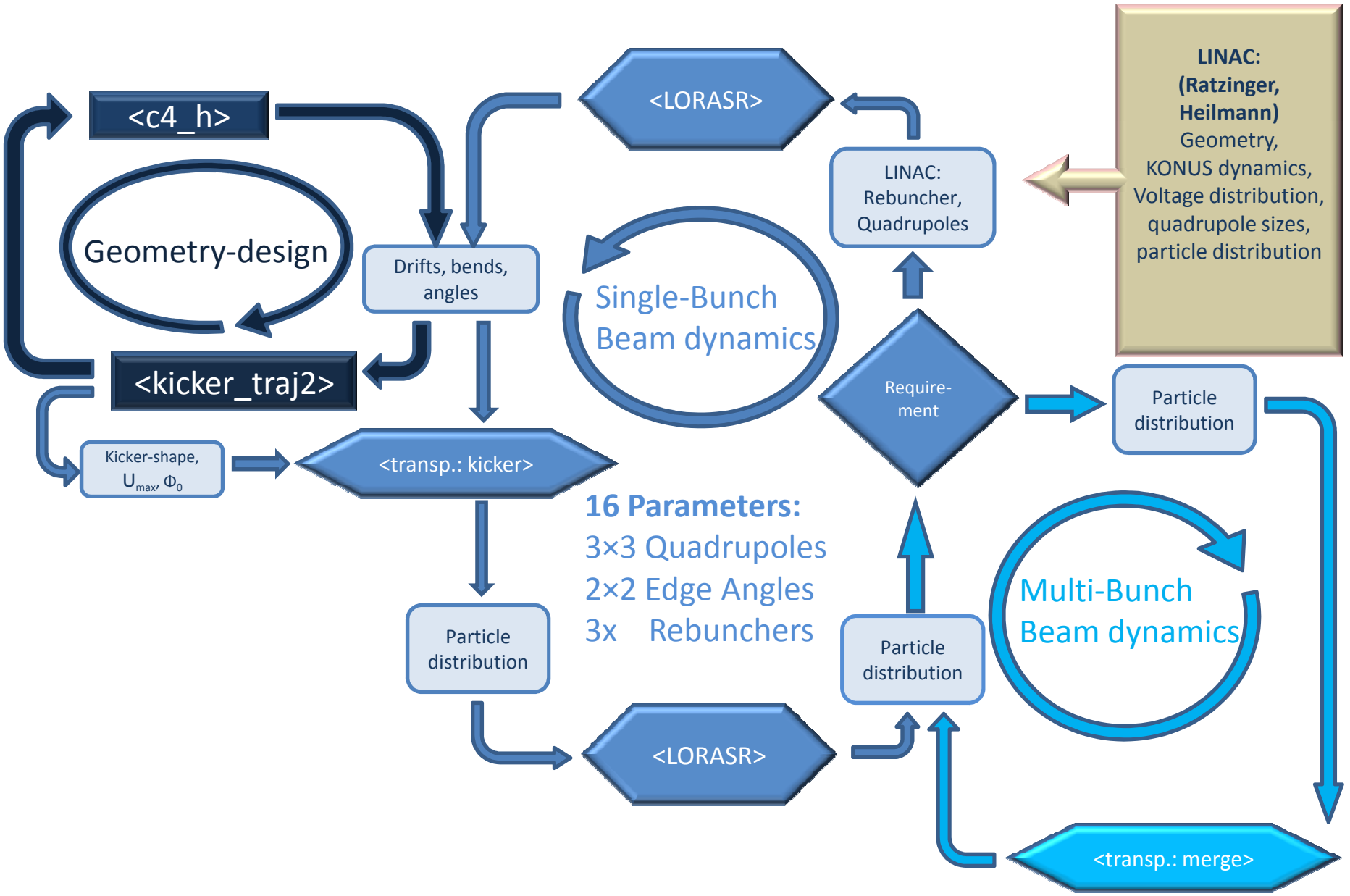

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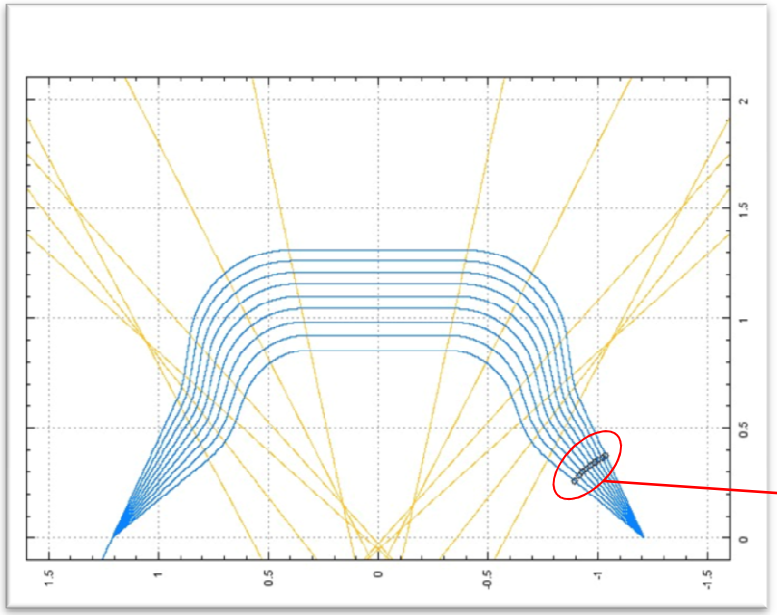
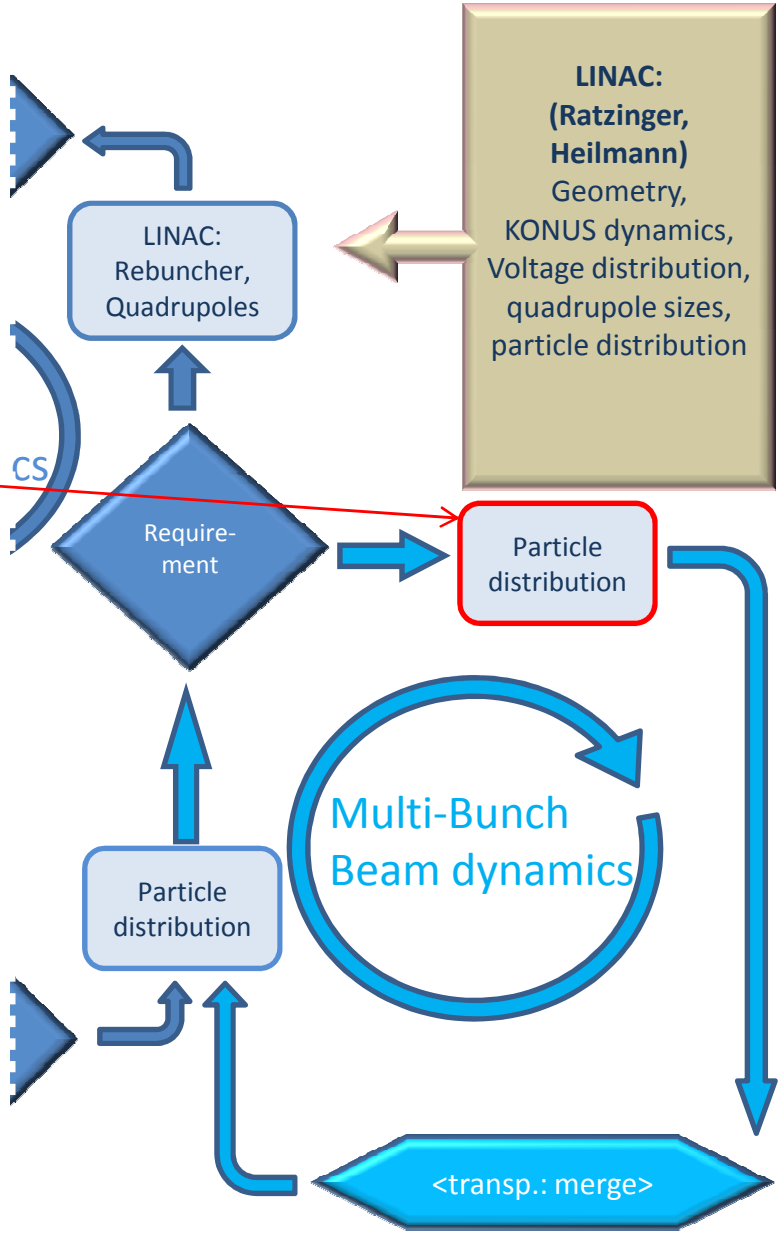
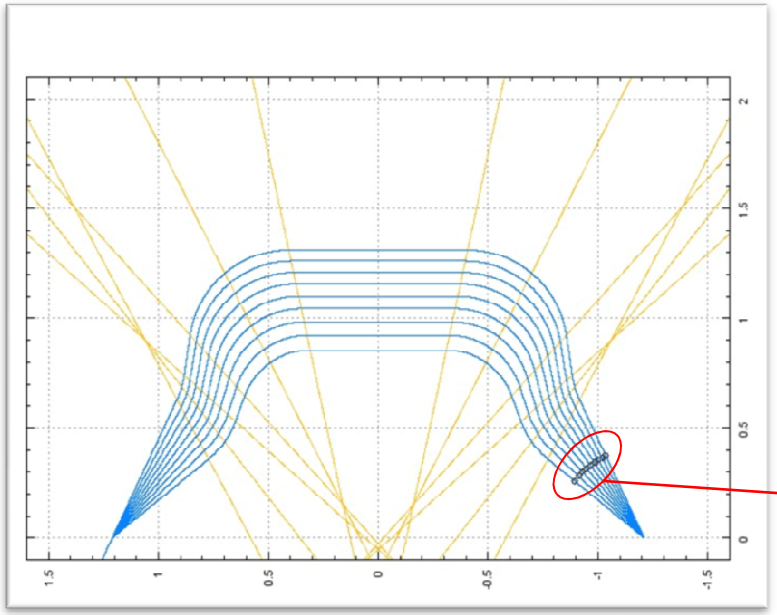
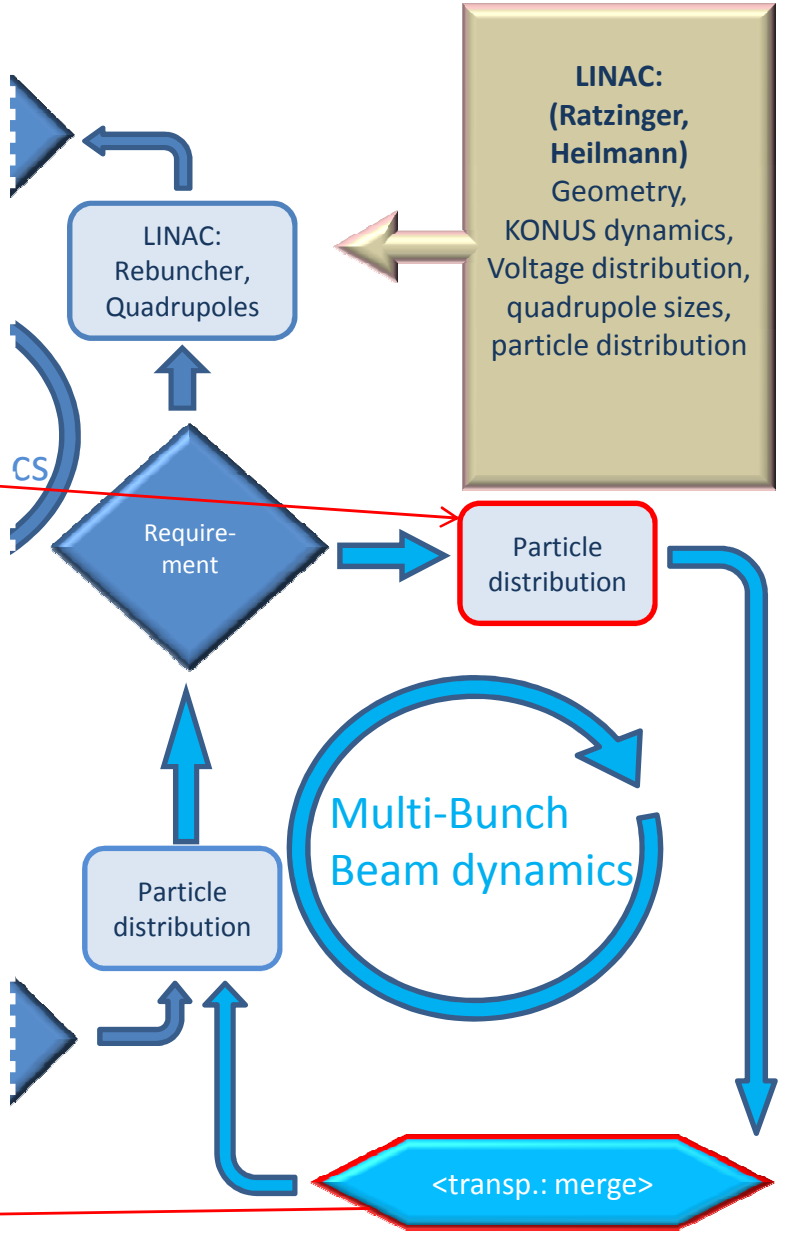




Bunch Compressor: Design / Optimization Cycles

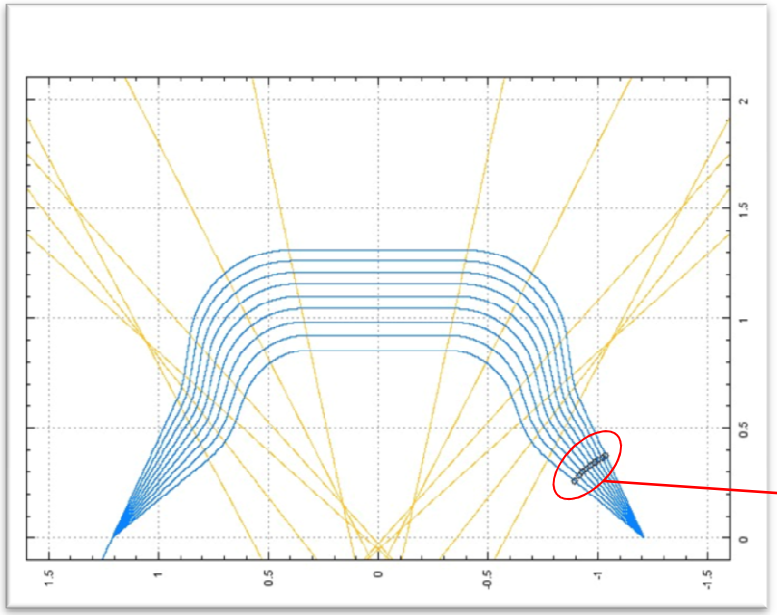




<transp.:merge>:

- Particle in Cell (PIC)
- dynamic lattice
- finite differences
- Poisson solver

Bunch Compressor: Design / Optimization Cycles



LINAC: (Ratzinger, Heilmann) Geometry, KONUS dynamics, Voltage distribution, quadrupole sizes, particle distribution

LINAC: Rebuncher, Quadrupoles

CS

Require-ment

Particle distribution

Multi-Bunch Beam dynamics

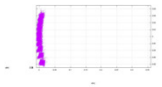
Particle distribution

<transp.: merge>

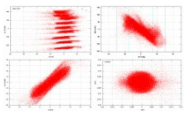
L = 35*cm*

I = 9x150*mA*
$N_{particle}$ ≈ 90k
N_{grid} = 100x100x100
$\Delta x_{stepsize}$ = 1*mm*
$\Delta t_{calc+plot}$ ≈ 50*s*

