Erzeugung intensiver Protonenpulse durch Kompression

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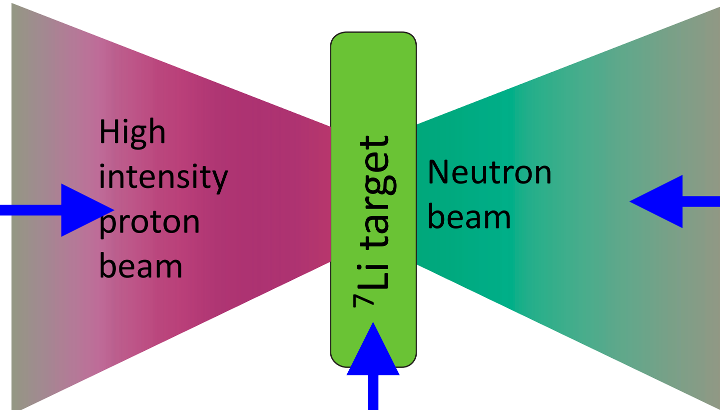
Outlines:

- **FRANZ:**
  - Overview & Status
- **Bunch Compressor: Design & Optimization**
  - Concepts: Geometry
  - 5MHz Kicker
  - Single Bunch Beam Dynamics
  - Merging Scenario
  - Rebuncher Cavities
  - Magnet Design
  - Beam Dynamics with Realistic Field Distributions
- **Outlook**

FRANZ

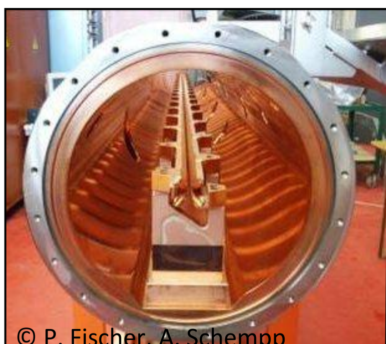
Development of new **accelerator concepts** for intense proton and ion beams.



Measurement of neutron capture cross sections, nuclear **astrophysics**, **material research** and detector development.

Development of high power targets.

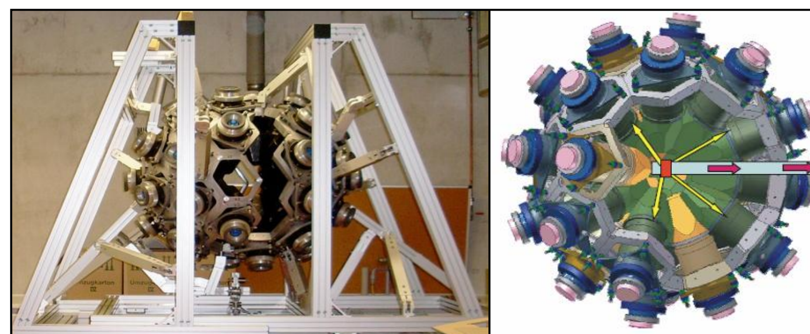
Expertise of IAP in linac design



4-rod RFQ

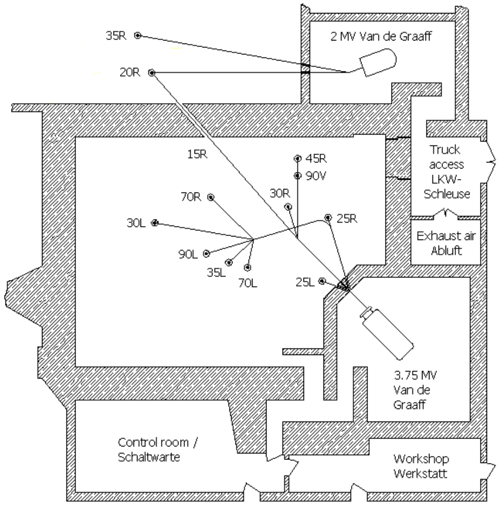
IH-DTL

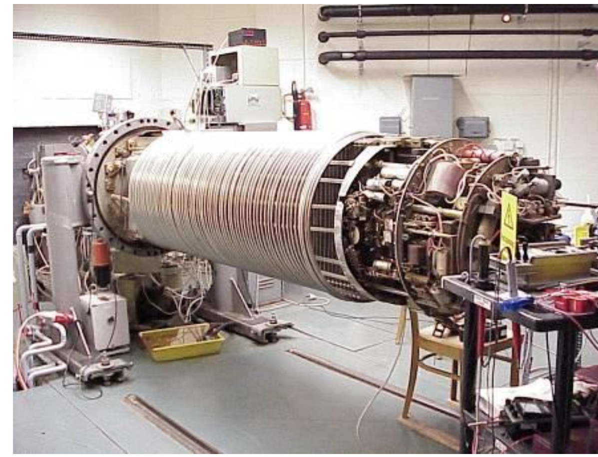
Technology and knowledge transfer from Karlsruhe.



4π BaF_2 Detector

- Continuation and extension of the physics programme started around 1980 at the 3.7 MV Van-de-Graaff Laboratory at FZ Karlsruhe.





- Franz Käppeler retired since 2008: his research group is dissolved.
- Technology and knowledge transfer to GSI and Goethe-University.
- FRANZ will increase the intensities by about 3 orders of magnitude. Allows investigations on radioactive samples with N about 10^{15}: Sub-milli-gramm sample of short-lived isotopes.

Comparison with existing intense neutron sources

Facility	Neutron flux at sample position *) $[cm^{-2} s^{-1}]$	Repetition Rate [Hz]	Flight path [m]	Pulse Width [ns]	Neutron energy range [keV]
FZ Karlsruhe	$1 \cdot 10^4$	250000	0.8	0.7	1-200
DANCE, Los Alamos	$5 \cdot 10^5$	20	20	250	th-10^5
n_TOF, CERN	$5 \cdot 10^4$	0,4	185	6	th-10^6
GELINA, Geel	$5 \cdot 10^4$	800	30	1	th-10^5
ORELA, Oak Ridge	$2 \cdot 10^4$	525	40	8	th-10^4
Elbe Dresden	$1 \cdot 10^5$	500000	3.7	0.4	50 - 10^4
FRANZ, Frankfurt	$1 \cdot 10^7$	250000	0.8	1	1-200 (500)

*) **Integrated flux between 1 keV and 100 keV only**

The Frankfurt neutron source will provide the highest neutron flux in the astrophysically relevant keV region (1 – 500 keV) worldwide.

Factor of 1000 higher than at FZK!!!

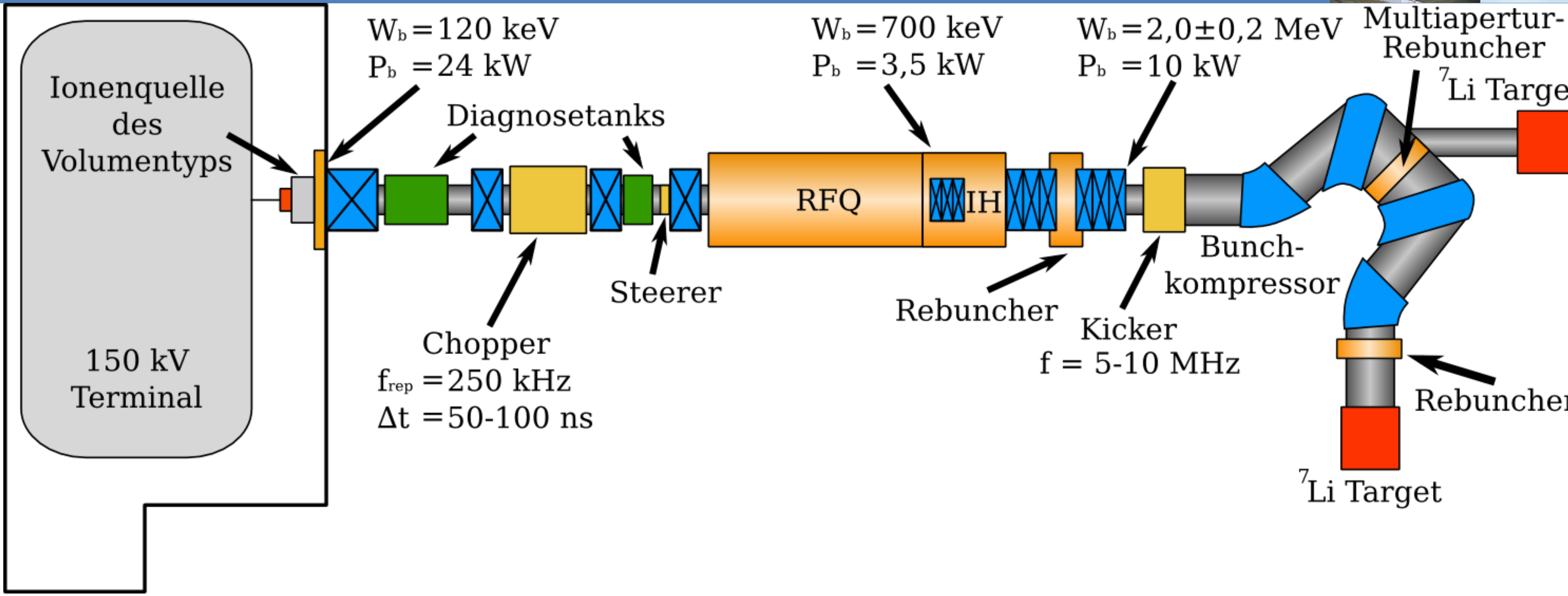
Neutron capture measurements of small cross sections:

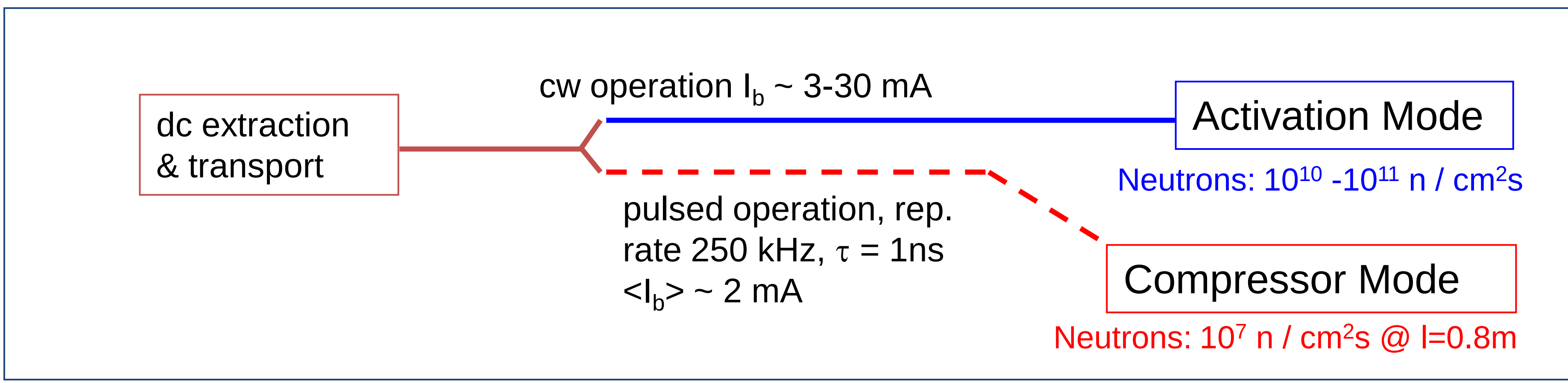
- Big Bang nucleosynthesis: ^{1}H(n,γ)
- Neutron poisons for the s-process: ^{12}C(n,γ), ^{16}O(n,γ), ^{22}Ne(n,γ).
- ToF measurements of medium mass nuclei for the weak s-process.

Neutron capture measurements with small sample masses:

- Radio-isotopes for γ-ray astronomy ^{59}Fe(n,γ) and ^{60}Fe(n,γ)
- Branch point nuclei, e.g. ^{85}Kr(n,γ), ^{95}Zr(n,γ), ^{147}Pm(n,γ), ^{154}Eu(n,γ), ^{155}Eu(n,γ), ^{153}Gd(n,γ), ^{185}W(n,γ)

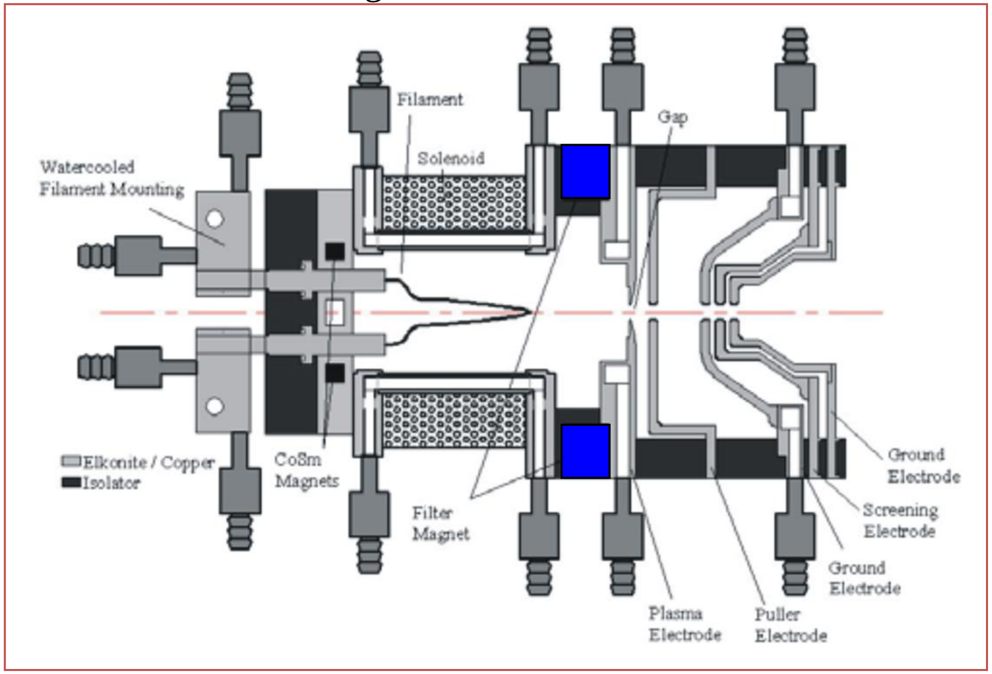
Ref.: René Reifarth (GSI / U. Frankfurt)





Operation Modes of the Frankfurt Neutron Source FRANZ.