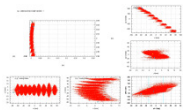
merge



Projections at target



projections

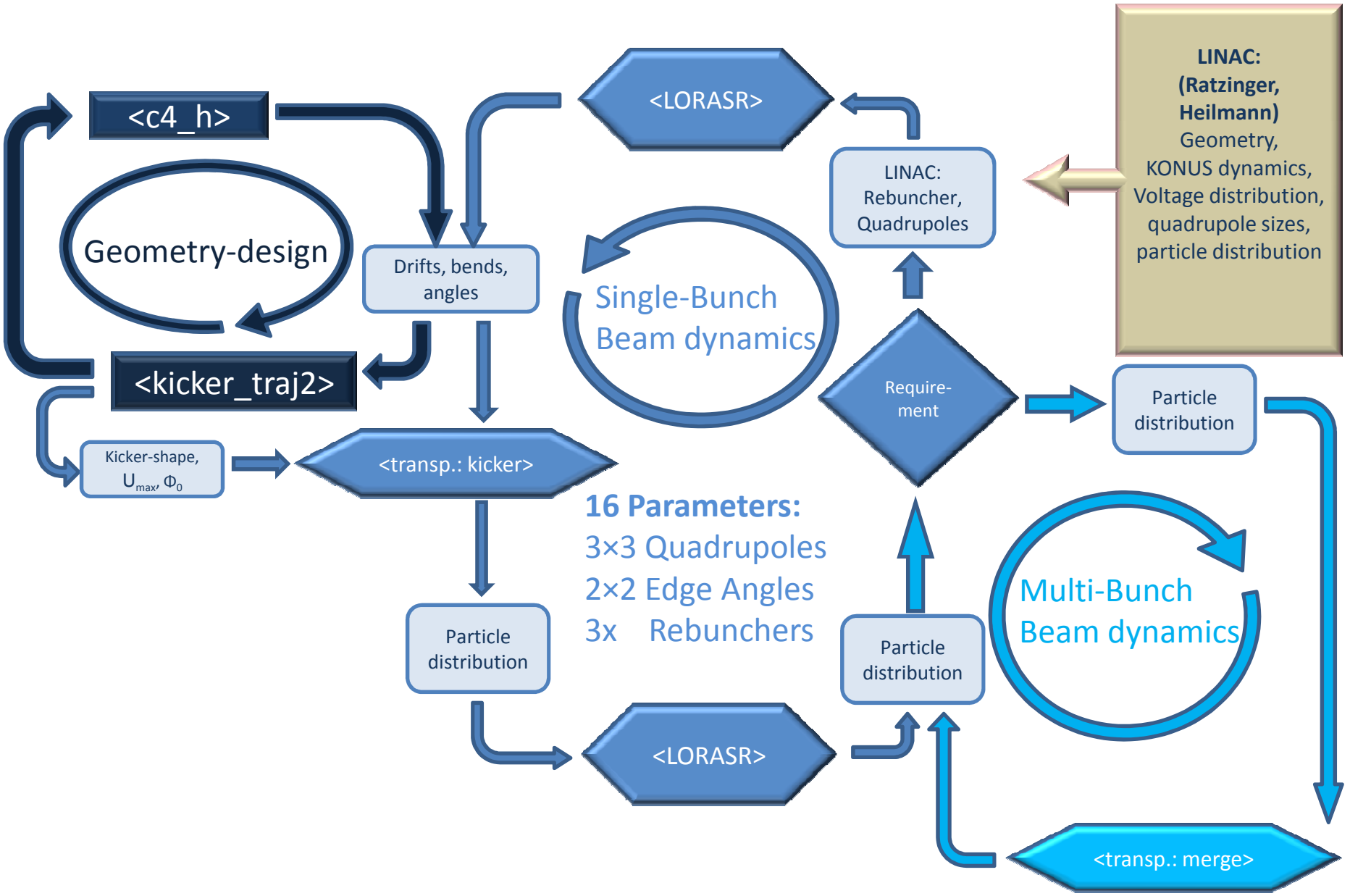


<transp.:merge>:
- Particle in Cell (PIC)
- dynamic lattice
- finite differences
- Poisson solver

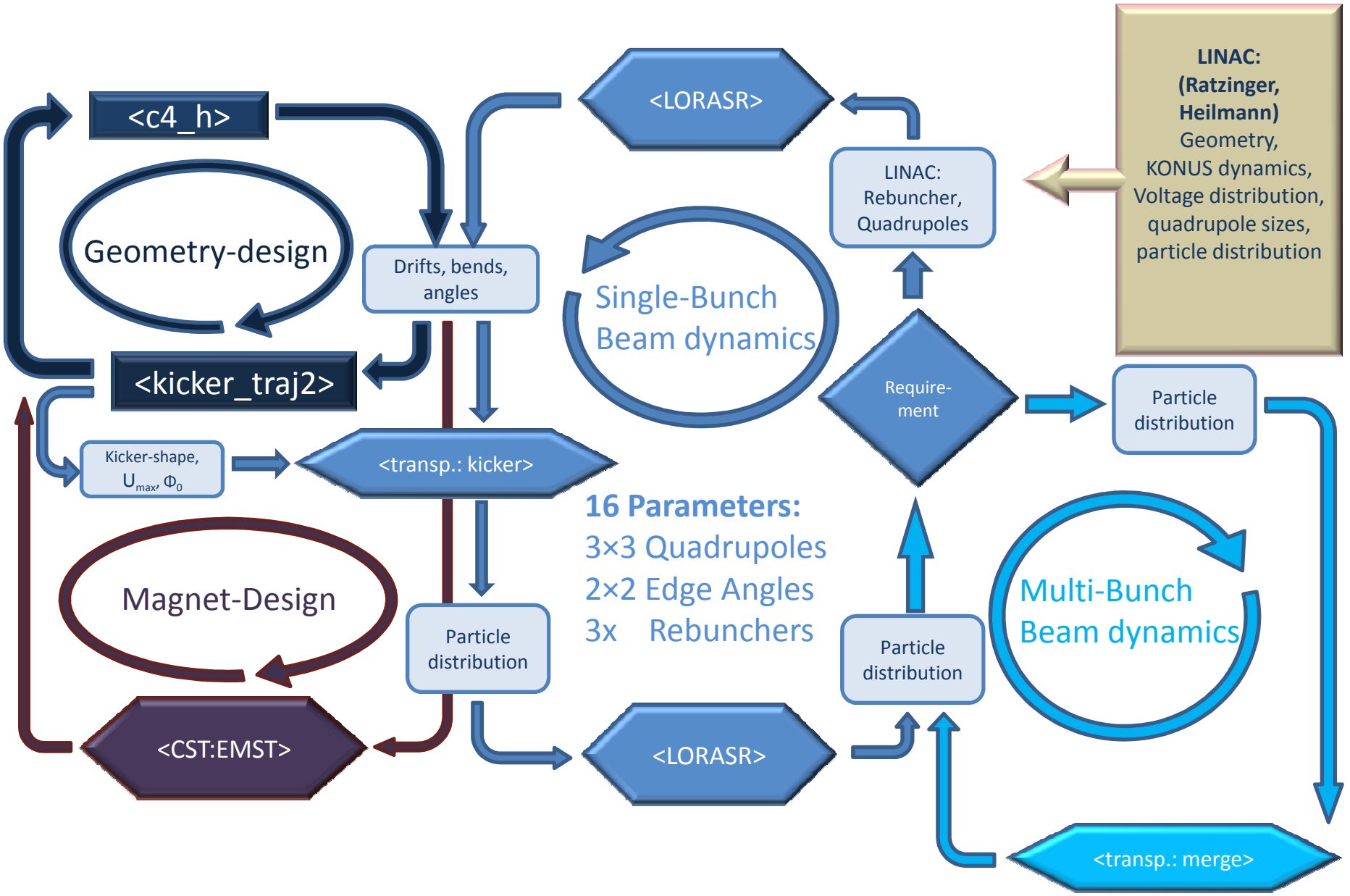
Outlines:

- Requirements
- **Design / Optimization Cycles**
  - Geometry
  - 5MHz Kicker
  - Single Bunch Beam Dynamics
  - Merging Scenario
  - Magnet Design
  - Beam Dynamics with realistic field distributions
- Outlook

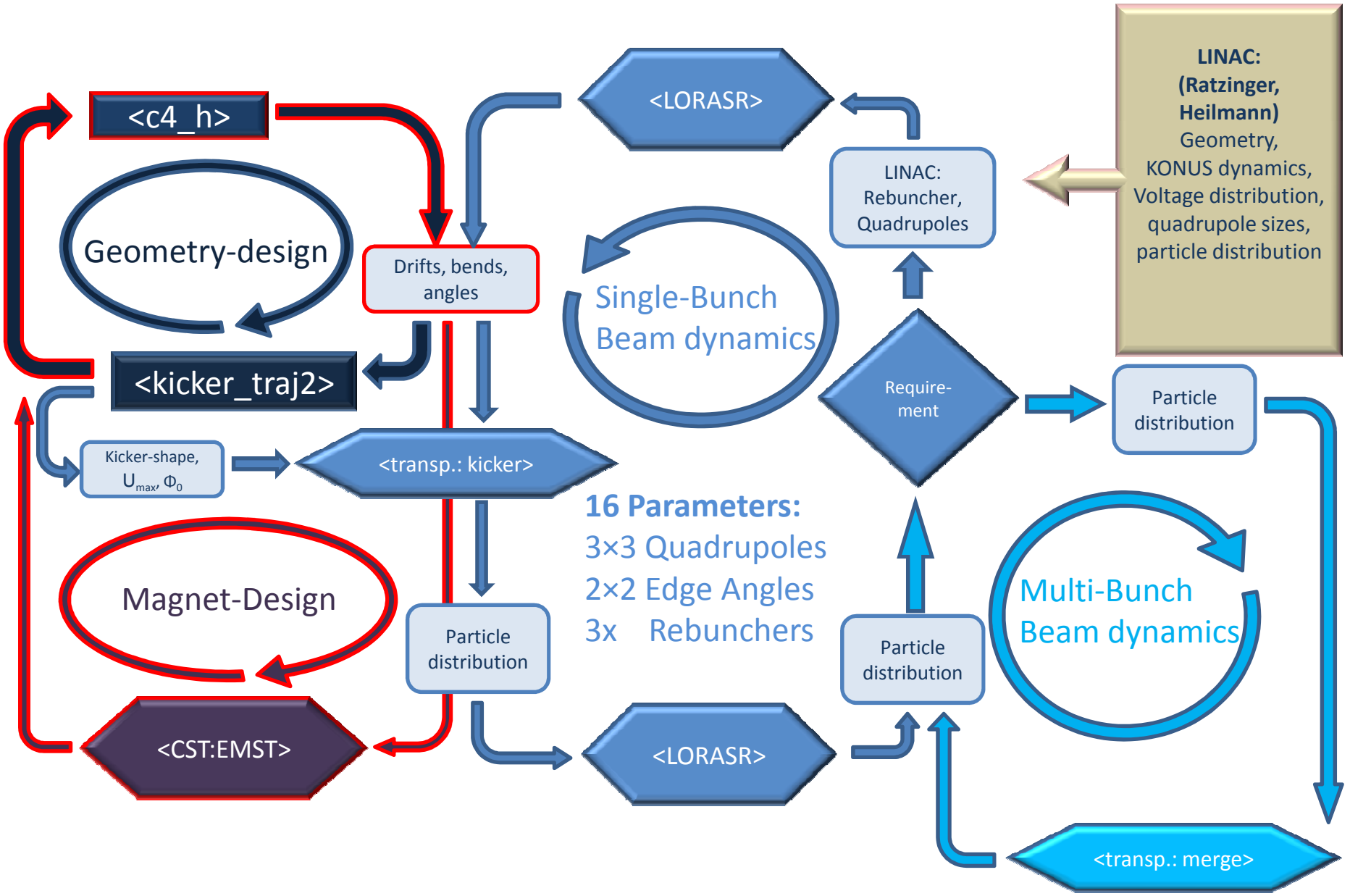
Bunch Compressor: Design / Optimization Cycles



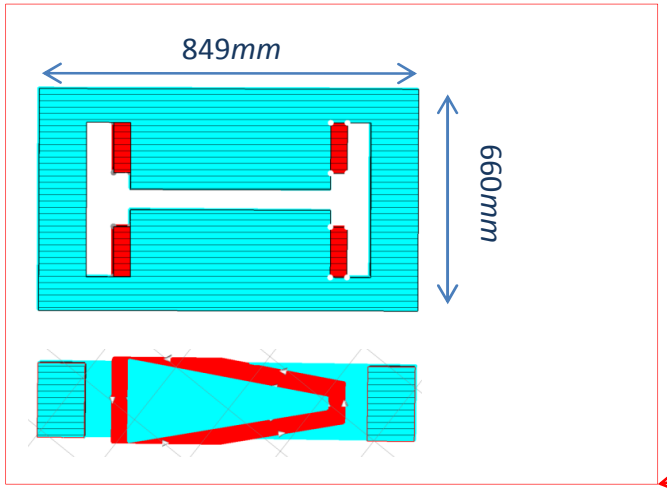
Bunch Compressor: Design / Optimization Cycles