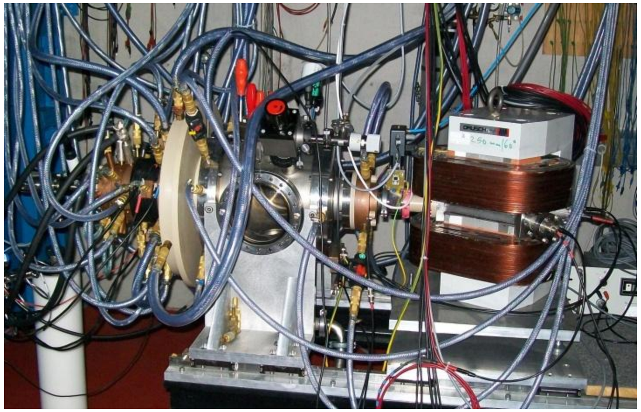
© K. Volk, R. Nörenberg



Cross-sectional view of the ion source

Operation mode	dc
Ion species / fraction	Protons / 90 %
Discharge power	10 – 12 kW
Extraction current	200 mA
Extraction voltage	62 kV
Extraction field strength	5 kV/mm
Beam energy	120 keV
Input emittance (norm. rms)	0.07 π mm mrad
Aspect ratio	0.2

- Filament driven discharge: high brilliance ion beam
- Filter magnet: high proton fraction
- First beam tests are running.



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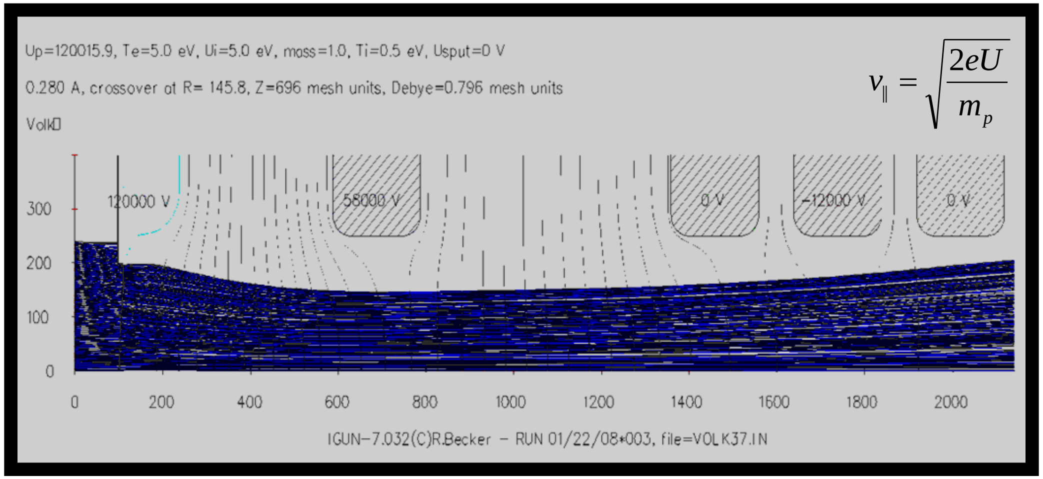
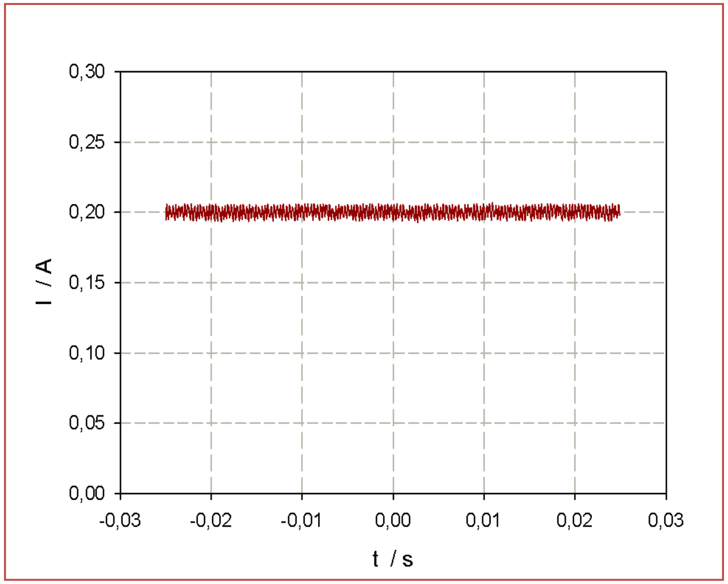


simulated beam extraction using a pentode system



extracted beam current with 3% noise (simulated)

$$n_p = \frac{I}{2\pi e \cdot v_\parallel \cdot r_b}$$

$$K = \frac{1}{4\pi\varepsilon_0}\sqrt{\frac{A}{2q}} \cdot \frac{I}{U^{3/2}}$$

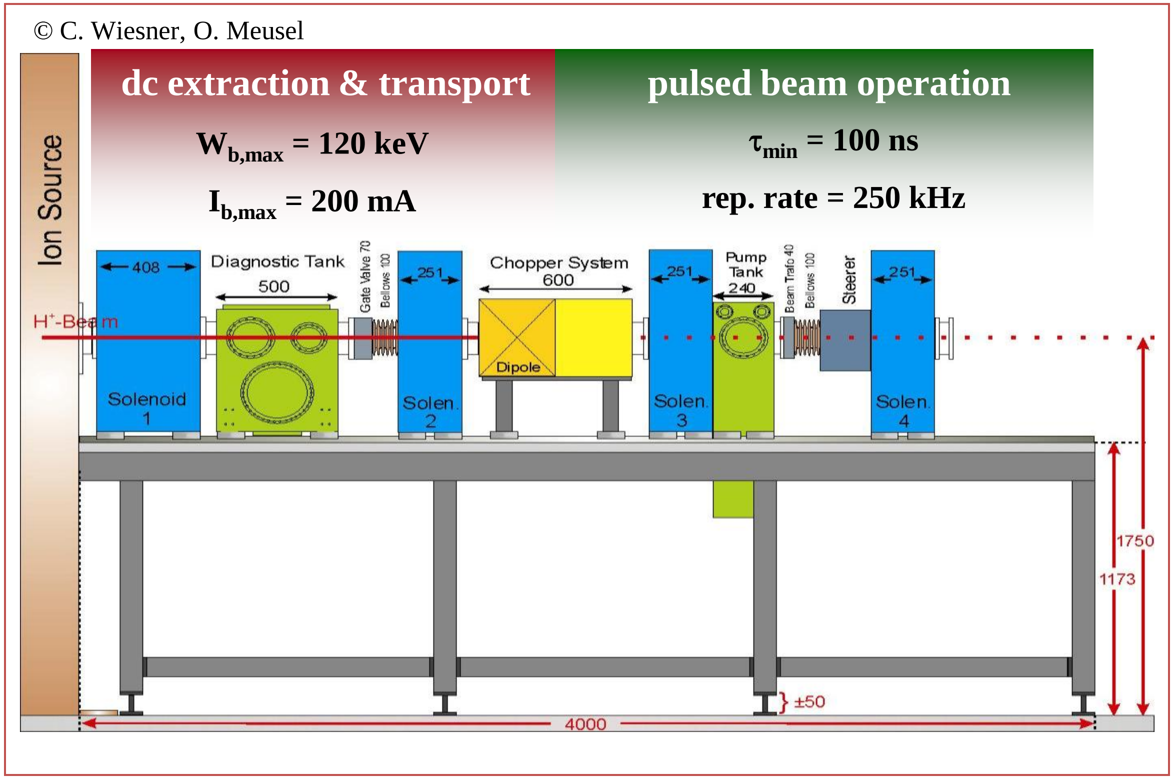
$$\eta = \frac{I_{peak}}{I_0}$$

proton density $n_p = 8.2 \cdot 10^{14}\ m^{-3}$

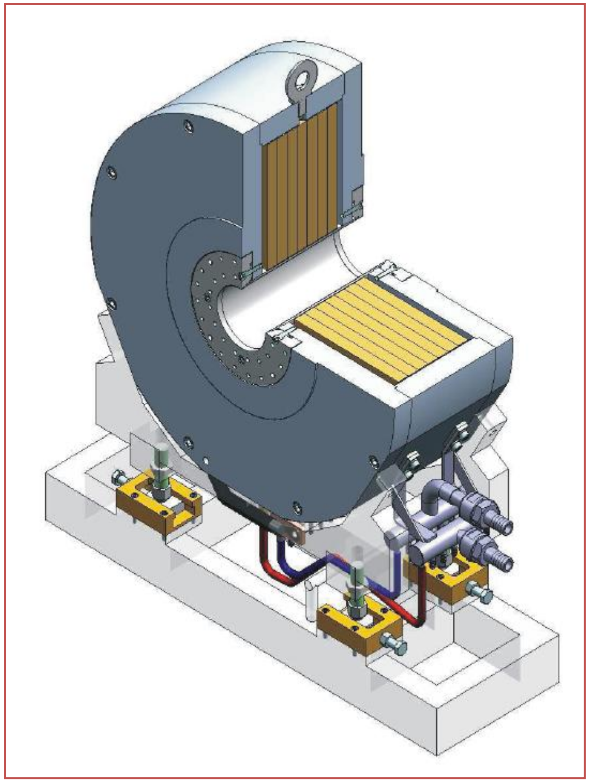
gen. Perveance $K = 3.1 \cdot 10^{-3}$

compression ratio $\eta = 1$

- Pentode extraction system: extraction properties independent to end energy
- Space charge compensation adjustable.

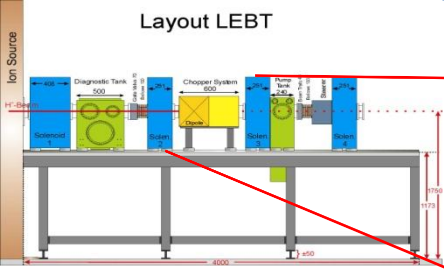


scheme of LEBT section



aperture 100 mm, B_z = 0.6 T

- Double telescopic system.
- Solenoidal transport section to provide space charge compensation.
- Pulsed Wien-filter: DC-beam => 100ns macro bunches with 250kHz repetition.



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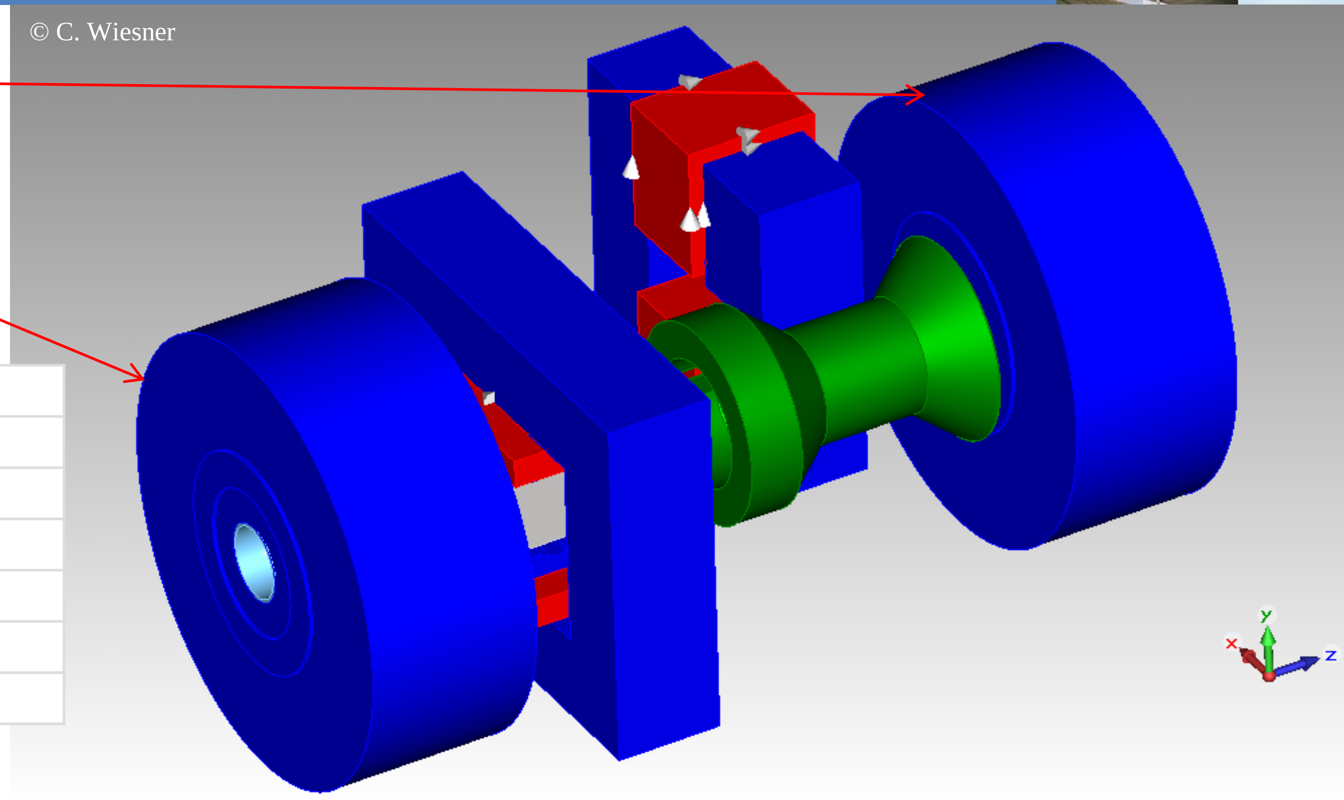
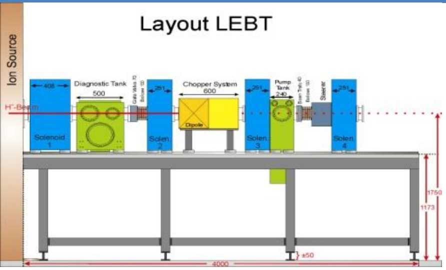


Kicker Frequency	250 kHz
Solenoid2	422 mT
Solenoid3	537 mT
Dipole	60 mT
C-magnet	300 mT
U_{max}	± 6 kV
Beam Energy	120 keV

- Static magnetic field, temporally compensated by electric field.
- C-magnet : deflection enhancement.
- Fast switch array (MOSFET) + nano-crystaline tape wound core.