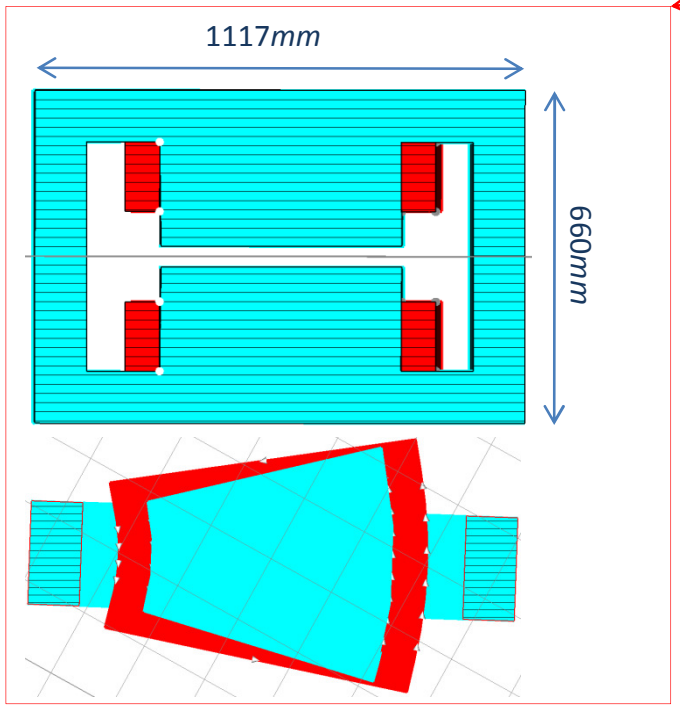


Bunch Compressor: Design / Optimization Cycles

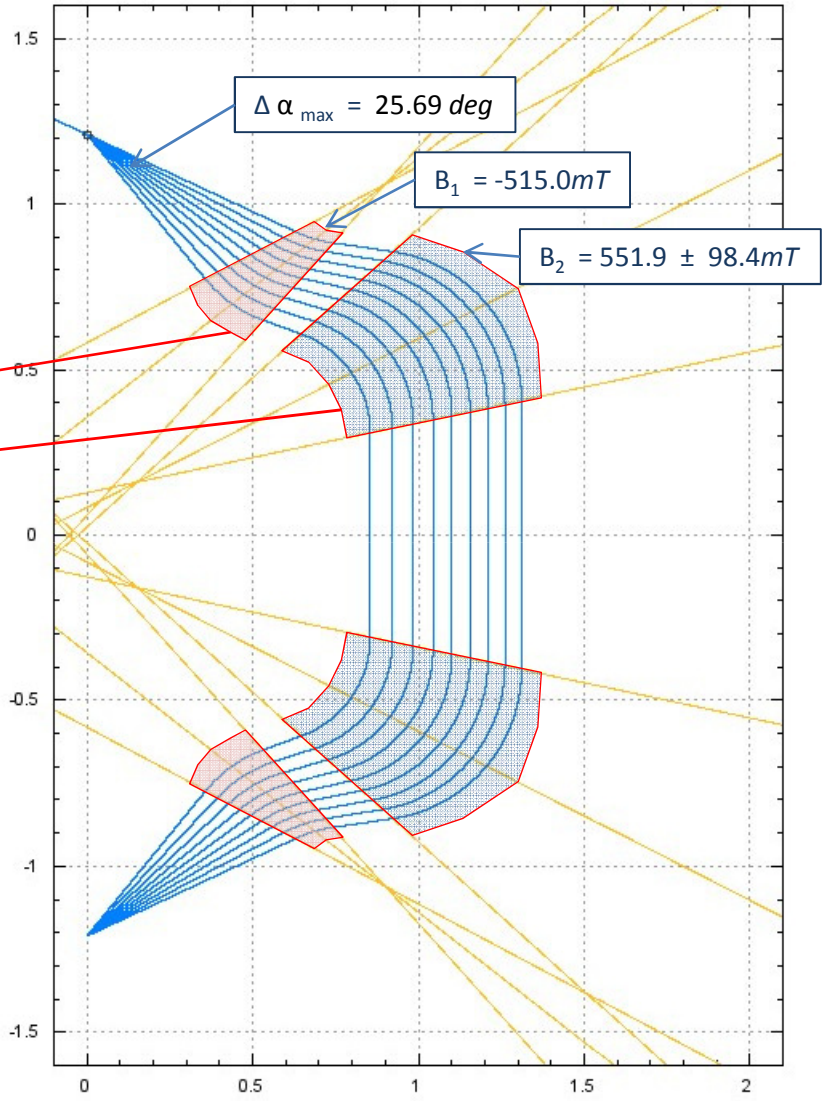


Bunch Compressor: Dipoles

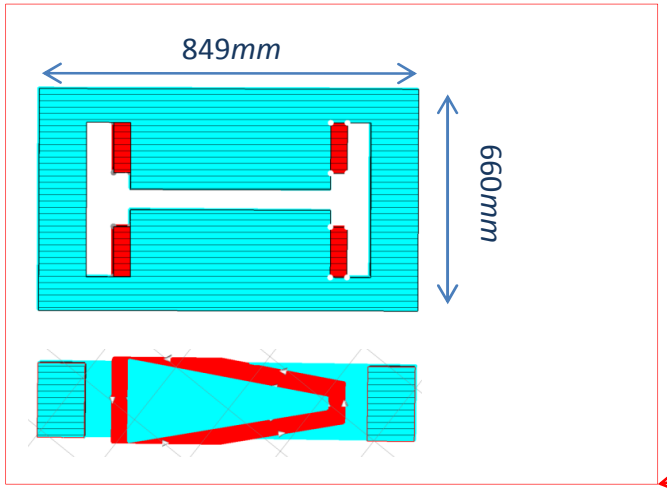




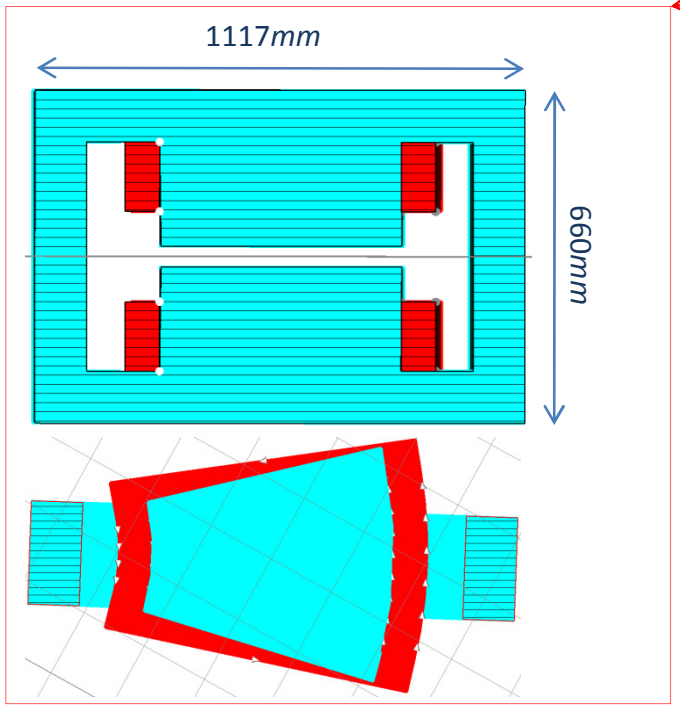
Geometry: g9_5x



Bunch Compressor: Dipoles

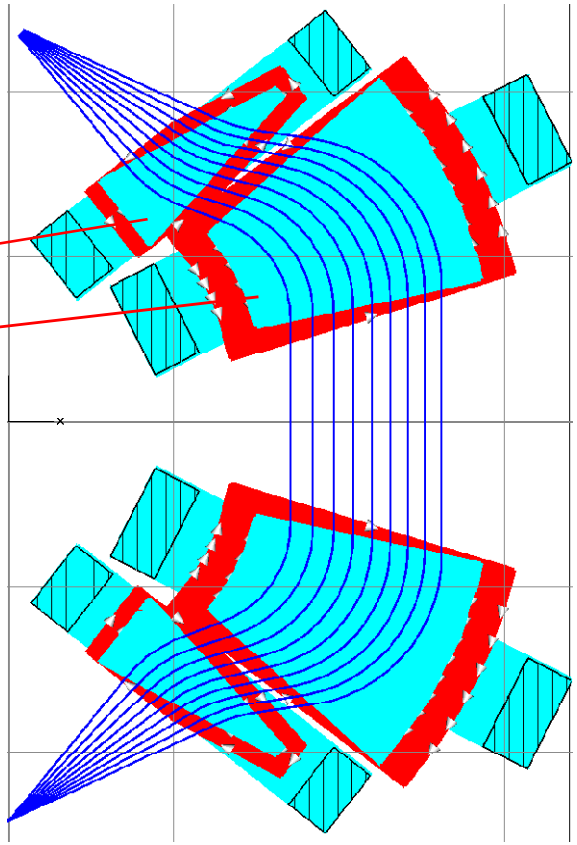


Dipole(1)	
B_1/[mT]	515
g/[mm]	60
N·I/[A]	10420
A_{coil}/[mm²]	50×150
A_{wind}/[mm²]	7×7
N	153
I/[A]	68

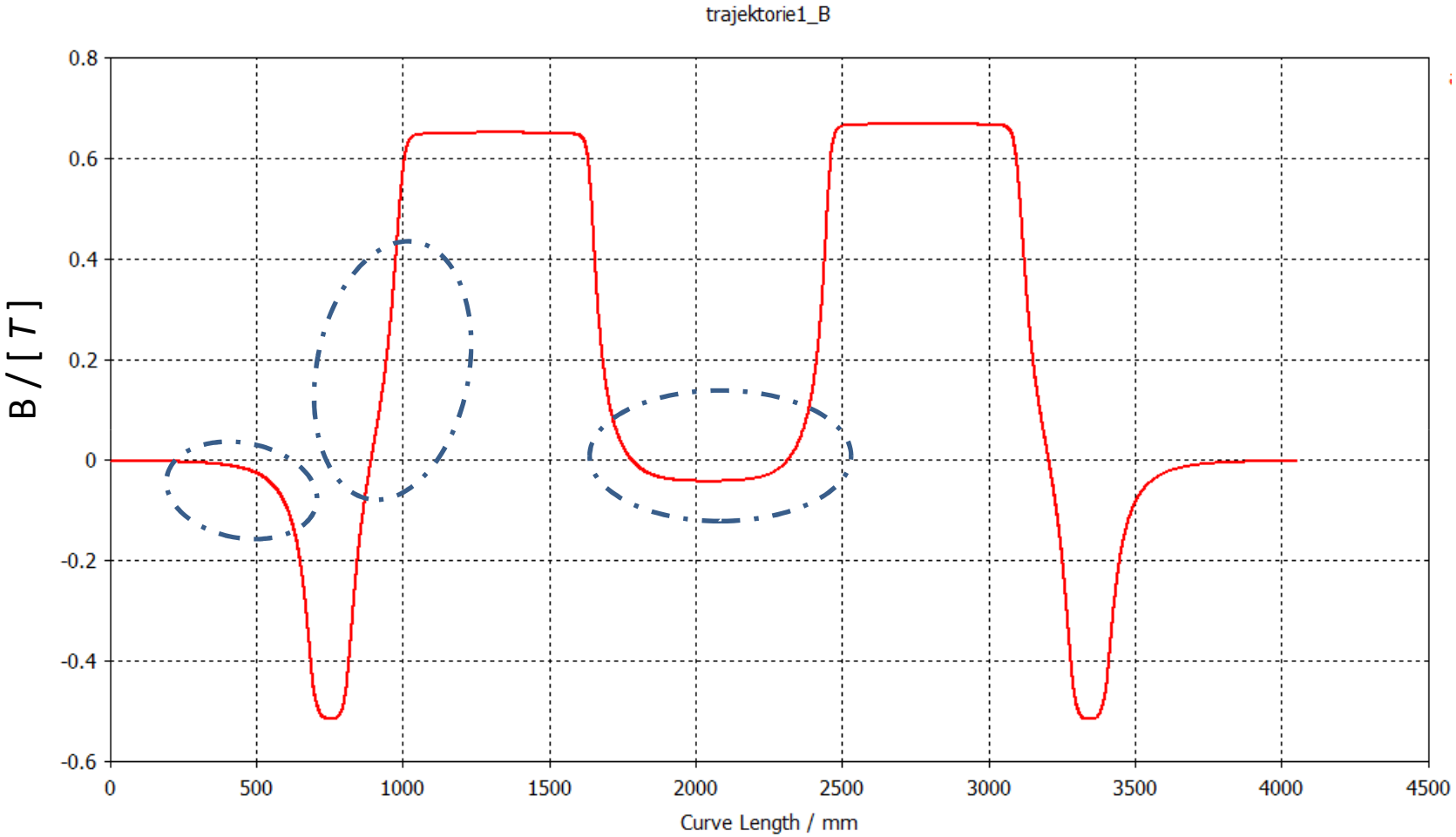


Dipole(2)	
B_2/[mT]	650
g/[mm]	60
N·I/[A]	60476
A_{coil}/[mm²]	100×200
A_{wind}/[mm²]	7×7
N	408
I/[A]	148

Geometry: g9_5x



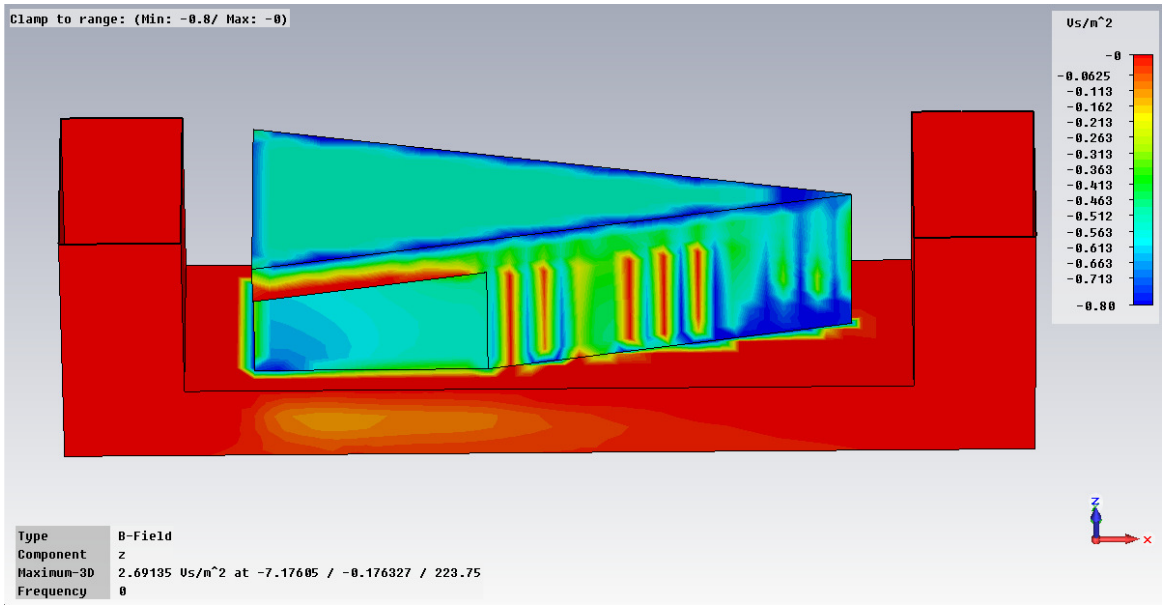
Bunch Compressor: field along the first trajectory at preliminary dipole design

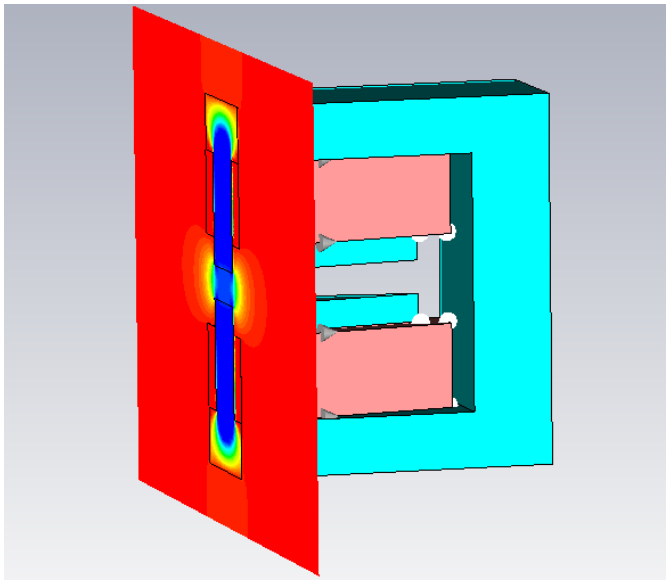


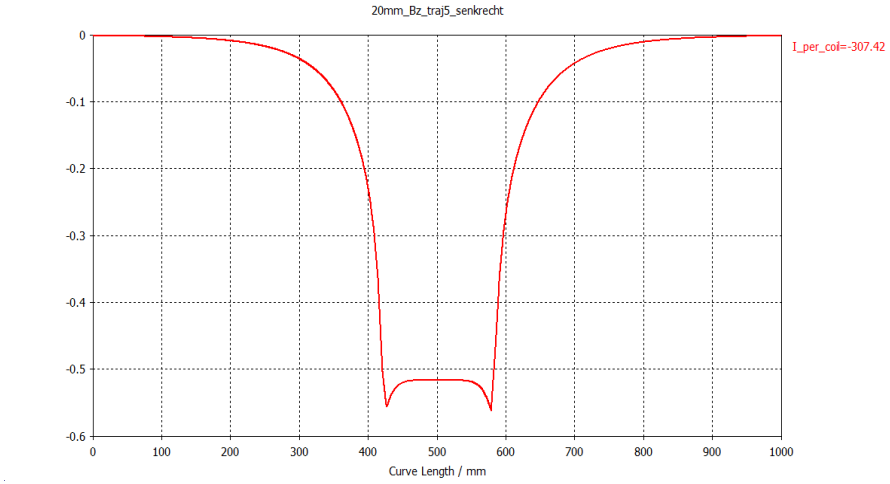
- large fringing field
- Connected fringing field region

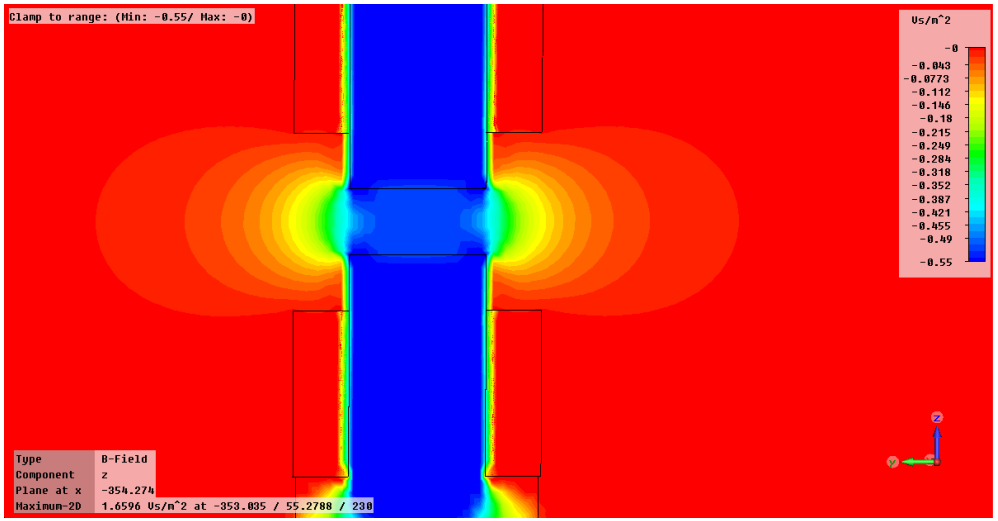
=> Effects of fringing fields on beam dynamics?

field enhancement at the edges due to saturation effects

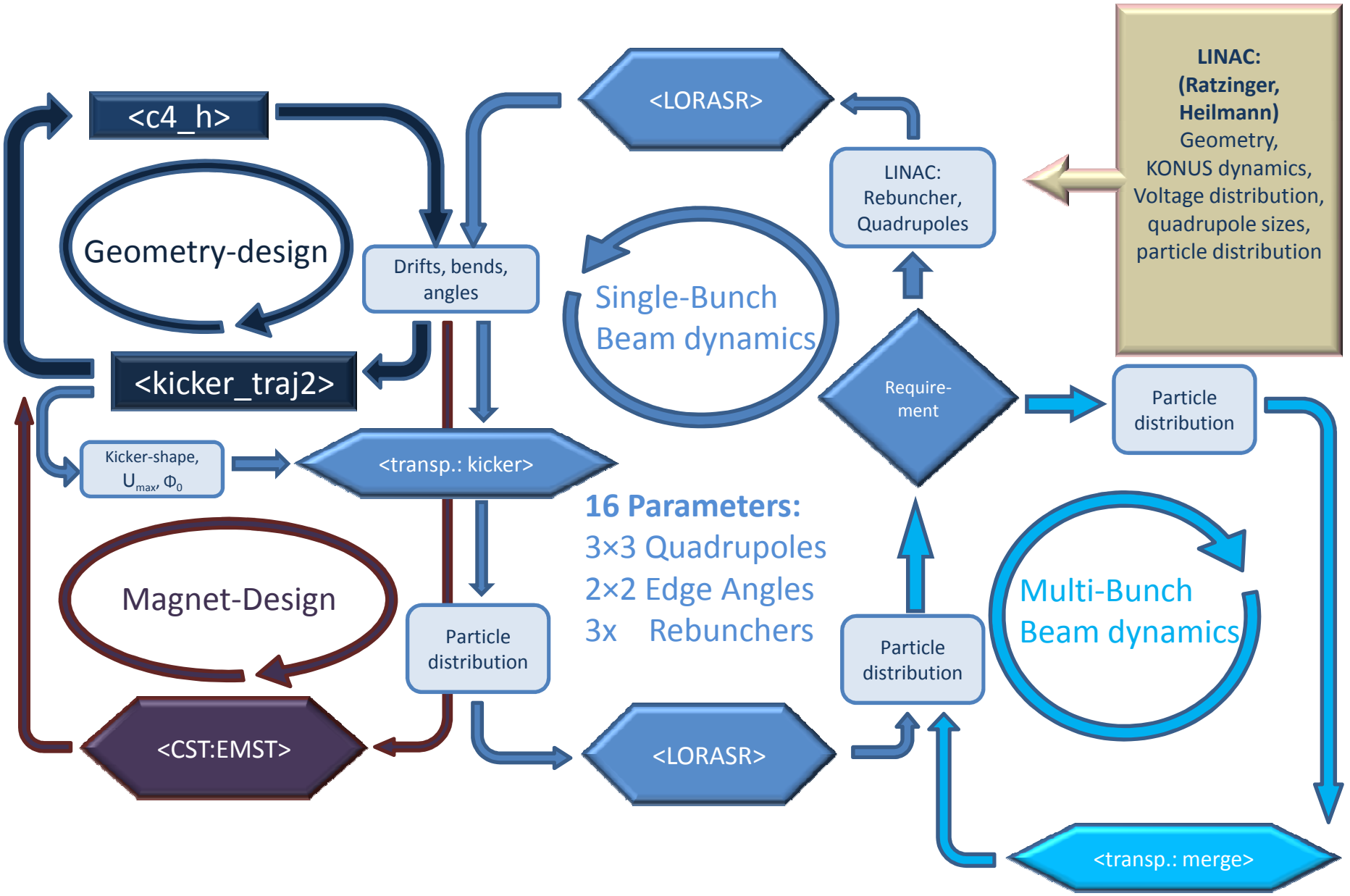




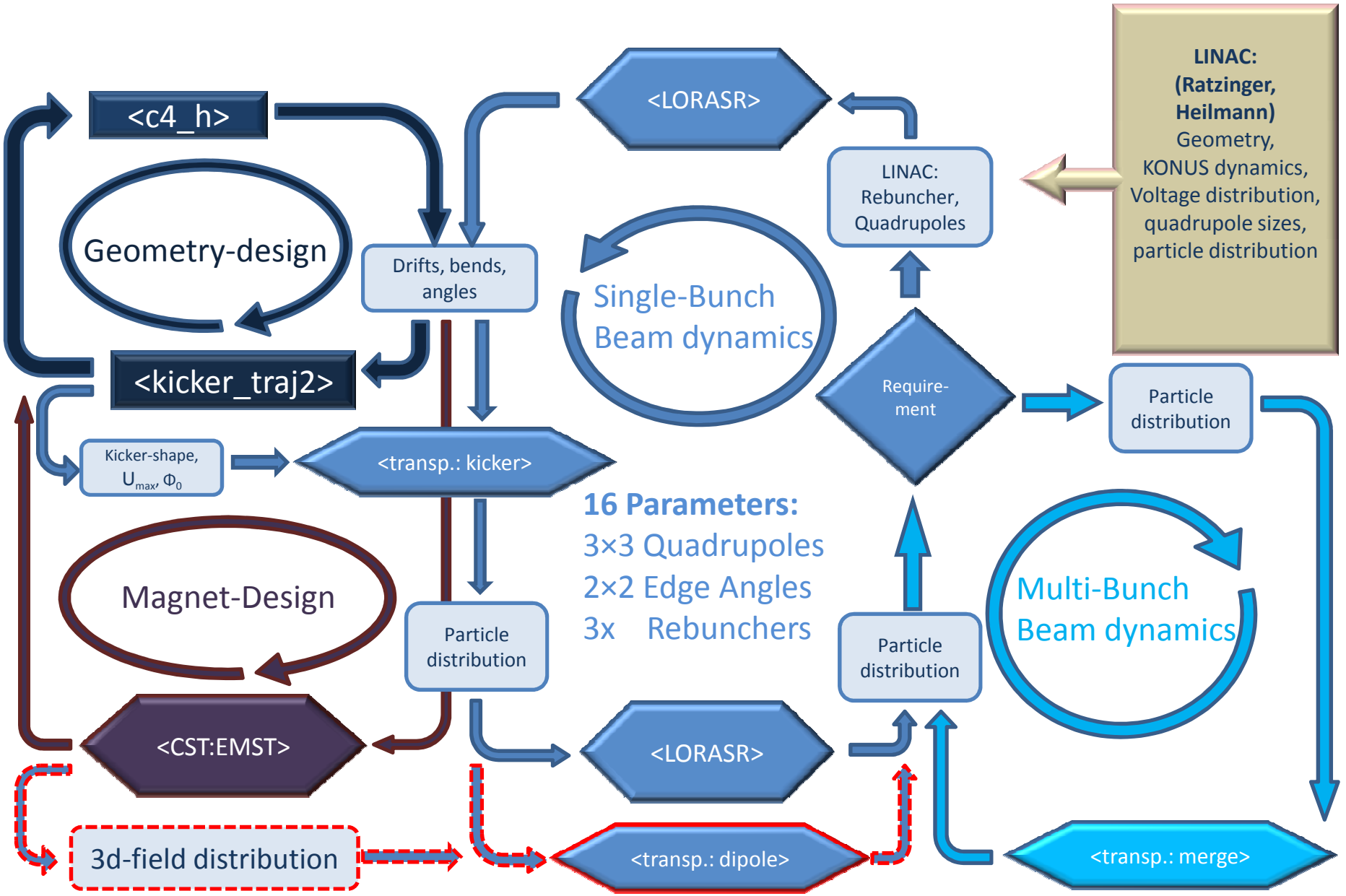




Bunch Compressor: Design / Optimization Cycles



Bunch Compressor: Design / Optimization Cycles



Effect of the fringing fields in paraxial approach

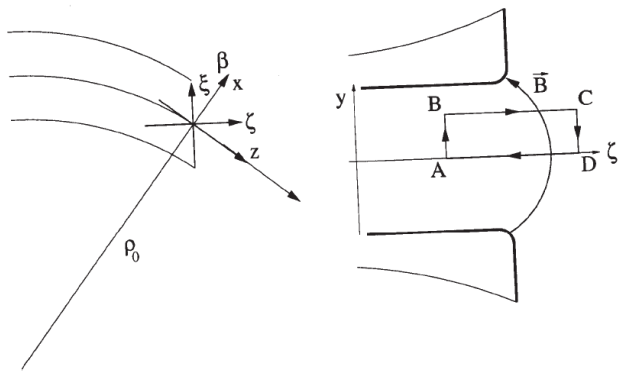
The complete effect of the fringing field is applied in one instantaneous kick in the transverse planes:

$$x' = x'_0 + k_x(\phi, \rho_0) \cdot x_0$$

$\Delta x'$

$$y' = y'_0 + k_y(\phi, \frac{g}{\rho_0}, K) \cdot y_0$$

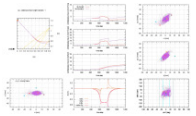
$\Delta y'$



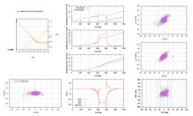
Parameters of the first dipole:

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]

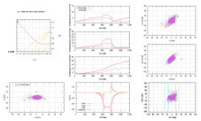
Comparison with realistic field distribution:



0mA: real field dist. vs. matrix



150mA: real field dist. vs. matrix

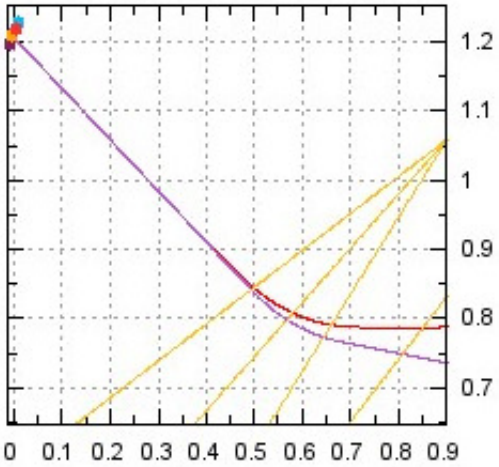


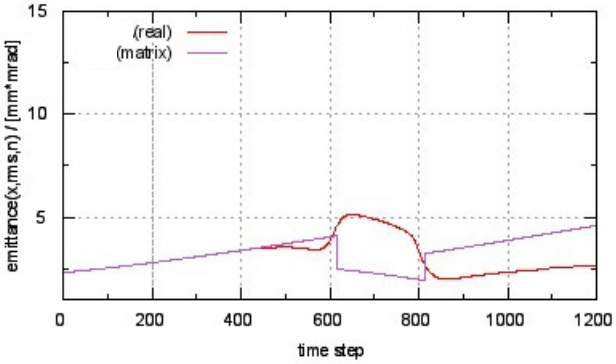
real field dist.: 0mA vs. 150mA

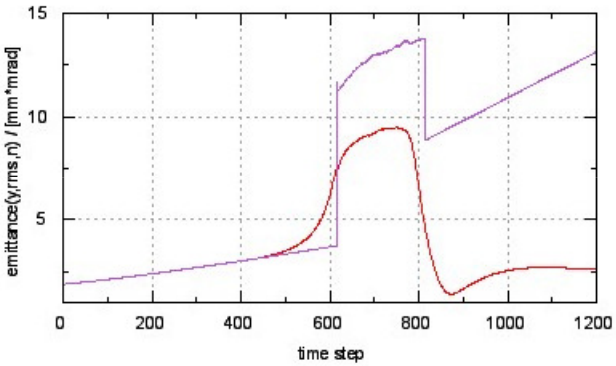
Beam dynamics with realistic field distribution

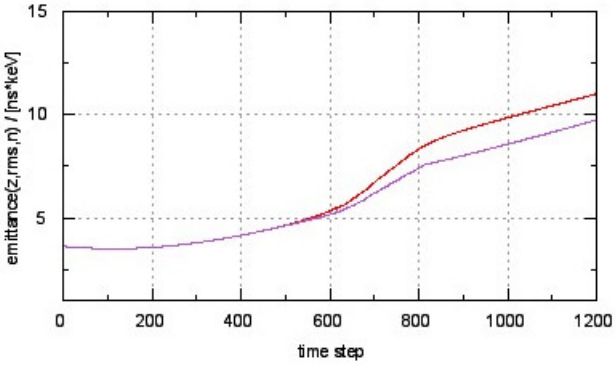
- Center motion significantly changed by large fringing field.
- paraxial approach over estimate the emittance growth in transverse plane.
- bigger emittance growth in long. plane with realistic fields.
- field enhancement nearby the edges due to saturation

  Insufficiently described by first order matrix formalism.