Pulsed Wien-Filter: E×B-Kicker



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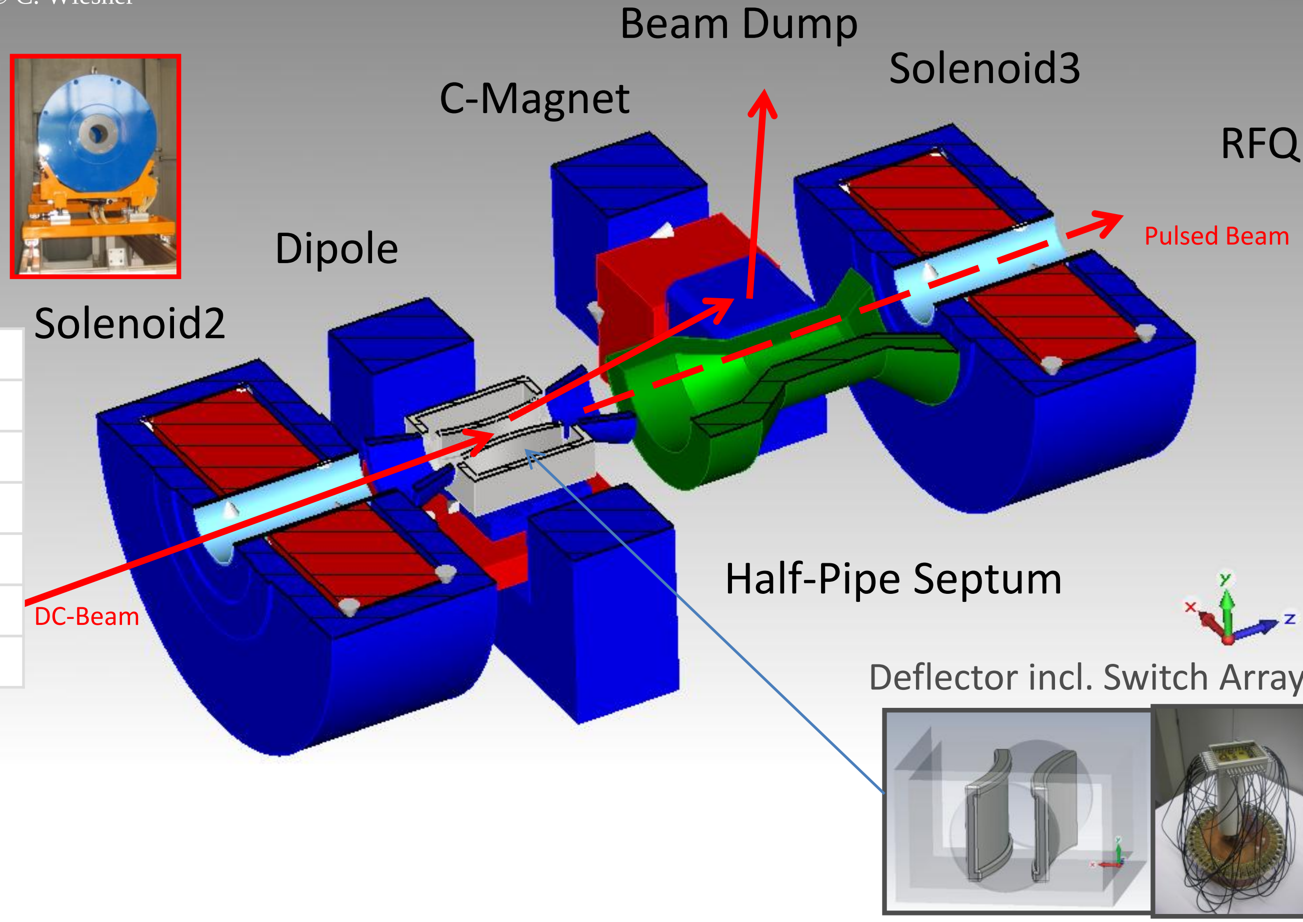

- Static magnetic field, temporally compensated by electric field.
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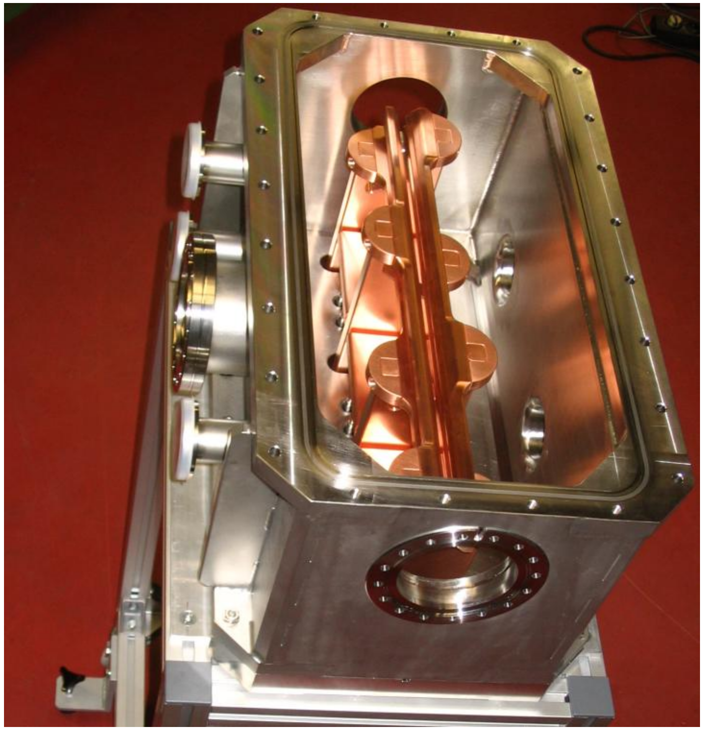
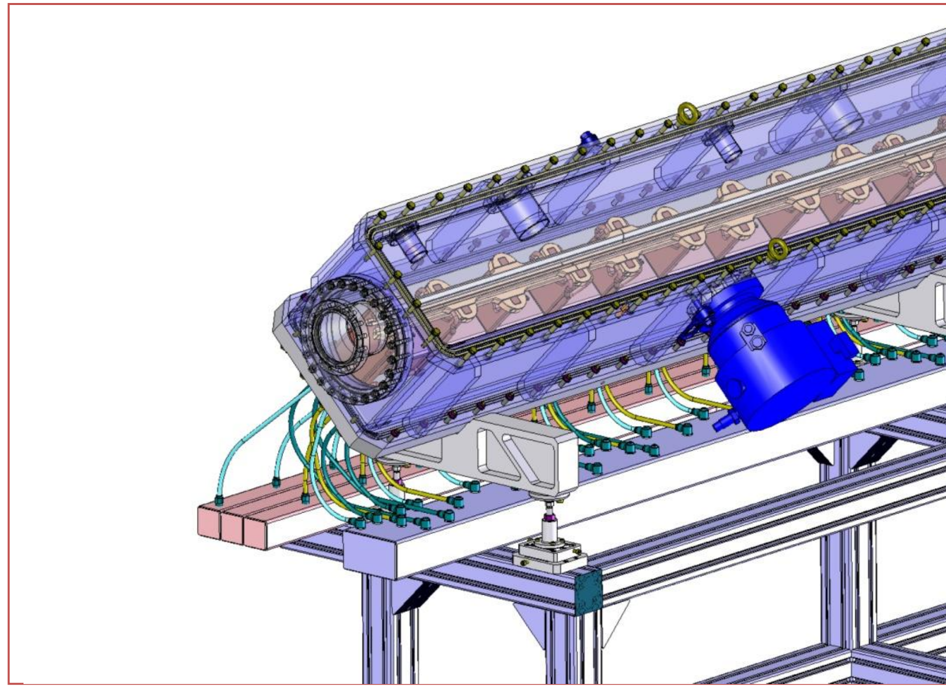
- Fast switch array (MOSFET) + nano-crystaline tape wound core.

Radio Frequency Quadrupole - RFQ



RFQ test module

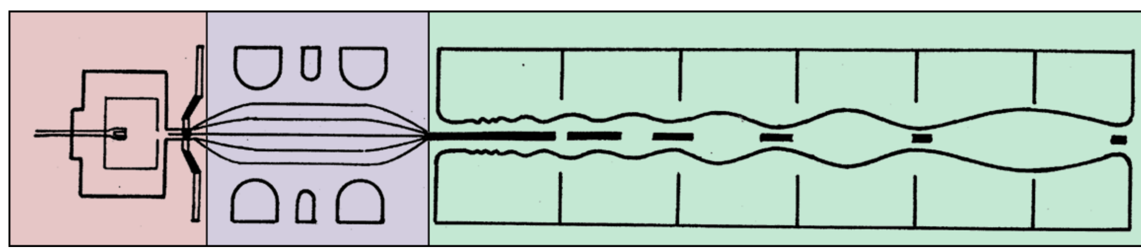
© A. Schempp / NTG company



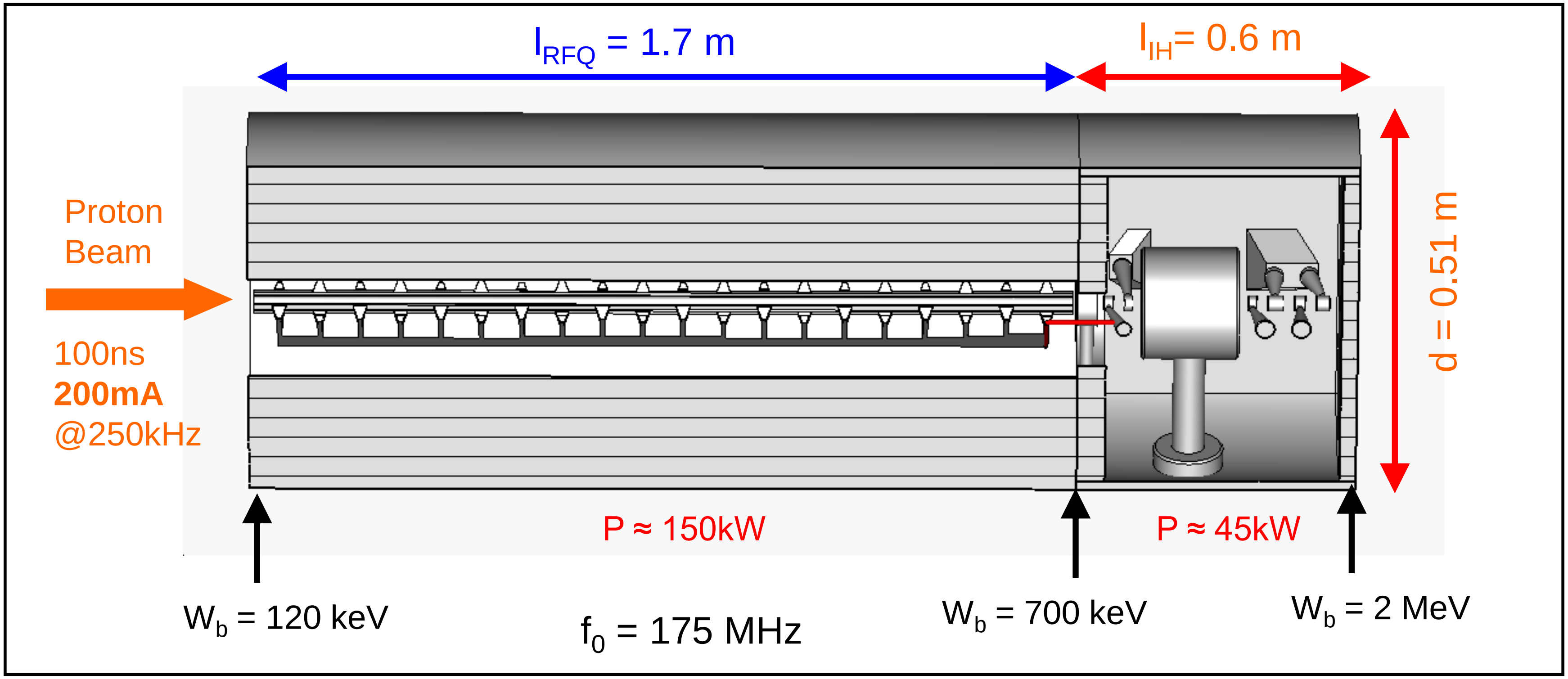
RFQ technical design

- Beam dynamics
- Design studies
- Construction in progress
- Power test at scaled model