Outlines:

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- **Design / Optimization Cycles**
  - Geometry
  - 5MHz Kicker
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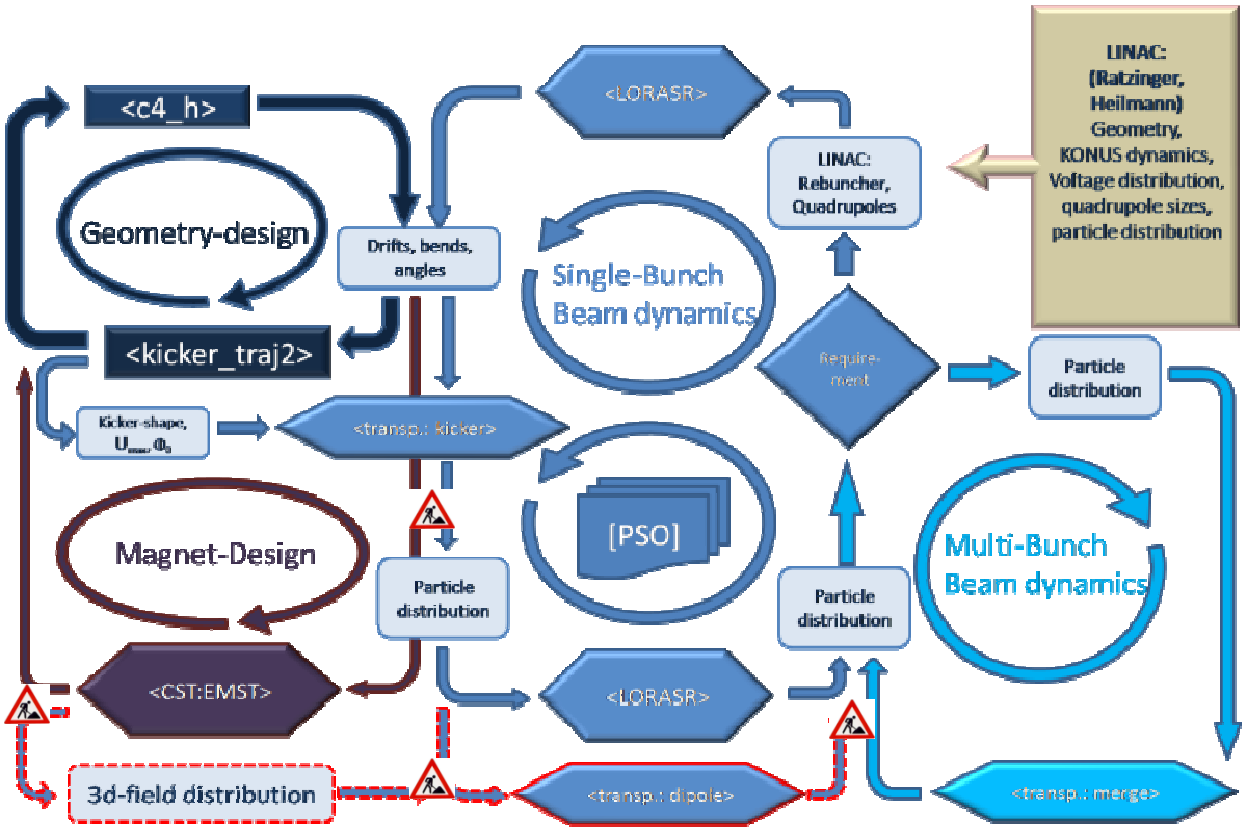
  - Merging Scenario
  - Magnet Design
  - Beam Dynamics with Realistic Field Distributions
- **Outlook**

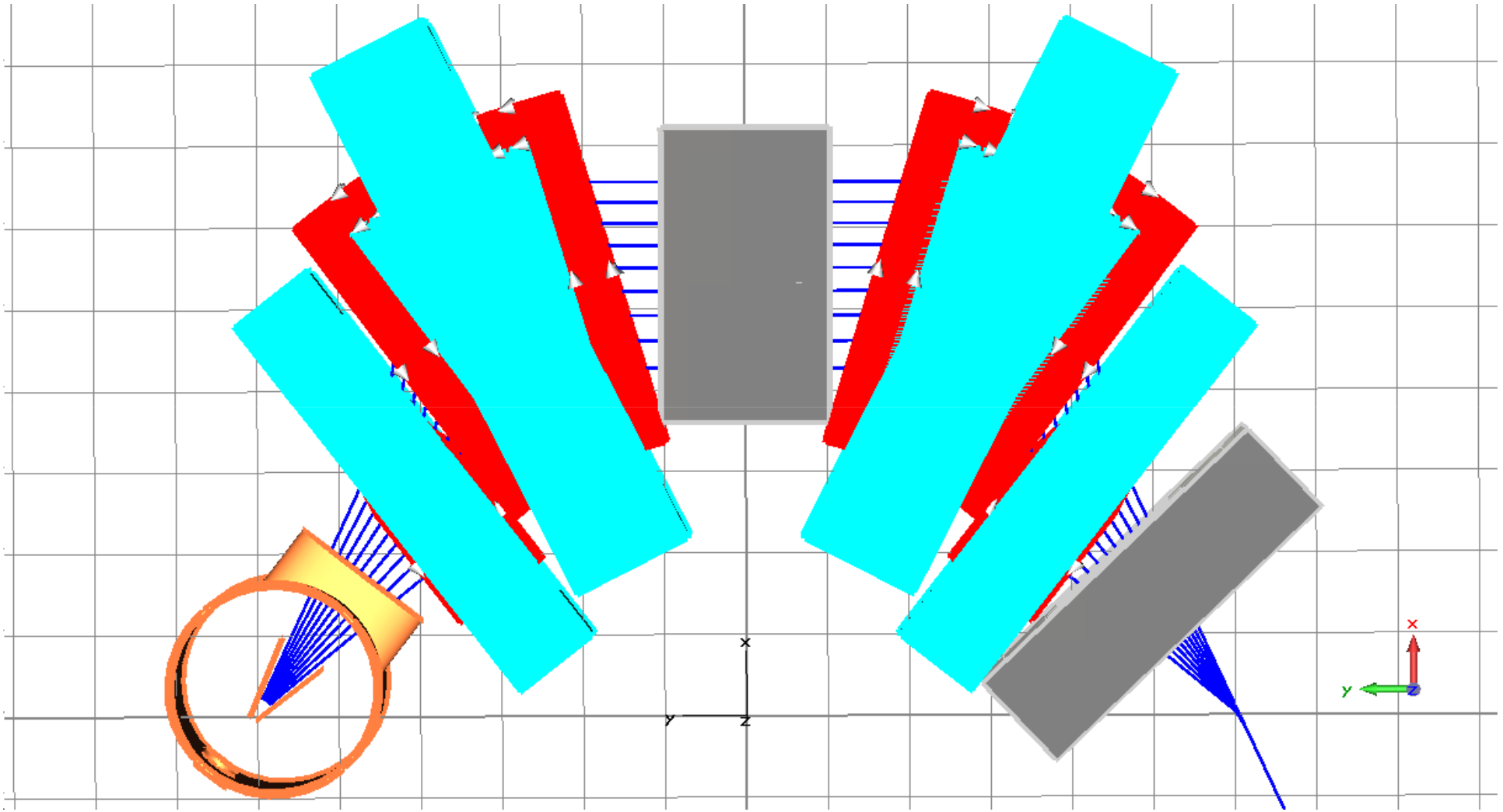
Bunch Compressor: Design / Optimization Cycles



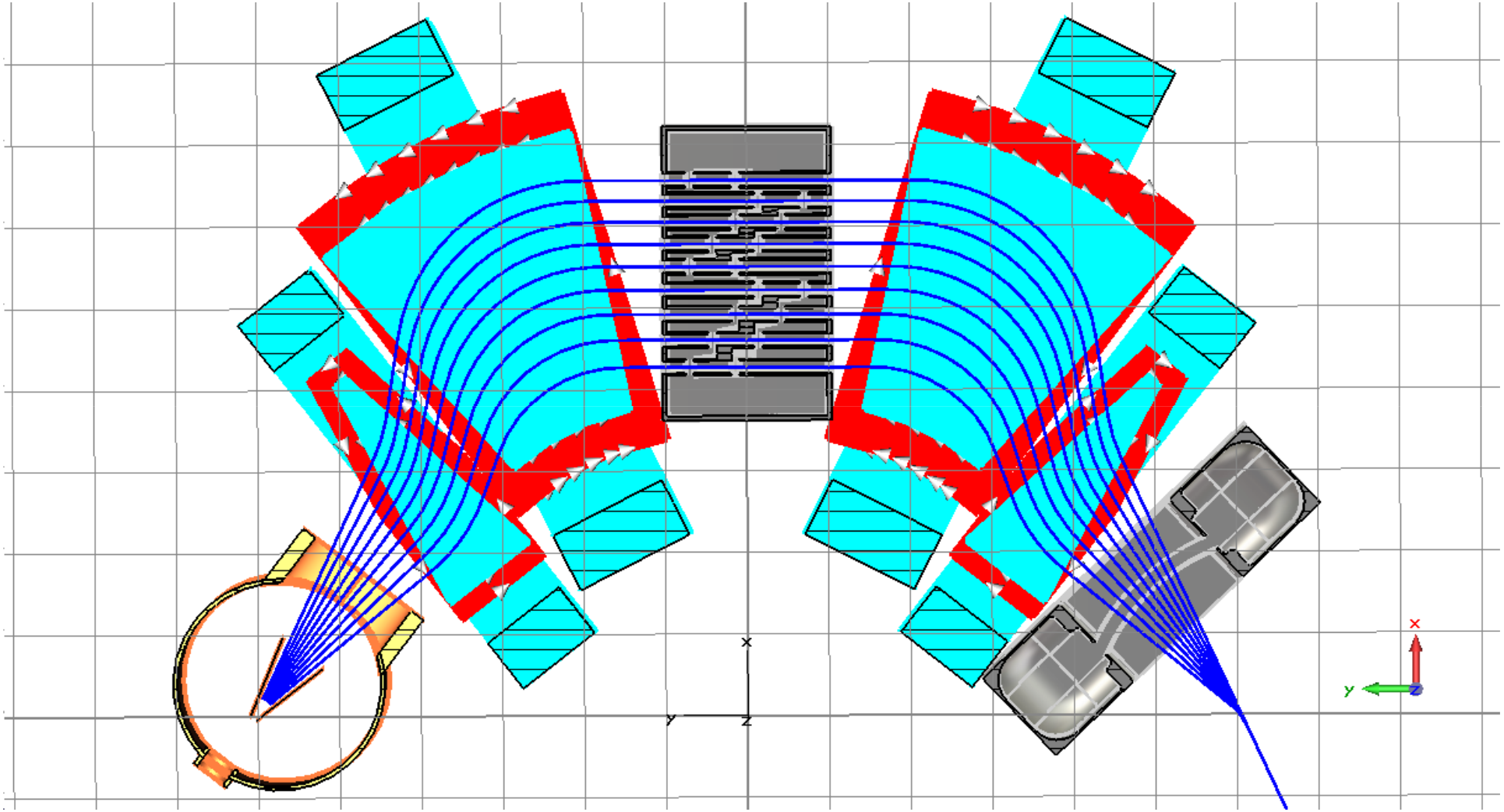
Outlook:

- Improve magnet design, magnet with gradient
- Beam dynamics: Front to end simulation
- Kicker + dipoles + rebunchers + merging scenario

FRANZ: Bunch Compressor

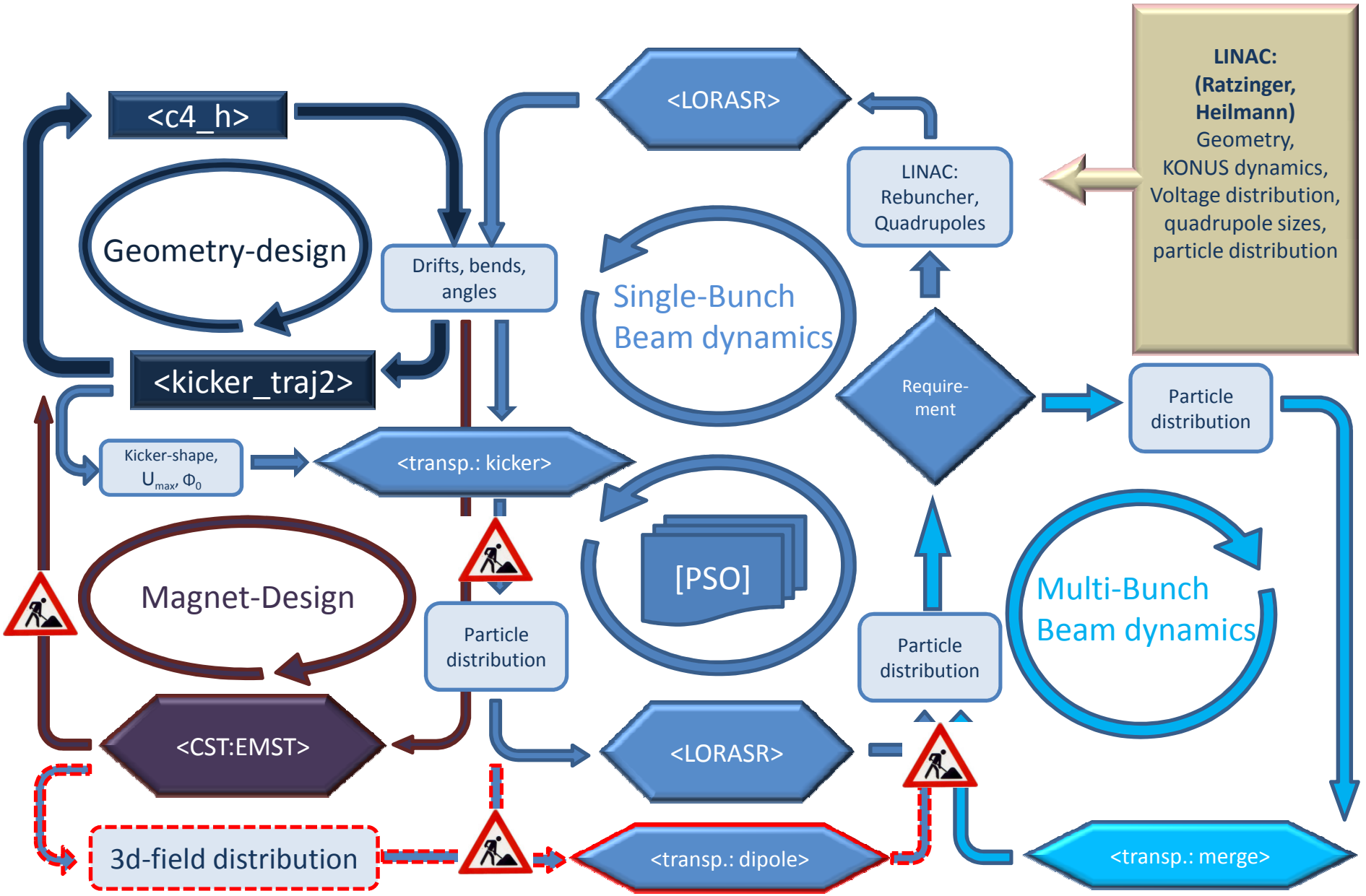


FRANZ: Bunch Compressor

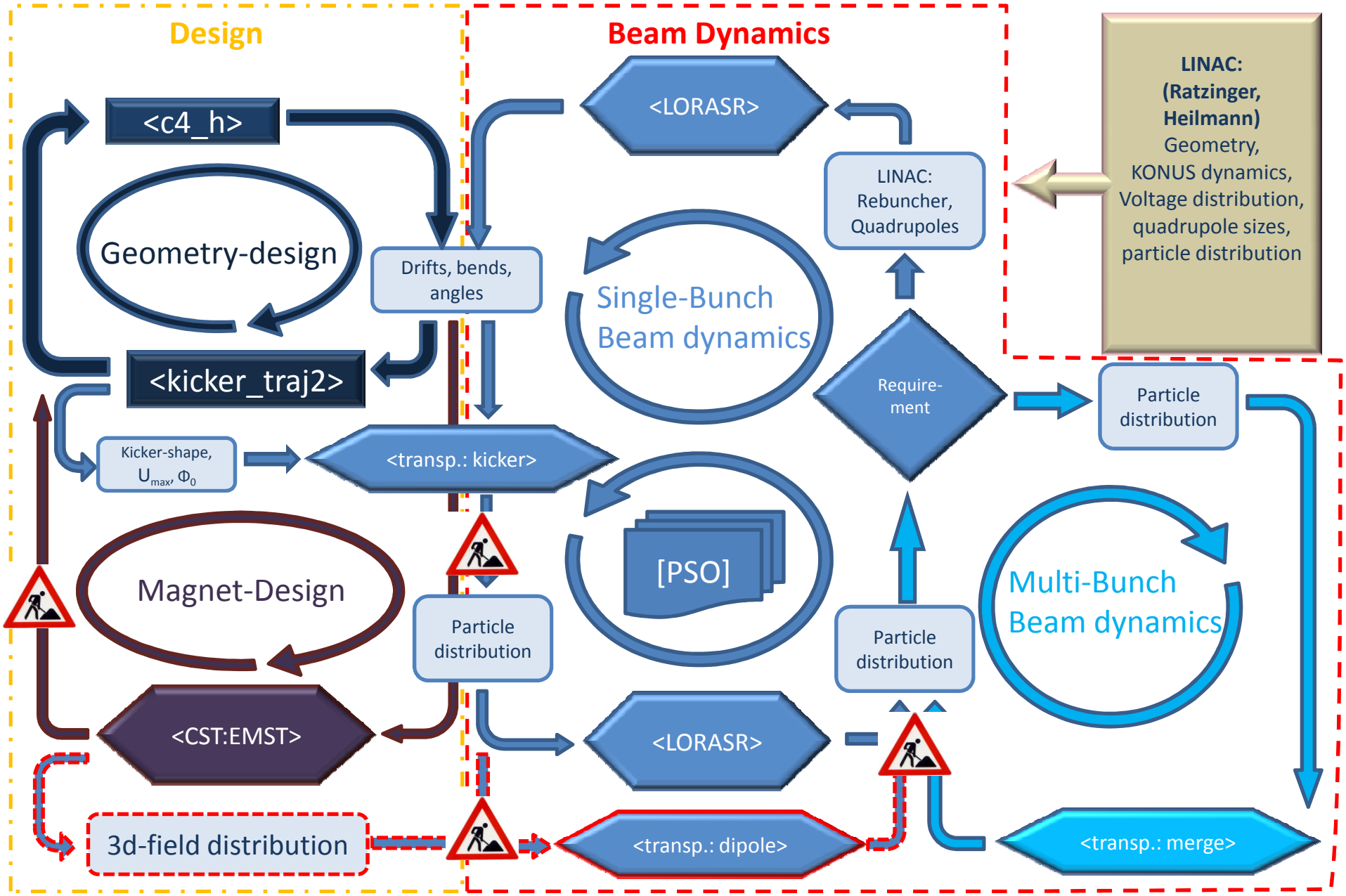


Thank you for your Attention!