proton source



LEBT RFQ

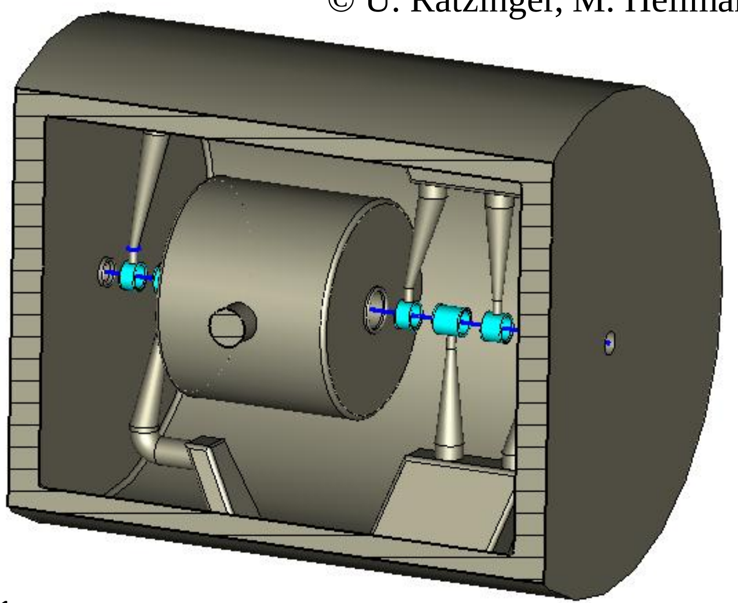


- RFQ: Micro bunching + pre-acceleration.
- RFQ-IH combination (coupled cavities): one power amplifier, shorter drift space.
- IH-cavity: main acceleration, KONUS dynamics.

IH-DTL and CH-Rebuncher

final energy 2 MeV

© U. Ratzinger, M. Heilmann

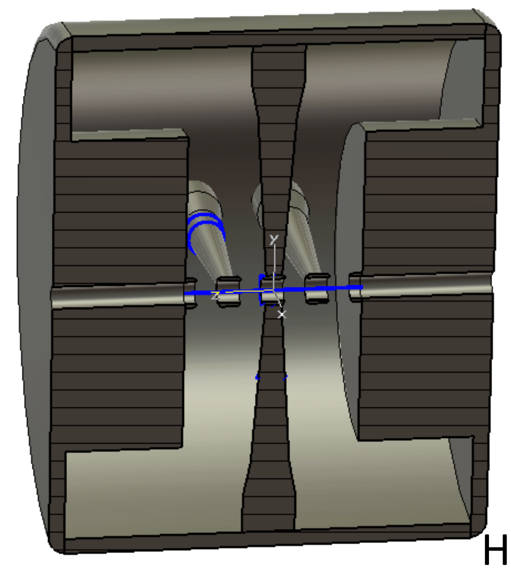


H_{111}

8 gap and internal msq triplet
output beam energy 2MeV

energy variation ± 0.2 MeV

© H. Podlech, A. Metz

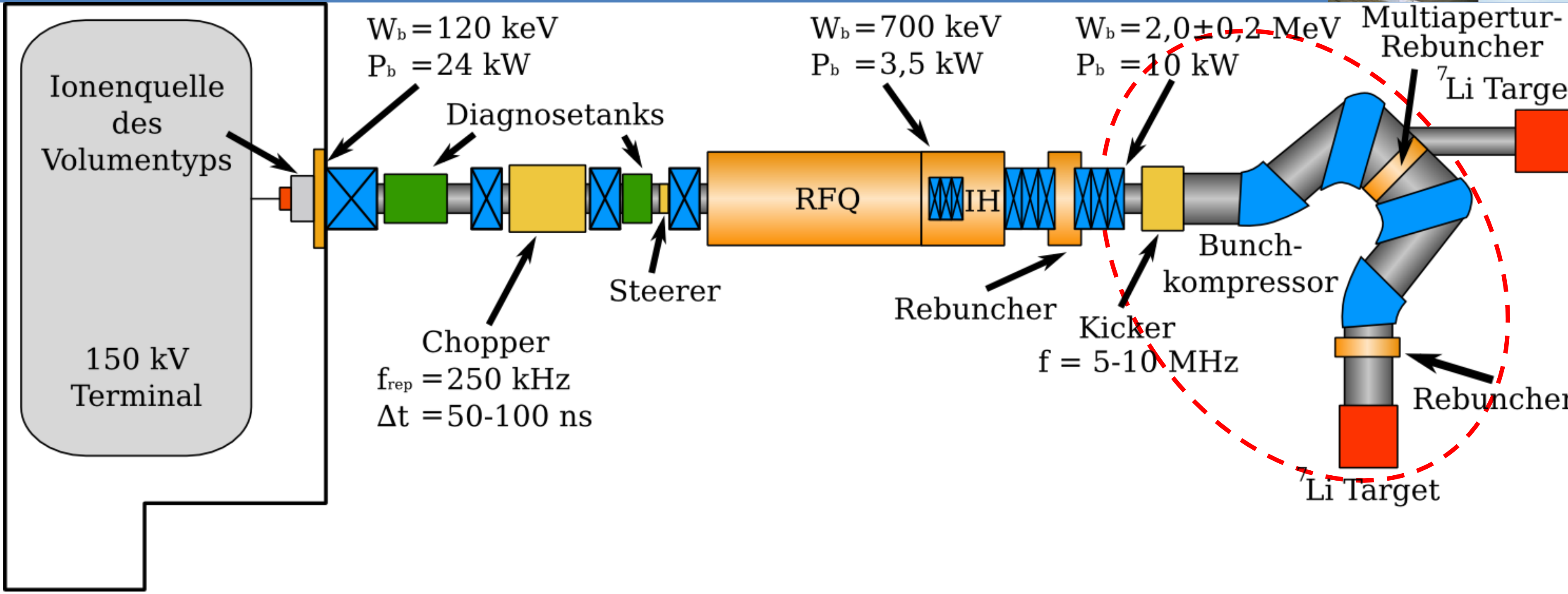


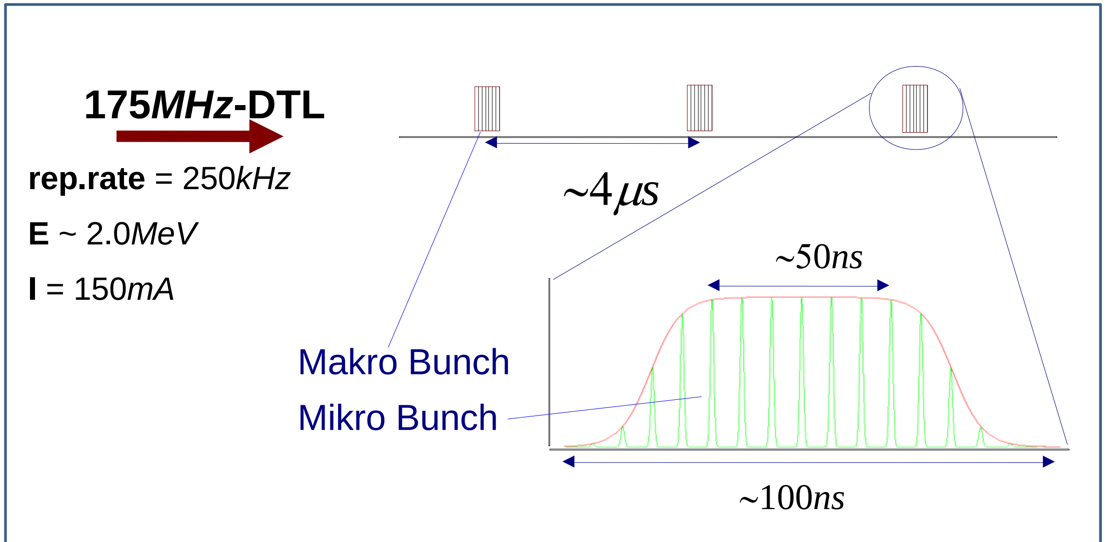
H_{211}

CH type cavity 4gap

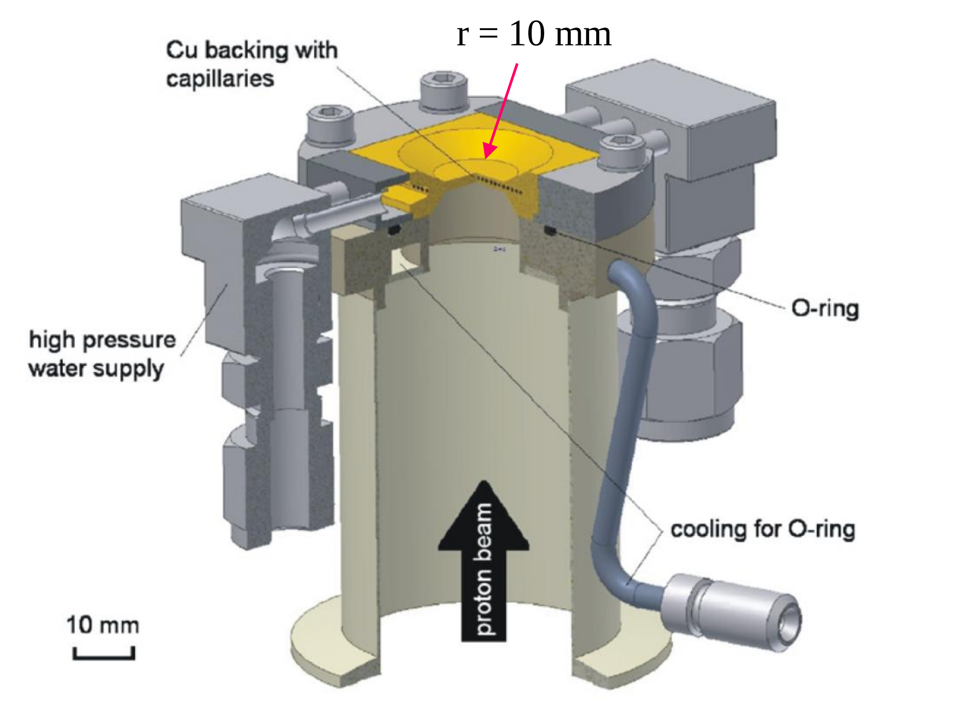
- IH-cavity: main acceleration.
- KONUS (Combined Zero degree structure) dynamics: high efficiency acceleration.
- CH-cavity: rebunching and variation of end energy (activation mode).

FRANZ: Requirements at the Target

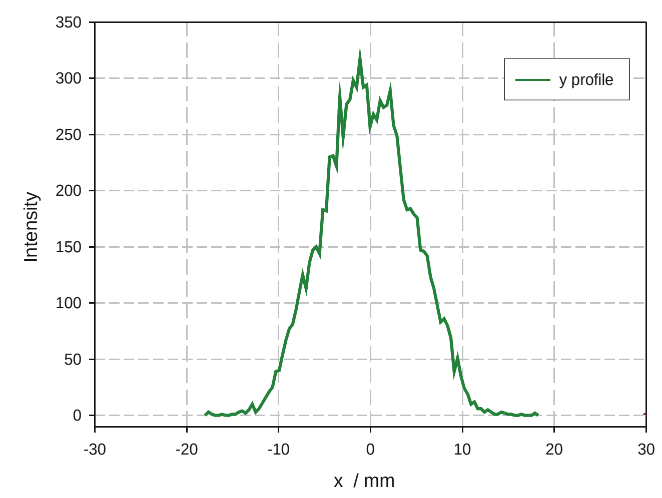




- N_{bunch} = 9
- ΔT = 50-100ns => $\Delta T_{rms} \approx 1ns$
- $A_{(beam\ at\ target)}$ < $3x3cm^2$
- $I_{(per\ pulse)}$ ≈ $8A$
- ΔW < ± 5%



target prototype for beam power up to 6 kW



transverse beam profile (simulated)

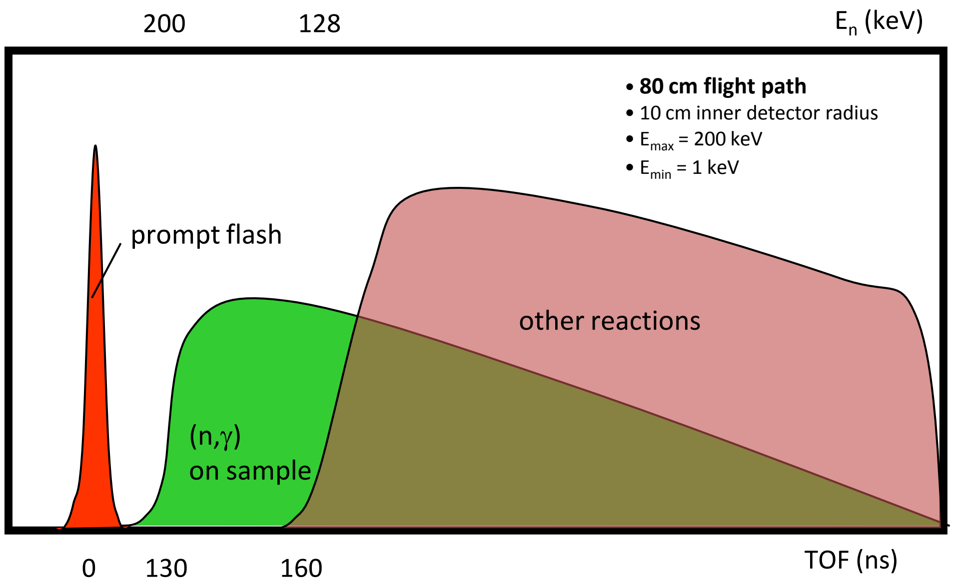
avg. power ~ 4 kW

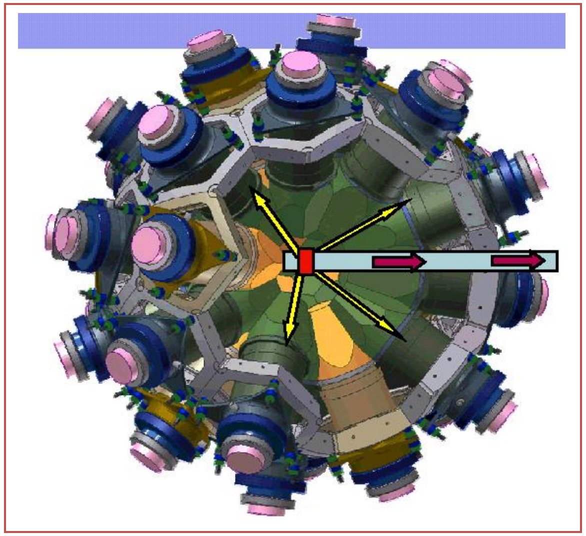
peak power ~ 20 MW

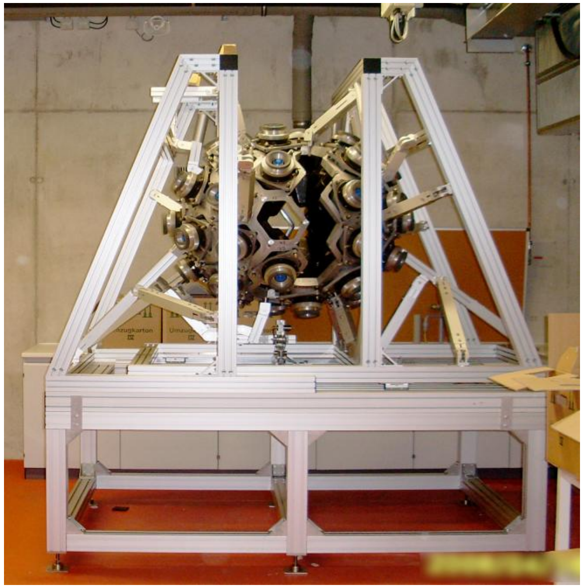
- Scaled prototype was built and tested.
- D. Petrich et al., Nucl. Instr. Methods A **596**, 269-275(2008)

4πBaF$_2$ Detector Array

- 4π colorimetrical measurements: good energy resolution.
- high granularity (#42): signal to noise ratio.
- fast timing (< 1ns) to achieve acceptable TOF resolution.
- suppression of other-reaction-signals.

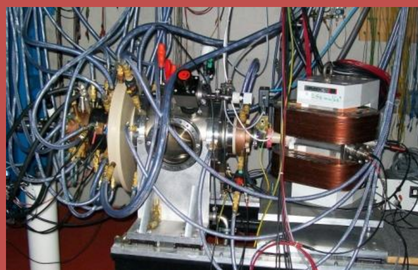






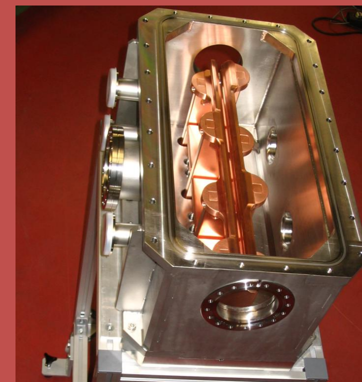
- M. Heil et al., Nucl. Instr. Methods A**459**, 229(2001).
- R. Reifarth et al., Publication of Astrophysical Society of Australia, **26**, 255-258(2009).

source is constructed

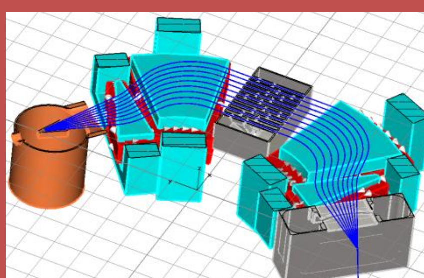


LEBT vacuum tests

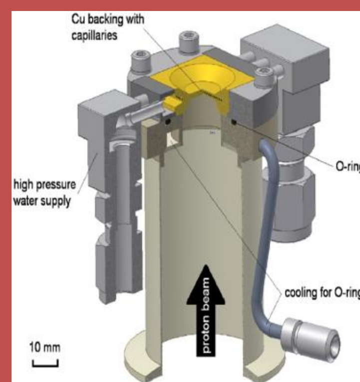
RFQ test module



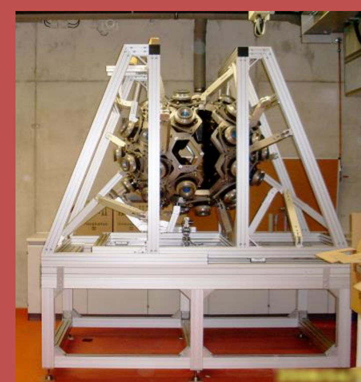
First Beam 2010



compressor design



high power target test



detector reassembled

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Beam size $r_0 \approx$ 1cm

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

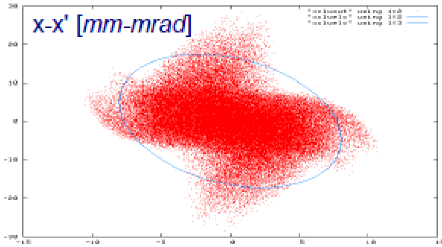
Center energy of the Bunch: W = 2*MeV*

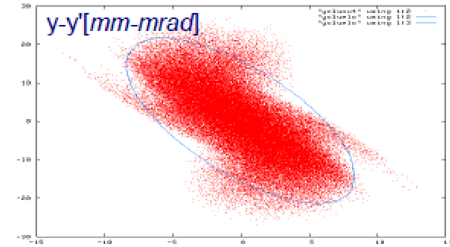
Velocity/speed of light : β = 0.065

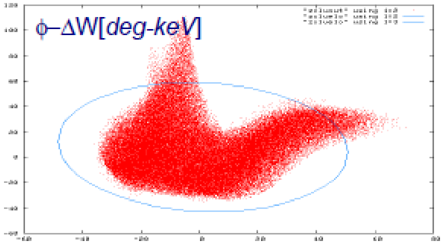
Charge per micro bunch: Q_{bunch} = 0.85*nC*

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

Path length(1. traj.) : L ≈ 4*m*







LORASR (IH): I = 150*mA*

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

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

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

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

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

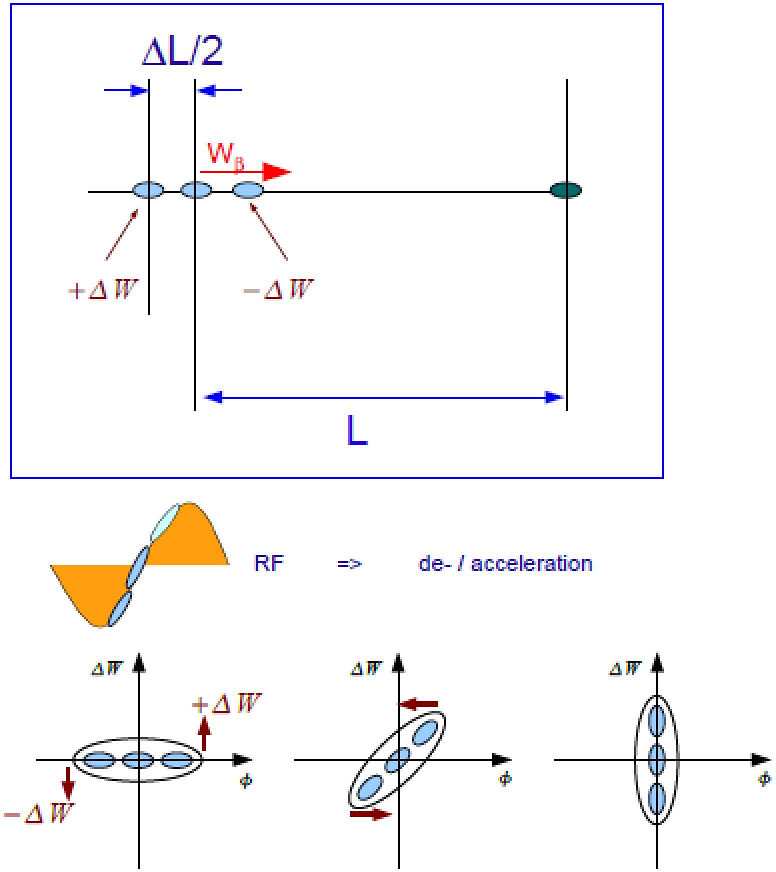
Potential Energy (proton on surface): W_{pot}=763.9 *eV*

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

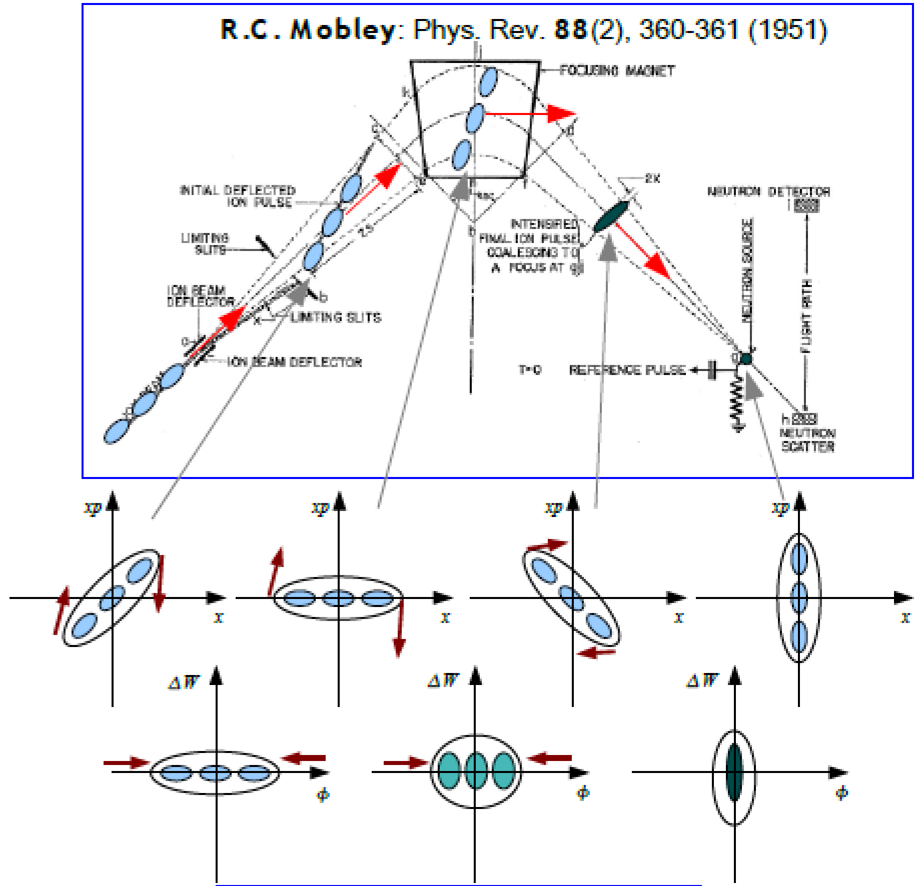
Significant
Space charge forces!