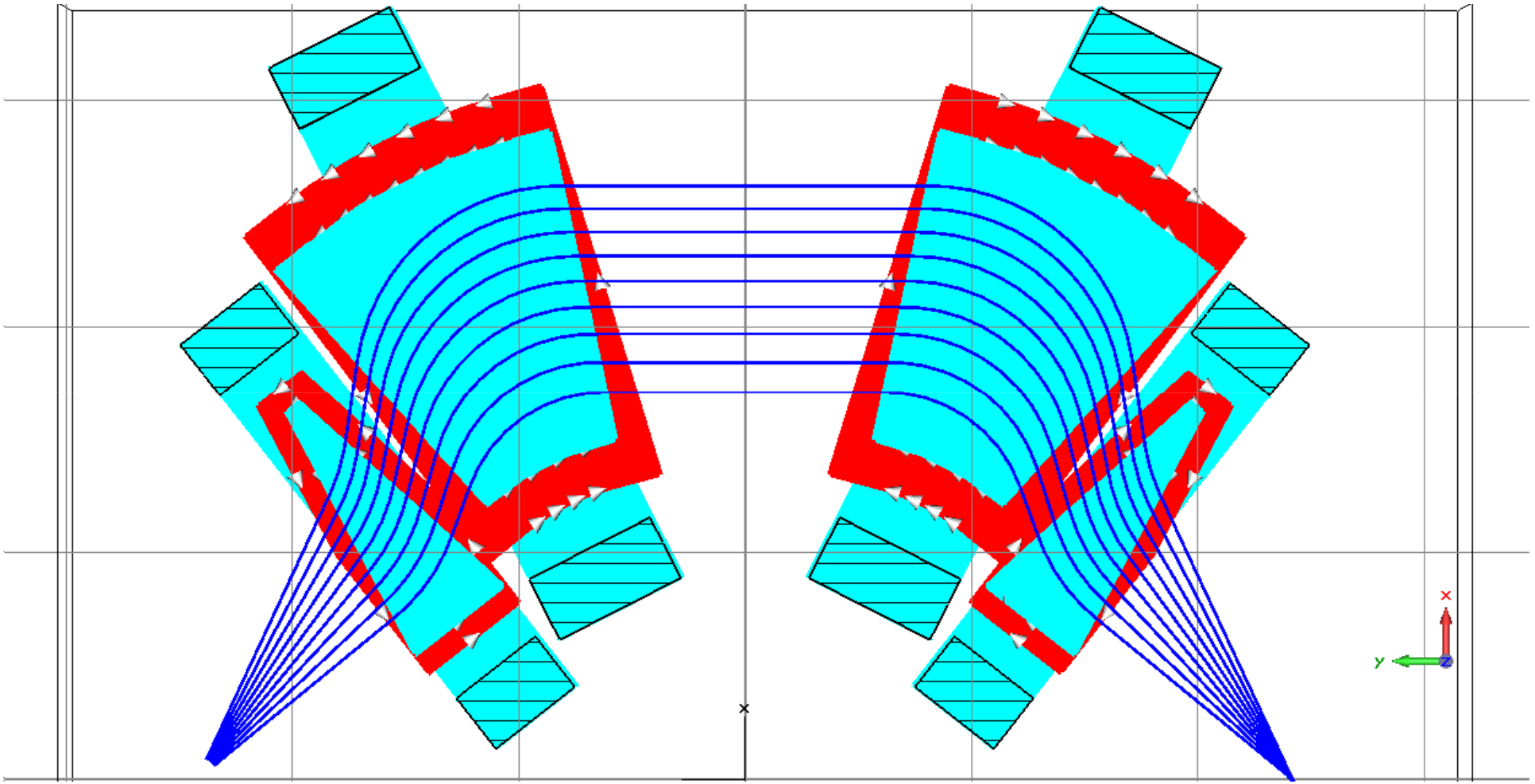
Bunch Compressor: Design / Optimization Cycles



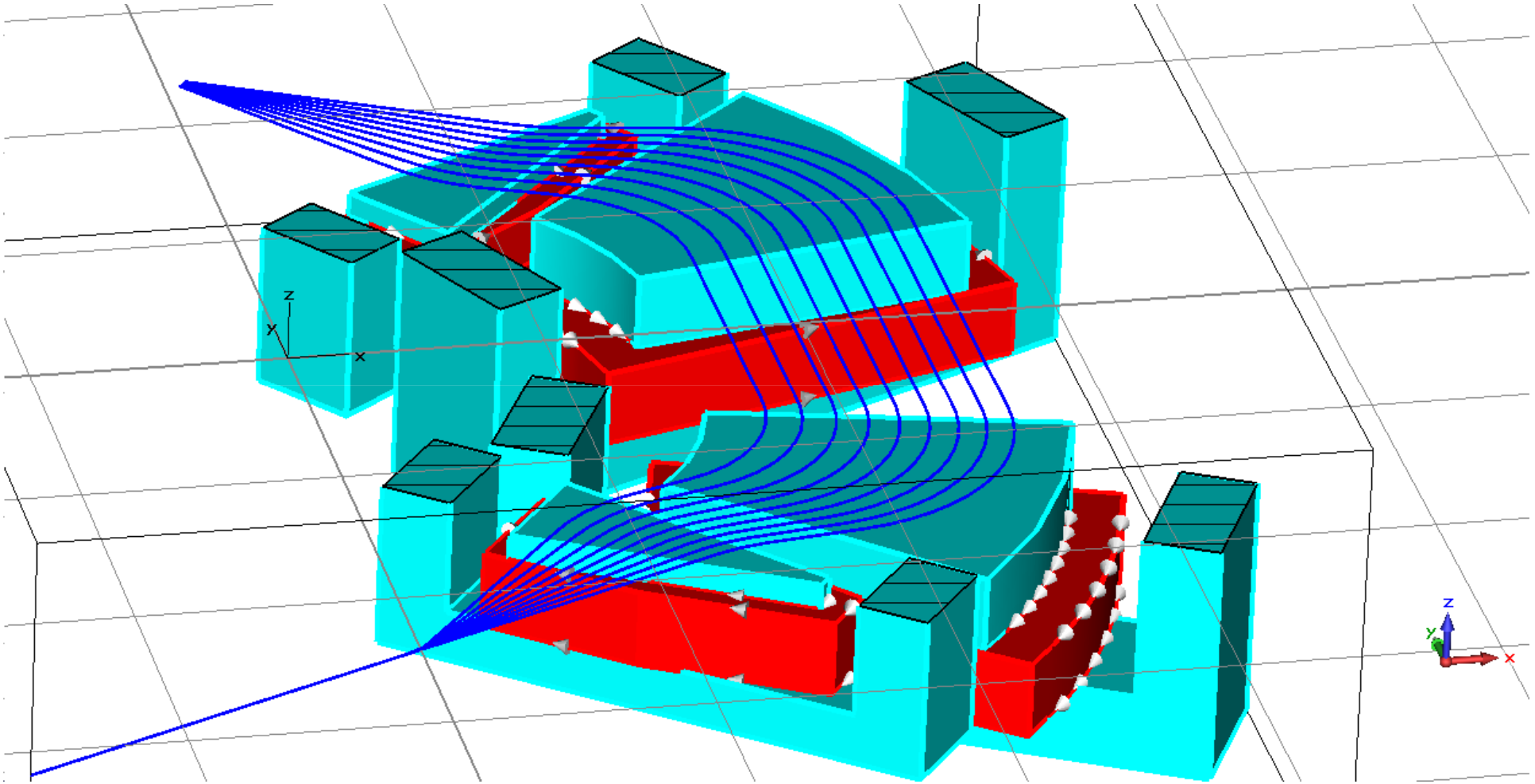
Bunch Compressor: Design / Optimization Cycles