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

Energy differences ⟵ **Transit time differences** ⟶ **Path length differences**



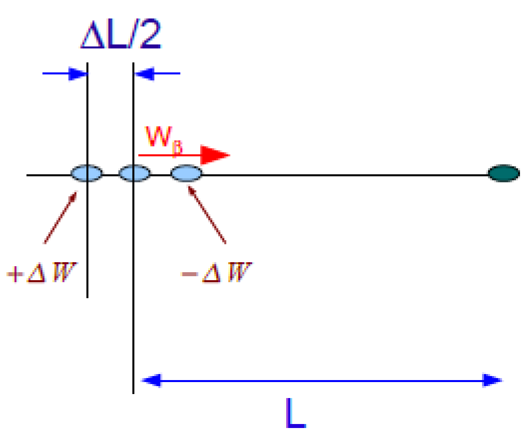
Large energy spread
(RF-cavity)



Negligible energy spread
(RF-deflector)

IAP

(without space charge, no intrinsic Energy spread of the Micro Bunches)



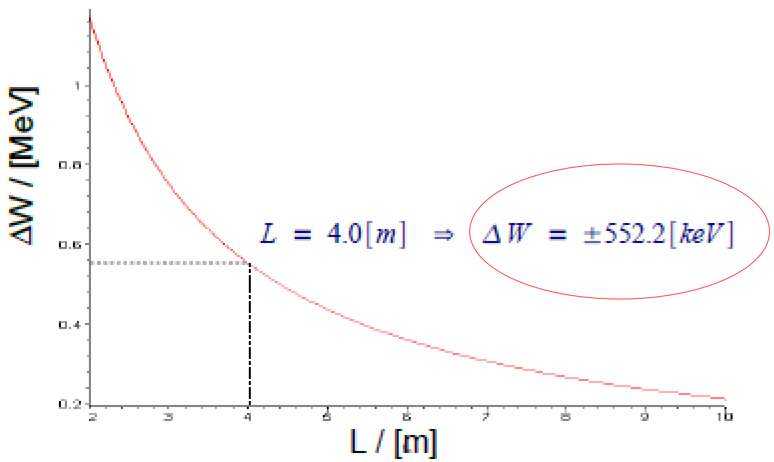
$$\gamma = \frac{W_\beta}{E_0} + 1 \quad , \quad \beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

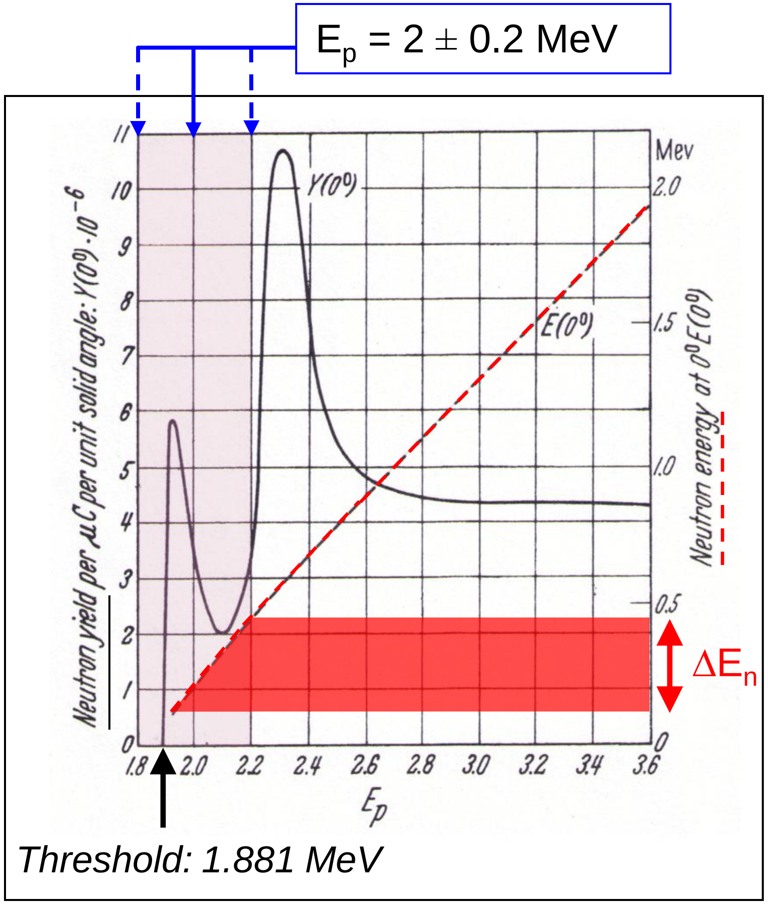
$$\frac{\Delta L}{2} = (\Delta\beta \cdot c)\underbrace{\left(\frac{L}{\beta \cdot c}\right)}_{\Delta T}$$

$$\Delta W = W_{\beta+\Delta\beta} - W_\beta$$

$$\Delta W = \left(\frac{1}{\sqrt{1-\beta^2\left(1+\frac{\Delta L}{2L}\right)^2}} - \frac{1}{\sqrt{1-\beta^2}}\right) \cdot E_0$$

$W_\beta = 2.07[MeV]$	(Central bunch) design energy
$\beta = 0.066$	(Central bunch) velocity
$E_0 = 938.3[MeV]$	Proton rest energy
$\Delta L = (N-1) \cdot \beta\lambda \approx 1.0[m]$	macro bunch length
$N=9$	Number of bunches
$f = 175[MHz]$	Bucket repetition rate
$L = 2 \ ... \ 10[m]$	Focuss lenght





Neutron yield per charge in forward direction.

$${}_1H^1 + {}_3Li^7 \rightarrow {}_4Be^7 + {}_0n^1 - 1{,}646 \text{ MeV}$$

Variable driver beam energy :

⇒ Adjustable Neutron Spectra + TOF

⇒ high resolution energy dependent Neutron capture cross sections.

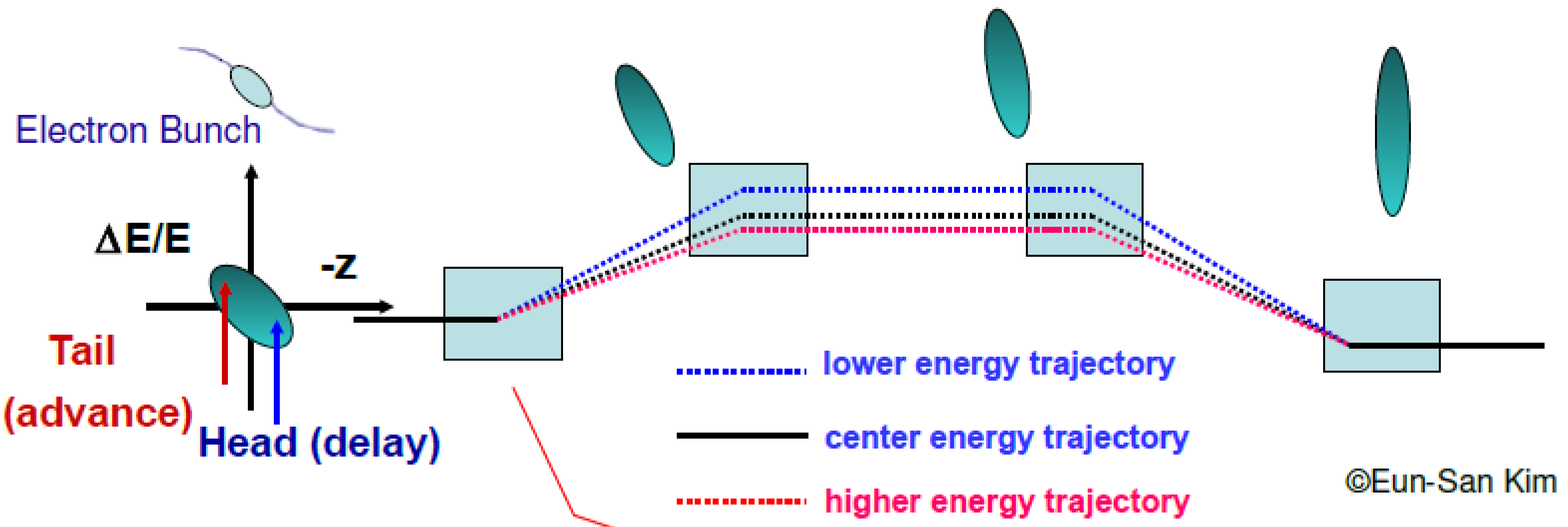
=> Reasonable energy spread of the proton beam: ΔW = ± 100[*keV*]

=> Bunch compression due to energy variation is ***unacceptable***!

Combination of both Bunch Compression Concepts

IAP

1 Bunch Kompressor Konzept für den „International Linear Collider" :



Parameter im Bunch-Kompressor :

$E = 5GeV$ => $\beta = 1$ (Elektronen!) → Weniger Probleme mit Raumladung

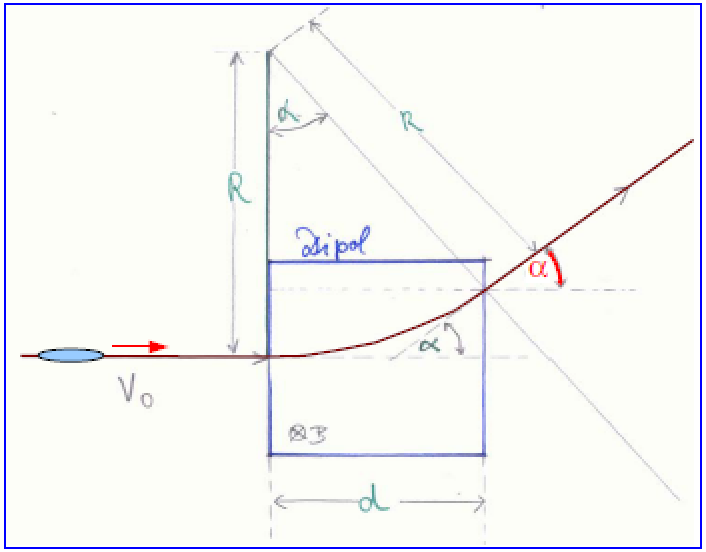
$z_{rms,in} = 6mm$

$z_{rms,out} = 0.15mm$ → Vergleichbare Kompressionsrate

$\kappa_L = 40$

$Q_{Bunch} = 3.2nC$ <=> $N(e) = 2x10^{10}$ → Weniger Ladung

Keine Kicker notwendig => ***statische*** Felder



2*MeV* Protonen => β = 0.065

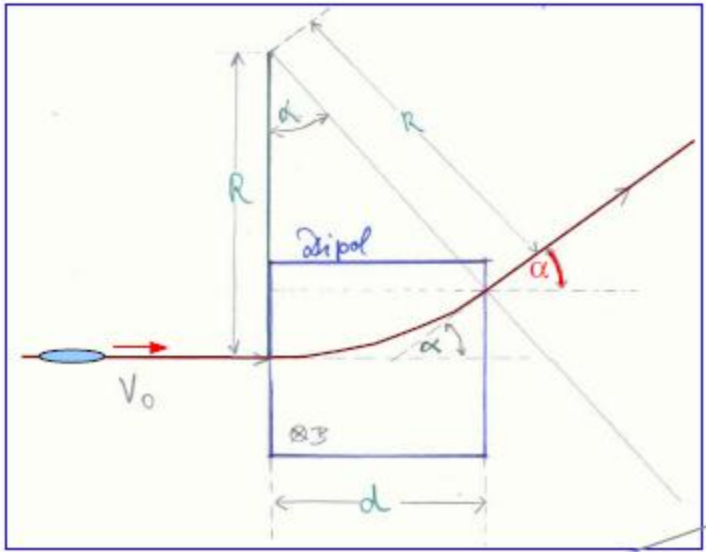
=> nicht relativistische Abschätzung für R > d :

$$R = \cancel{\gamma} \cdot \frac{E_0}{e} \cdot \frac{\beta}{c \cdot B} \quad ; \qquad \beta = \sqrt{1 - \frac{1}{(W/E_0 + 1)^2}}$$

$$\Rightarrow \boxed{\alpha = \arcsin\left(\frac{B \cdot c \cdot d}{\beta} \cdot \frac{e}{E_0}\right)}$$

Ablenkwinkel als Funktion der Geschwindigkeit

Estimation: Trajectory Separation due to Energy Variation



$B_1 = 0.5T = \text{konstant}$

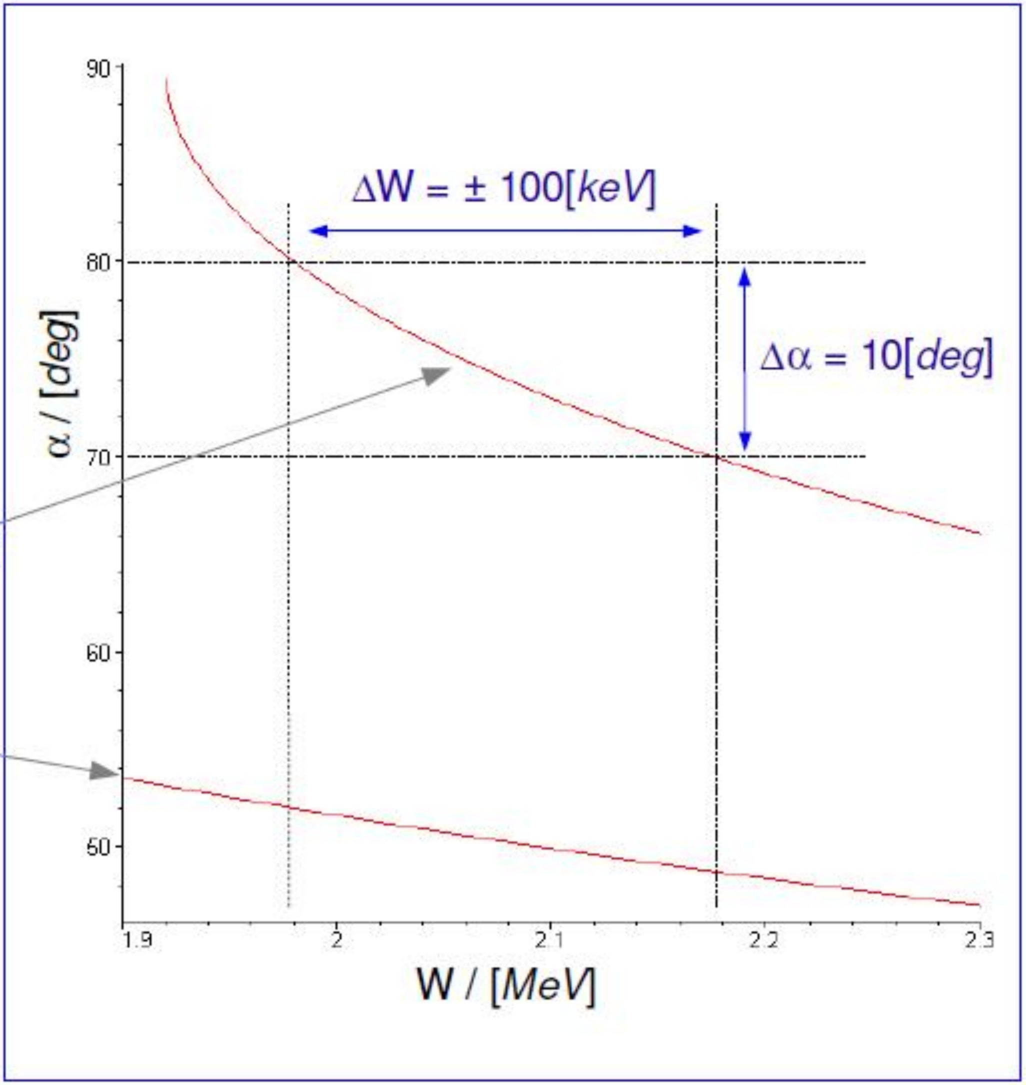
$B_2 = 0.4T = \text{konstant}$

$c = 3 * 10^8 m/s$

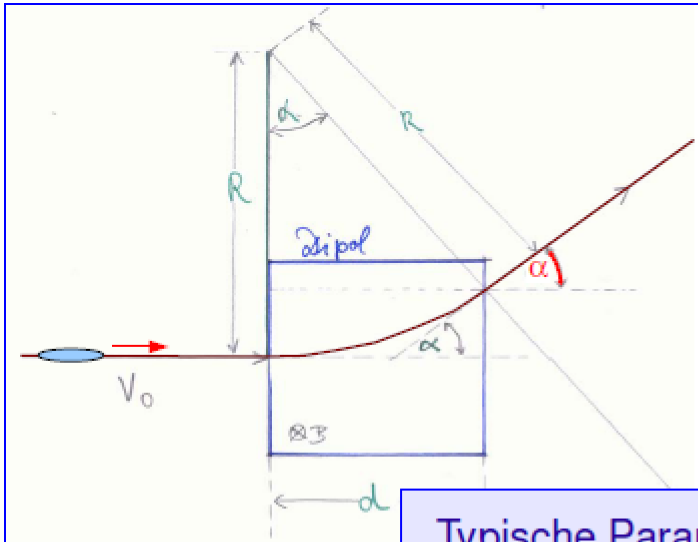
$d = 0.4m$

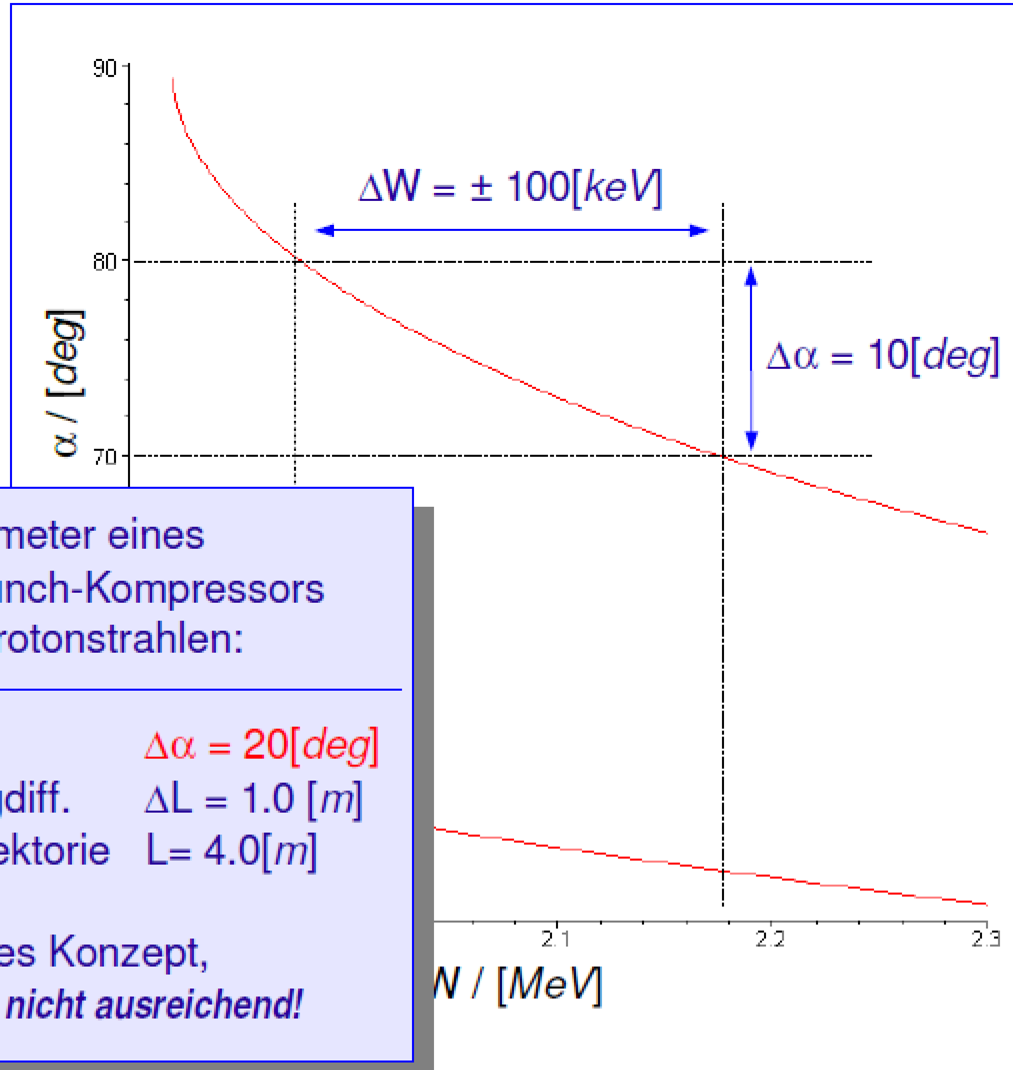
$e = 1.6 * 10^{-19} C$

$E_0 = 938.3 MeV$



Estimation: Trajectory Separation due to Energy Variation





$B_1 = 0.5T =$ konsta

$B_2 = 0.4T =$ konsta

$c = 3{*}10^8 m/s$

$d = 0.4m$

$e = 1.6{*}10^{-19}C$

$E_0 = 938.3MeV$

Typische Parameter eines ***kompakten(!)*** Bunch-Kompressors für intensive Protonstrahlen:

Winkeldiff.	$\Delta\alpha = 20[deg]$
maximale Wegdiff.	$\Delta L = 1.0\ [m]$
maximale Trajektorie	$L = 4.0[m]$

=> interessantes Konzept,
aber ***nicht ausreichend!***

Transit time differences → **Path length differences**

Mobley-Buncher: (µA-Proton beams)

Kicker

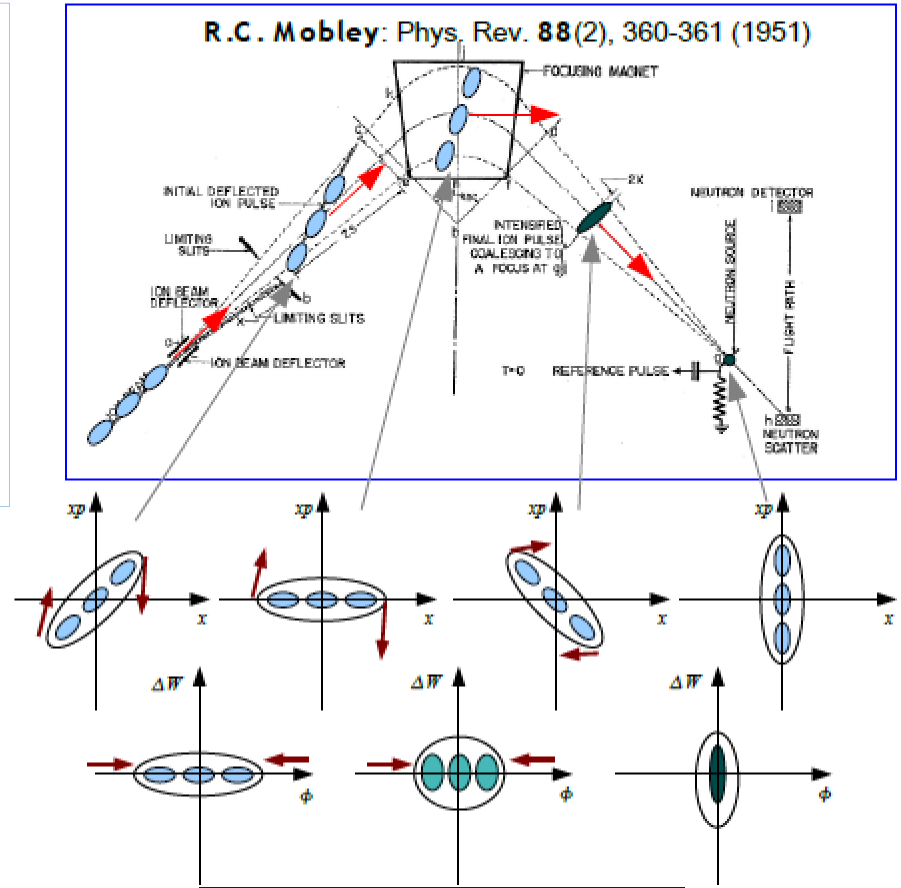
→ Separation of the micro bunches

Bending system (1 Dipole)

→ "weak" focusing

→ path length differences

→ longitudinal compression



Negligible energy spread
(RF-deflector)

Transit time differences → Path length differences

Mobley-Buncher: (μA-Proton beams)

Kicker

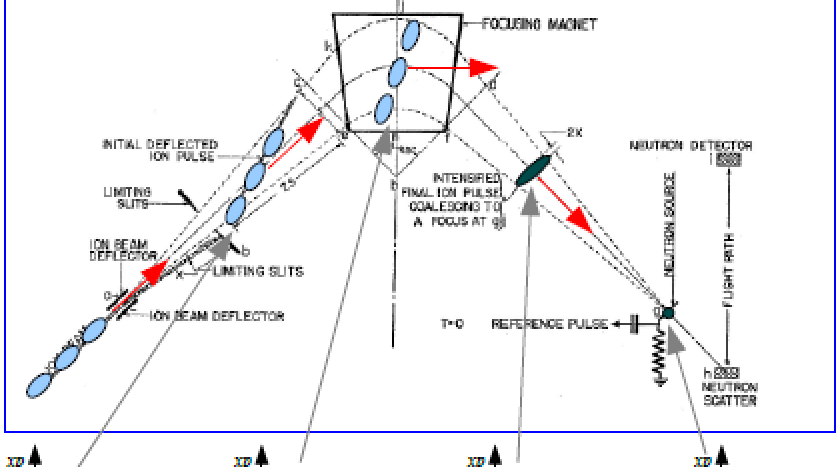
→ Separation of the micro bunches

Bending system (1 Dipole)

→ "weak" focusing

→ path length differences

→ longitudinal compression



Studied Systems:

- 1 Dipole: variable shape or gradient
- 2 Dipoles: rectangular magnets
- 3 Dipoles: 2 homogenous + 1 gradient

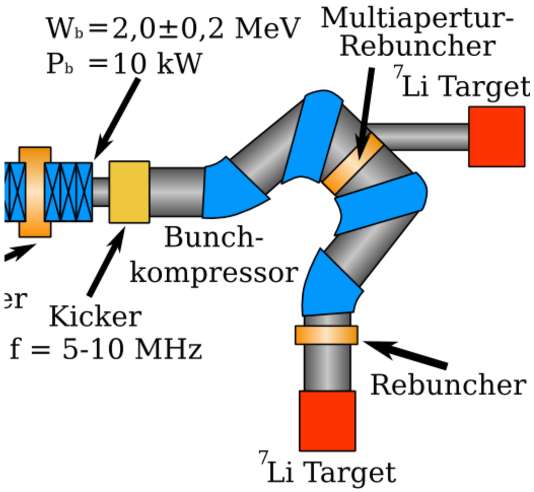
=> insufficient separation

=> big gradient for every trajectory

=> $(\partial s/\partial \alpha) \neq$ const

=> longitudinal defocusing

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

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

Studied Systems:

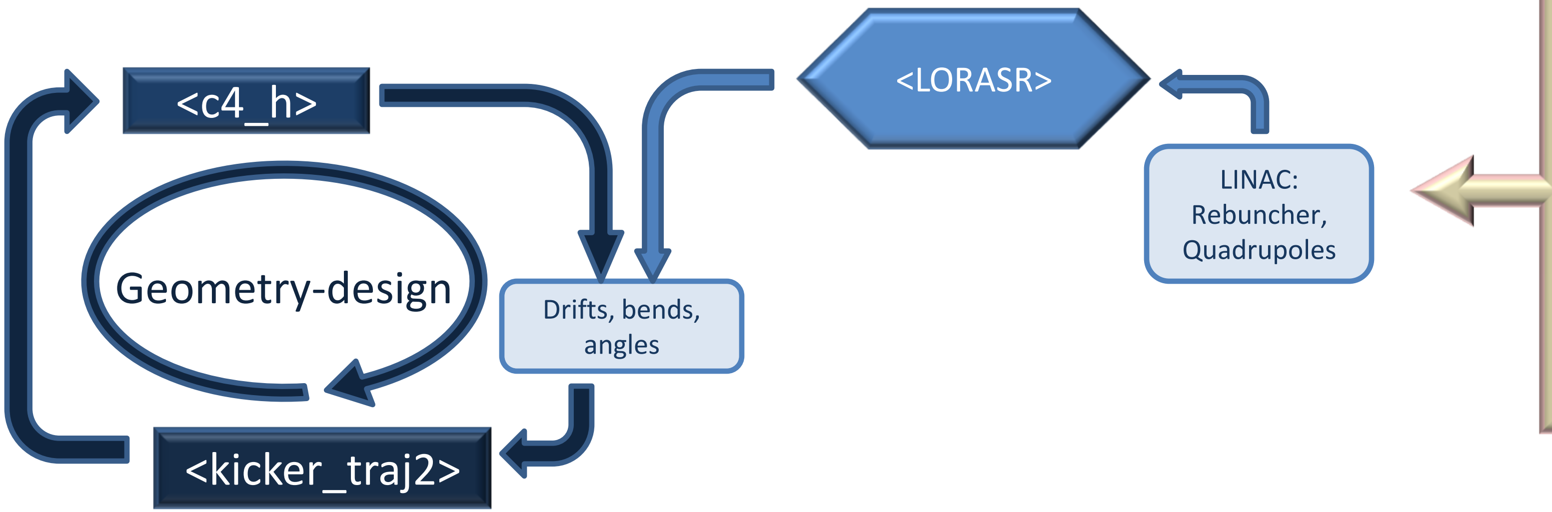
- 1 Dipole: variable shape or gradient
- 2 Dipoles: rectangular magnets
- 3 Dipoles: 2 homogenous + 1 gradient