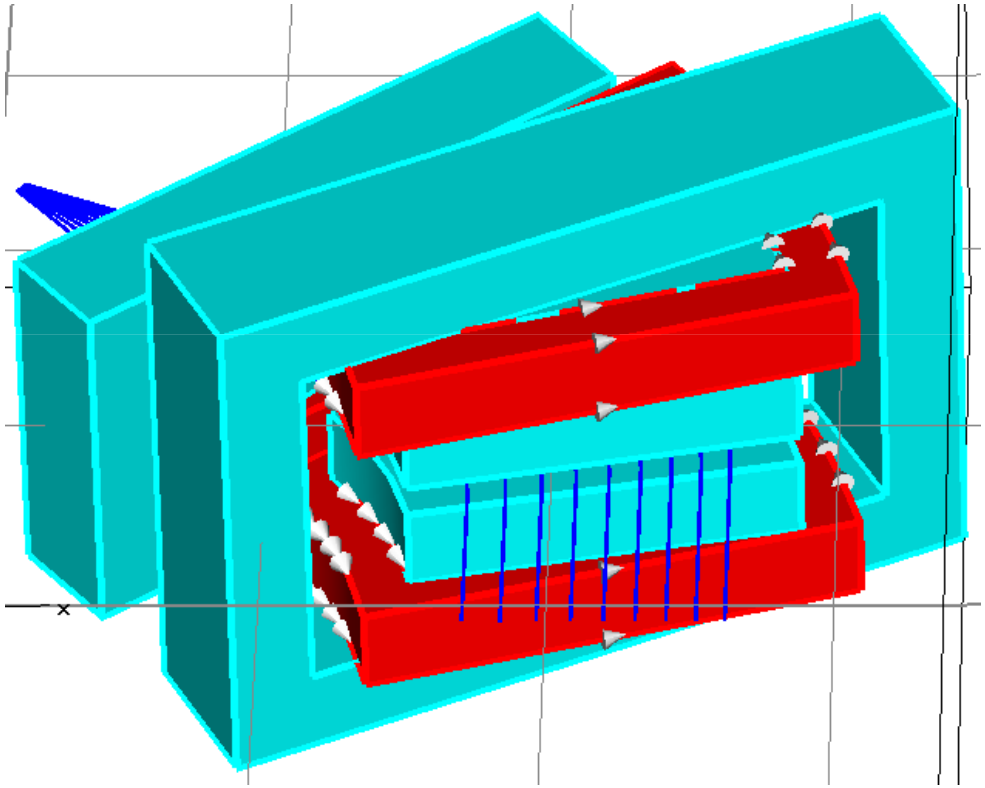
FRANZ: Bunch Compressor



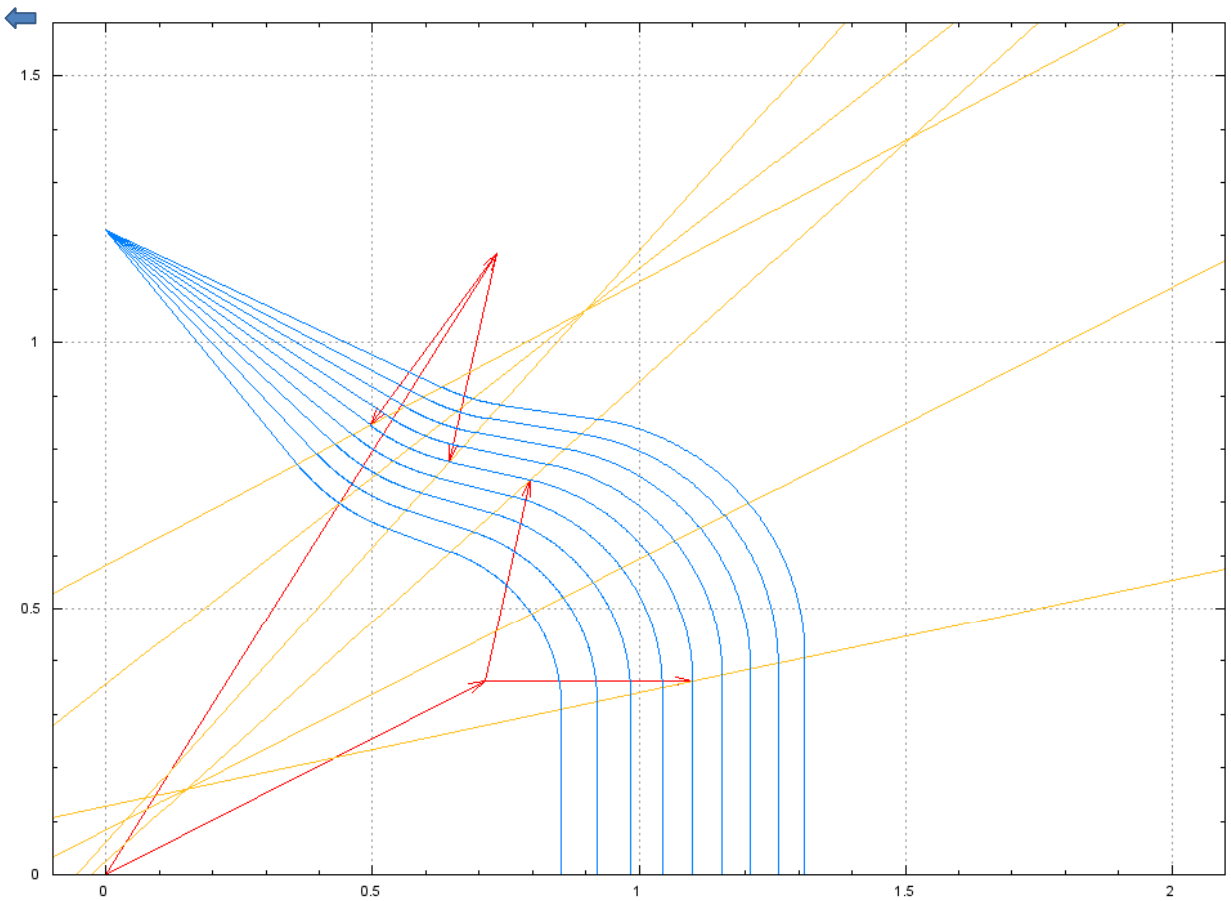
FRANZ: Bunch Compressor



FRANZ: Bunch Compressor



Bunch Compressor: geometrical parameters

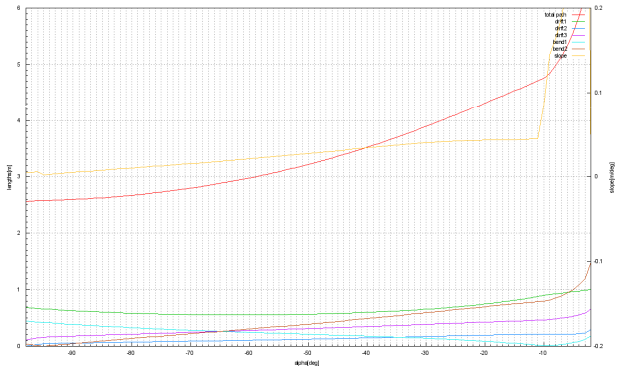


g9_5x

$B_1 = -0.51497[T]$

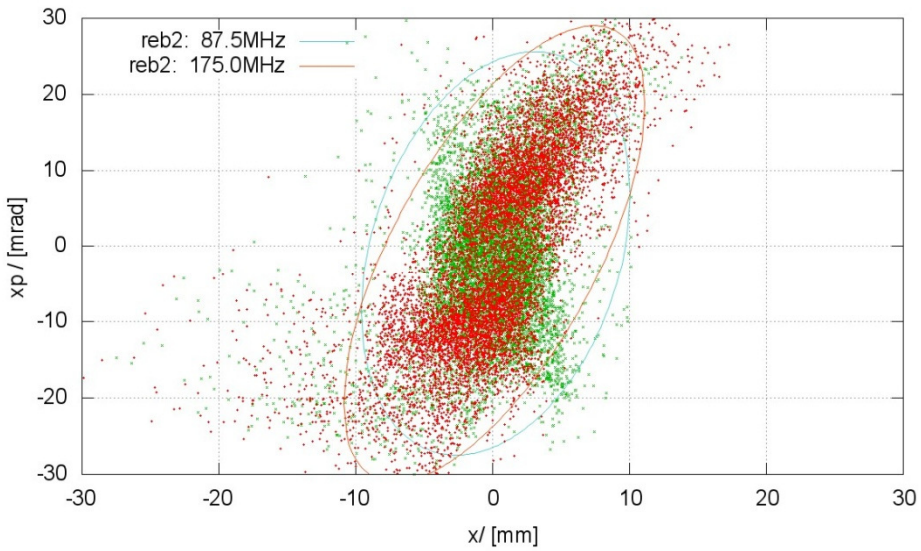
$\alpha_{max} = 25.69[deg]$

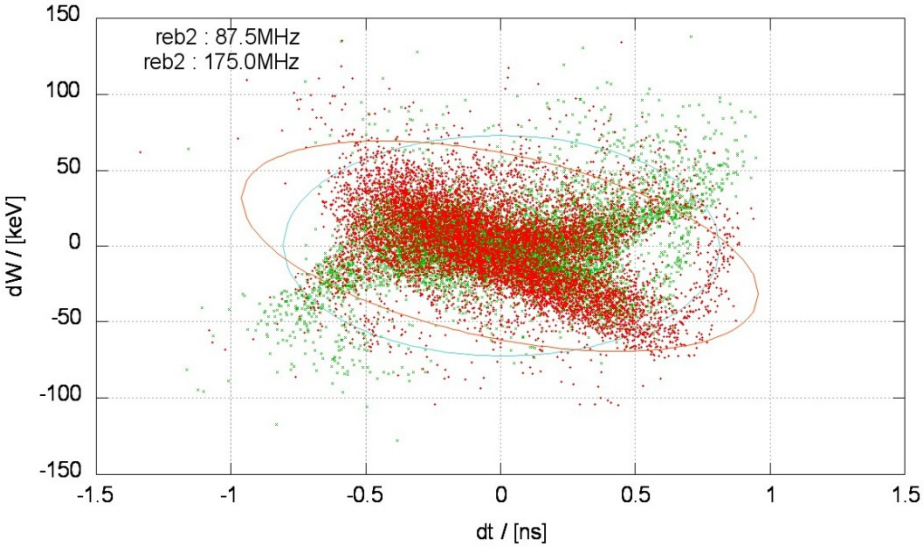
$< \alpha > = 3.21[deg]$

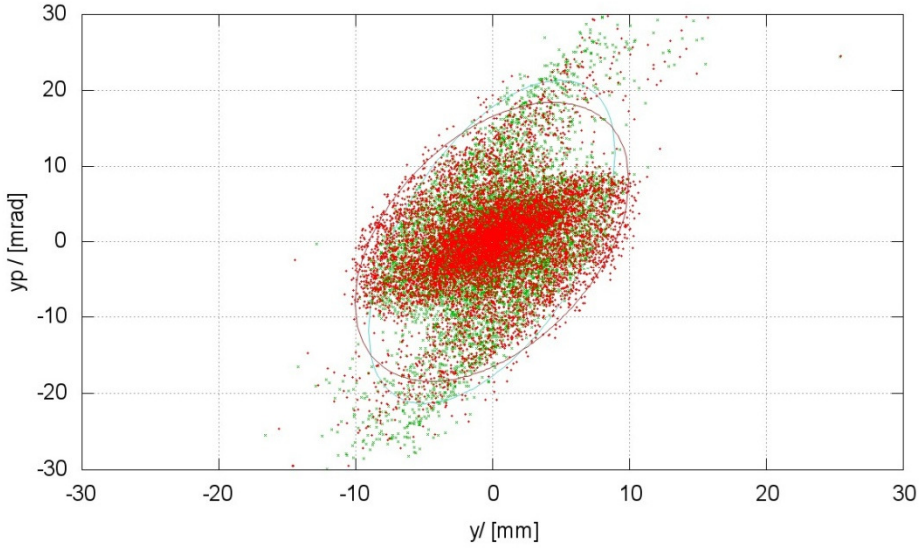


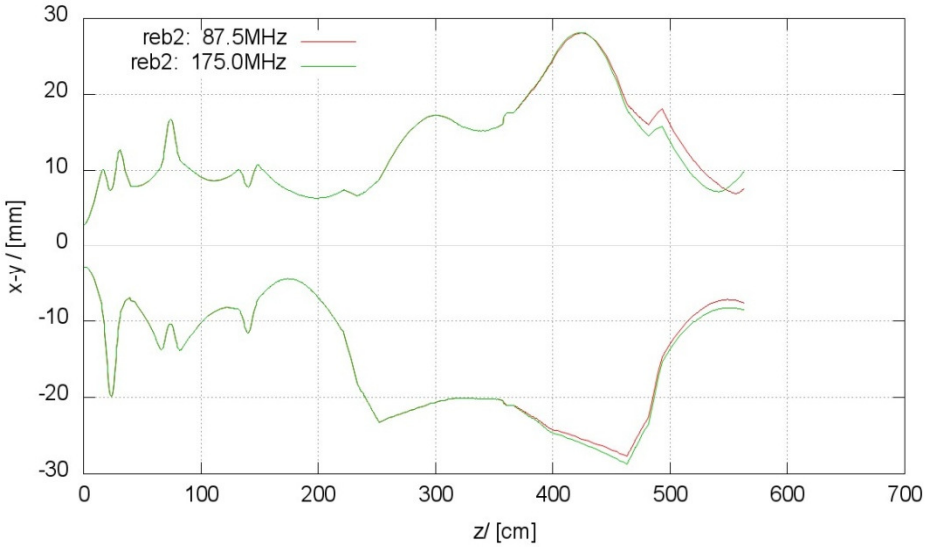
al [deg]	tp [m]	dr1 [m]	dr2 [m]	dr3 [m]	b1 [m]	b2 [m]	bet1 [deg]	bet2 [deg]	R2 [m]	B2 [T]	d_x1 [m]	d_x2 [m]	d_x3 [m]	d_x4 [m]	d_x5 [m]	d_a [deg]	d_x1p [m]	d_tp [m]	psi11 [deg]	psi12 [deg]	psi21 [deg]	psi22 [deg]
-25.000	4.0995	0.6949	0.1845	0.4069	0.1162	0.6472	16.645	-81.645	0.4542	0.4535	0.0397	0.0352	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

Bunch Compressor: Bunch(1) at the target

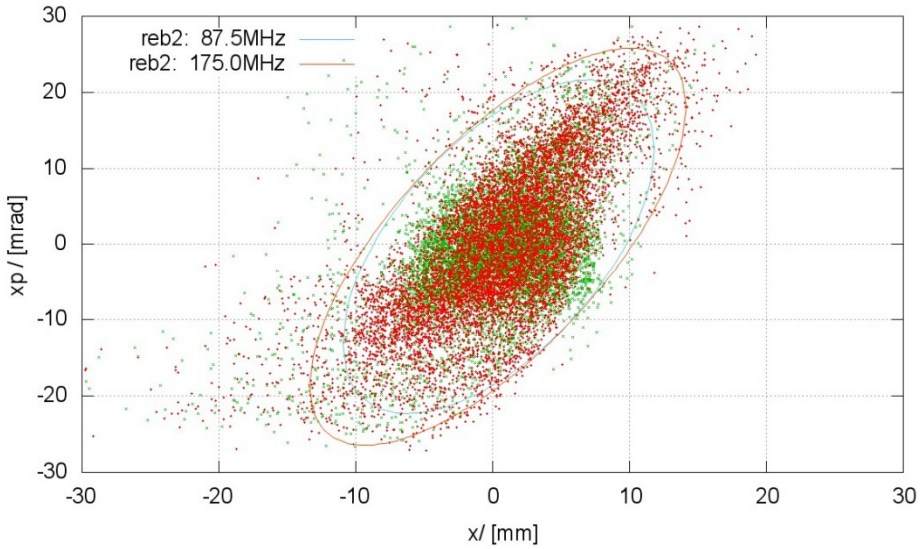


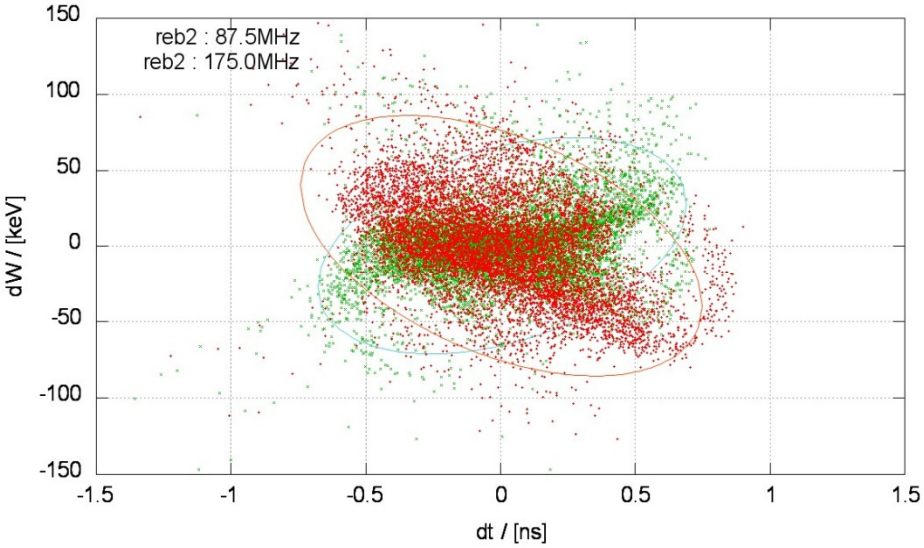


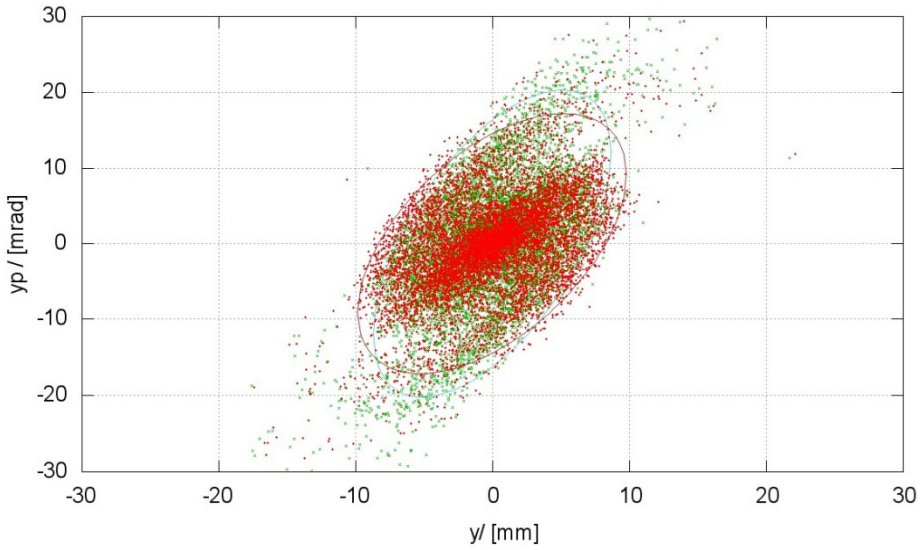


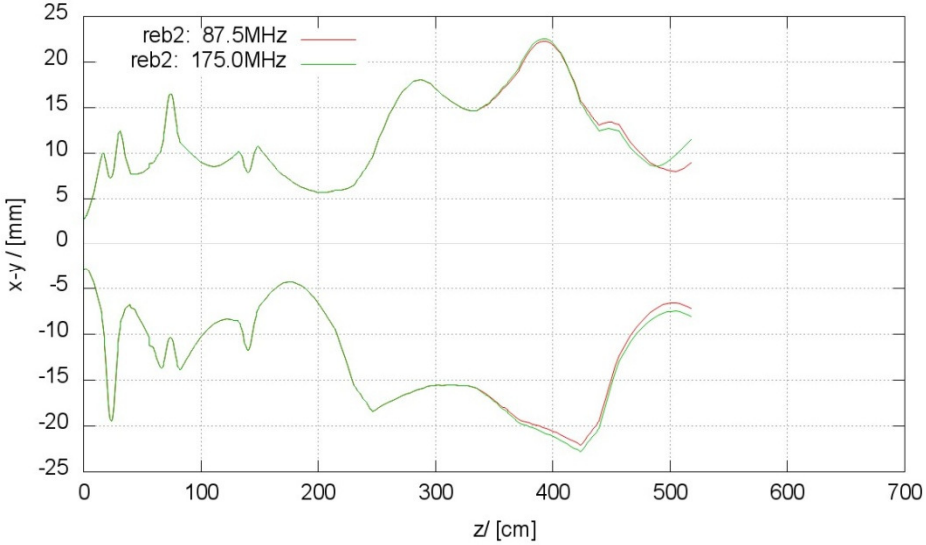


Bunch Compressor: Bunch(5) at the target

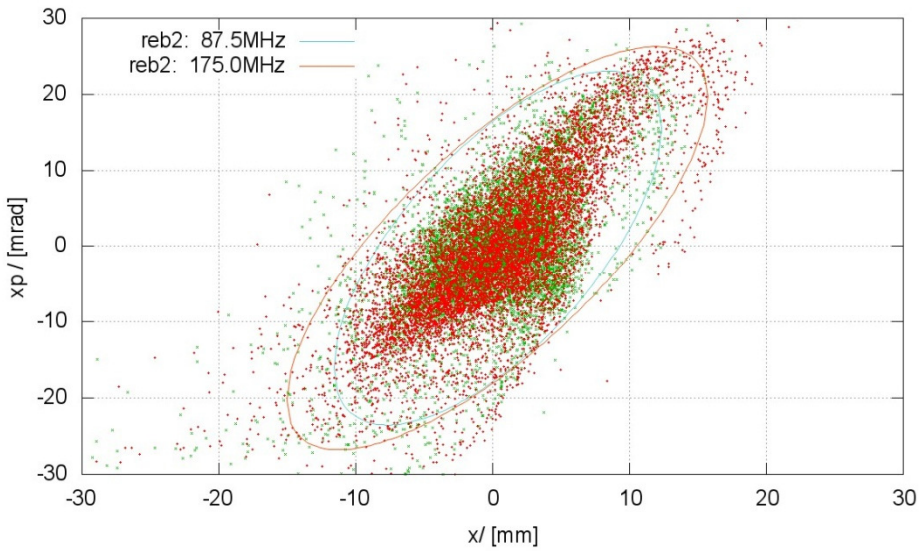


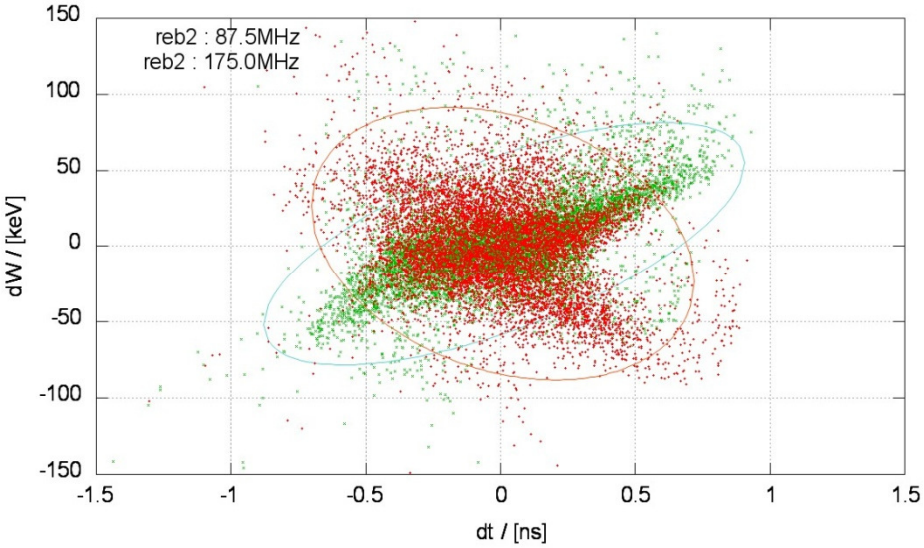


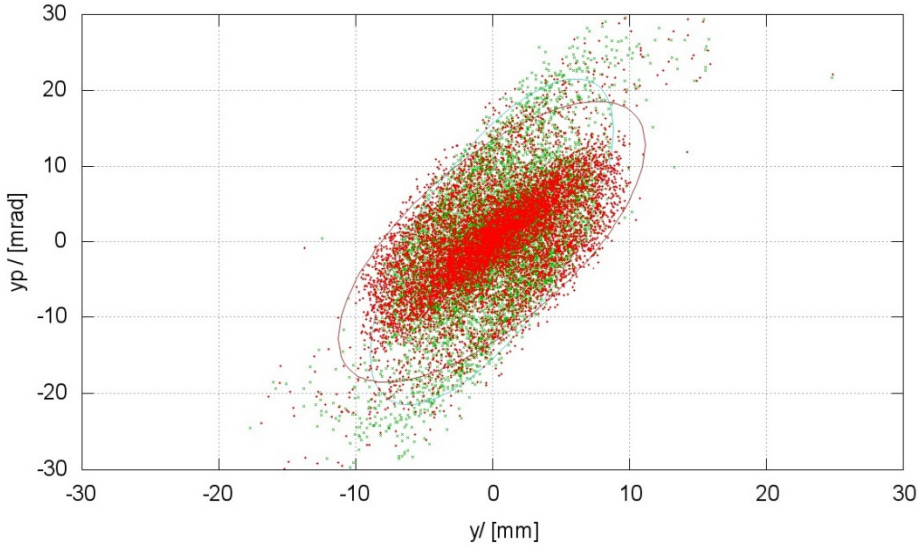


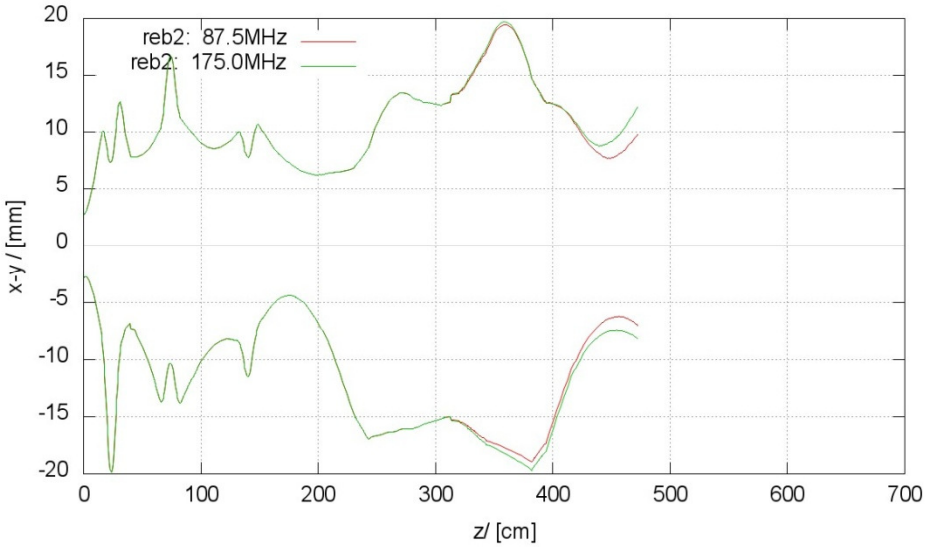


Bunch Compressor: Bunch(9) at the target

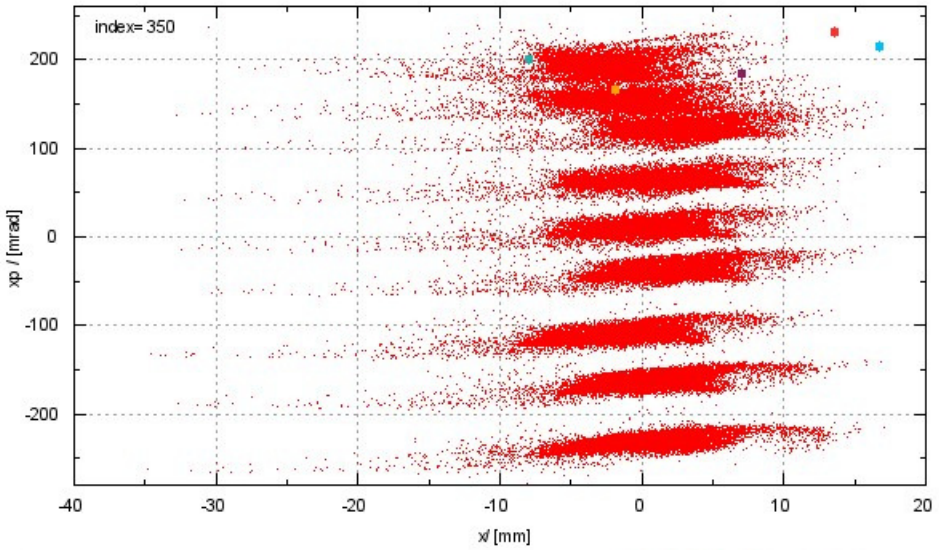


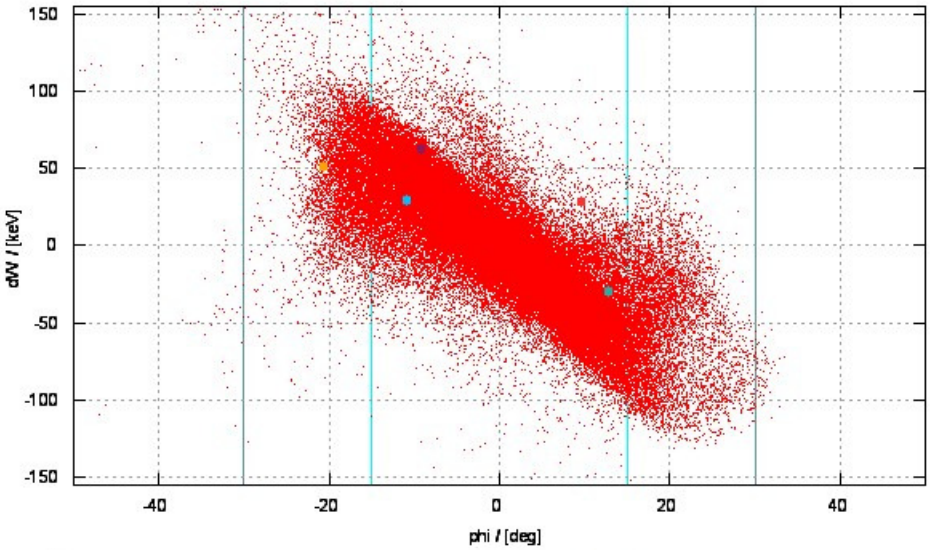


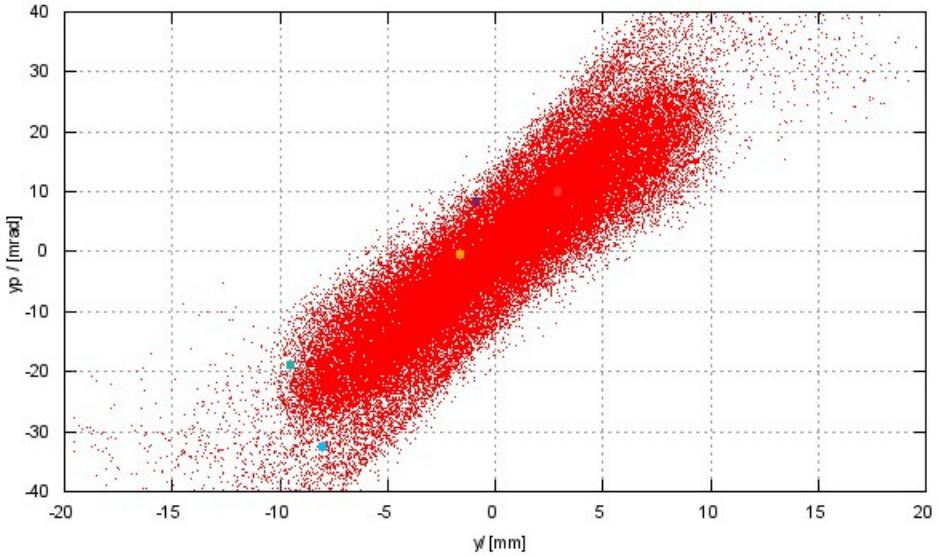


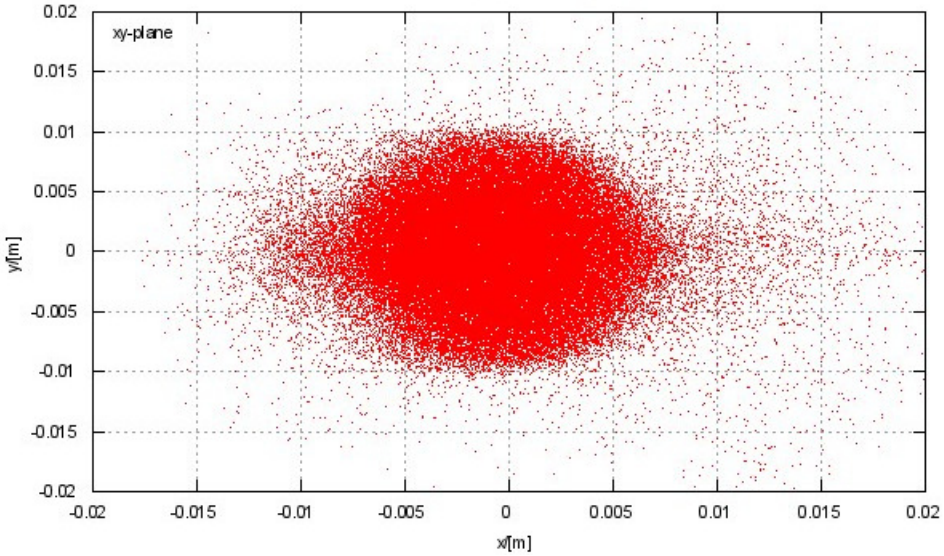


Bunch Compressor: Merging - Projections at the target









Kantenfokussierung

Beim Durchlaufen der Kante eines Dipols erfahren die Teilchen eine ***Impulsänderung*** abhängig vom β, g, ρ_0, K und ihrer Positionen (x_0, y_0) bezüglich des Sollteilchen.

$$x = x_0 \quad , \quad x' = \Delta x' + x'_0$$
$$y = y_0 \quad , \quad y' = \Delta y' + y'_0$$

radialer Kick: $$\Delta x' = +\frac{\tan(\beta)}{\rho_0} \cdot x_0 = k_x \cdot x_0$$

axialer Kick: $$\Delta y' = -\frac{\tan(\beta_{eff})}{\rho_0} \cdot y_0 = k_y \cdot y_0$$

$$\tan(\beta_{eff}) = \tan\beta - \underbrace{\left(\frac{g}{\rho_0} \cdot K\right) \cdot \frac{1+\sin^2\beta}{\cos^3\beta}}_{\text{Korrektur in 1. Ordnung von } \left(\frac{g}{\rho_0}\right)} = \tan\beta - \tilde{K} \cdot \frac{1+\sin^2\beta}{\cos^3\beta}$$

$$\tilde{K} = \frac{g}{\rho_0} \cdot K$$

$\tilde{K}$ => Symmetrie der Abbildung

ρ_0 => Stärke der Abbildung

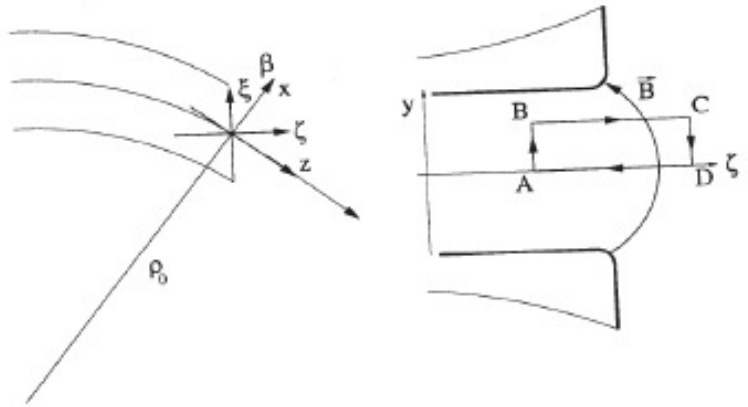
β = Kantenwinkel
g = Gap
ρ_0 = mittlerer Umlenkradius
K = Randfeld-Integral (später mehr...)

Randfeld-Integral

$$K = \int_A^D d\zeta \frac{1}{g(\zeta)} \frac{B_y(\zeta)}{B_0} \frac{(B_0 - B_y(\zeta))}{B_0}$$

ξ = paralell zur Kante

ζ = senkrecht zur Kante



- Typische Werte für reale Kanten: K= 0.3 ... 1.0, K=0 <=> „hard edge“
- Für g=const => K= „Maß für die Länge des Randfeld“

  je größer K, desto länger ist das Randfelds

- K läßt sich berechnen, wenn die Feldverteilung in ξ-Richtung beispielsweise aus *Meßungen* oder aus *Simulationsprogrammen* bekannt ist