=> insufficient separation

=> big gradient for every trajectory

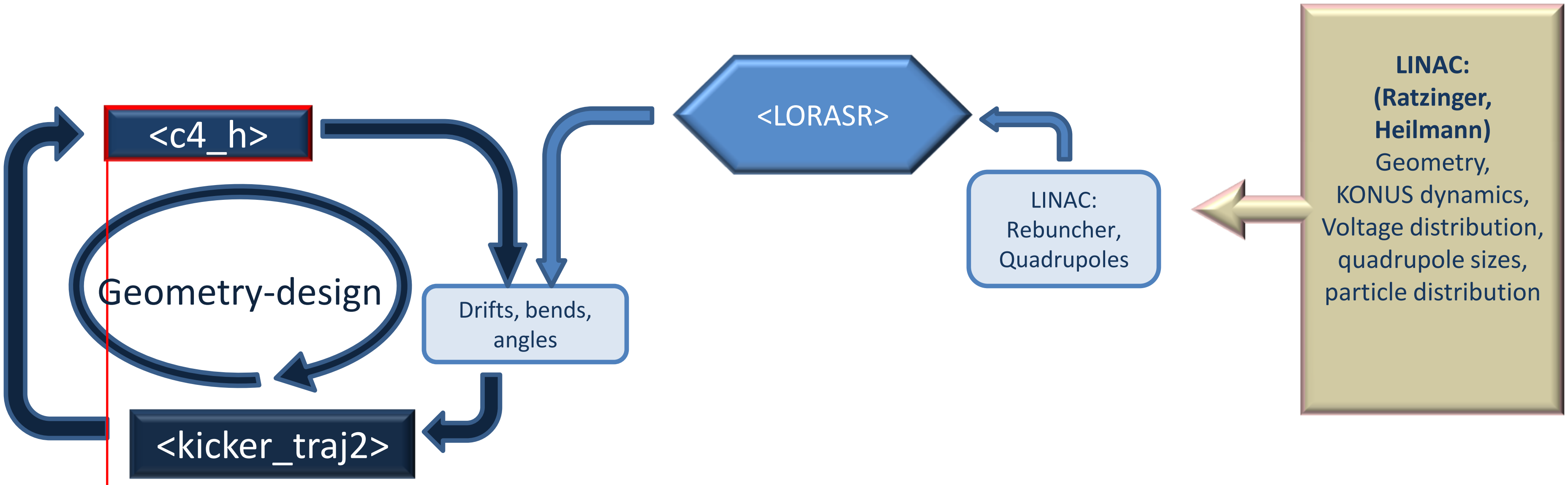
=> $(\partial s/\partial \alpha) \neq$ const

=> longitudinal defocusing



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

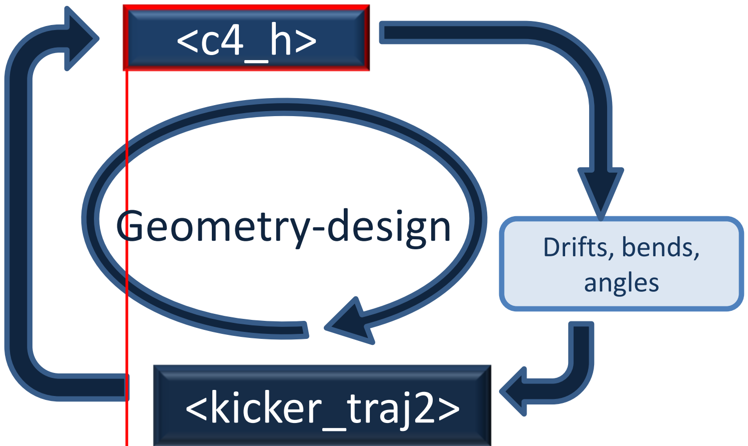
Bunch Compressor: Design / Optimization Cycles



<c4_h>: Geometrical parameters

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

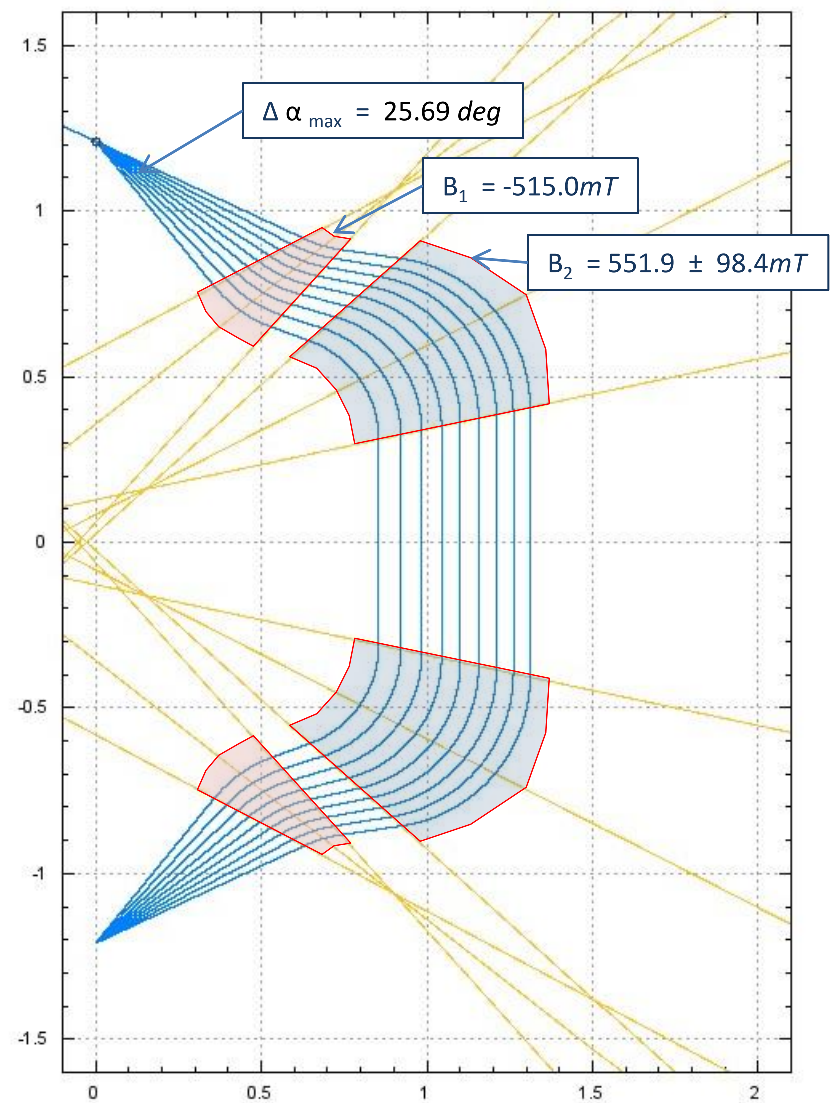
Bunch Compressor: Design / Optimization Cycles



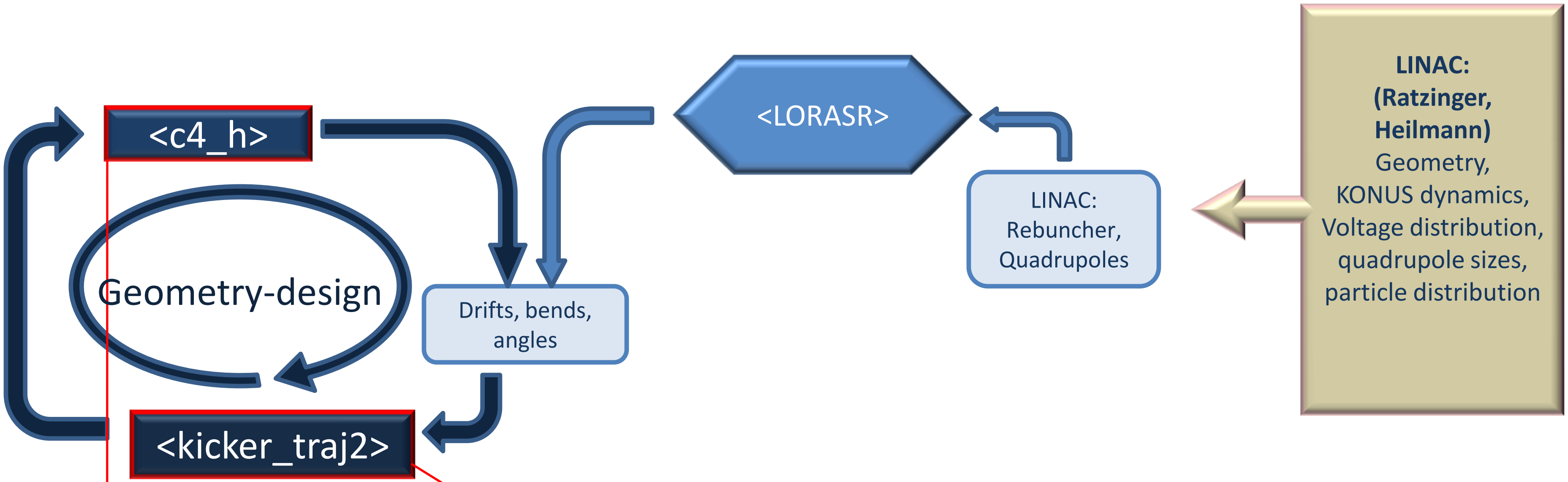
<c4_h>: Geometrical parameters

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

Geometry: g9_5x



Bunch Compressor: Design / Optimization Cycles

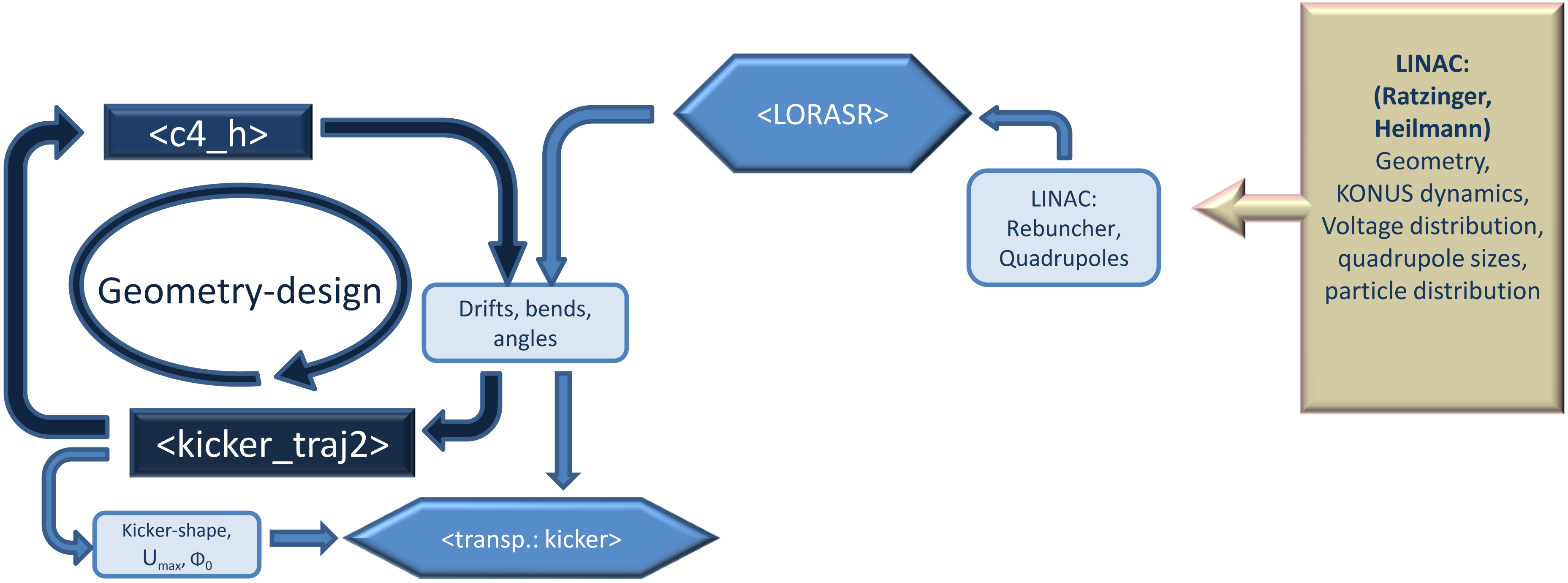


<c4_h>: Geometrical parameters

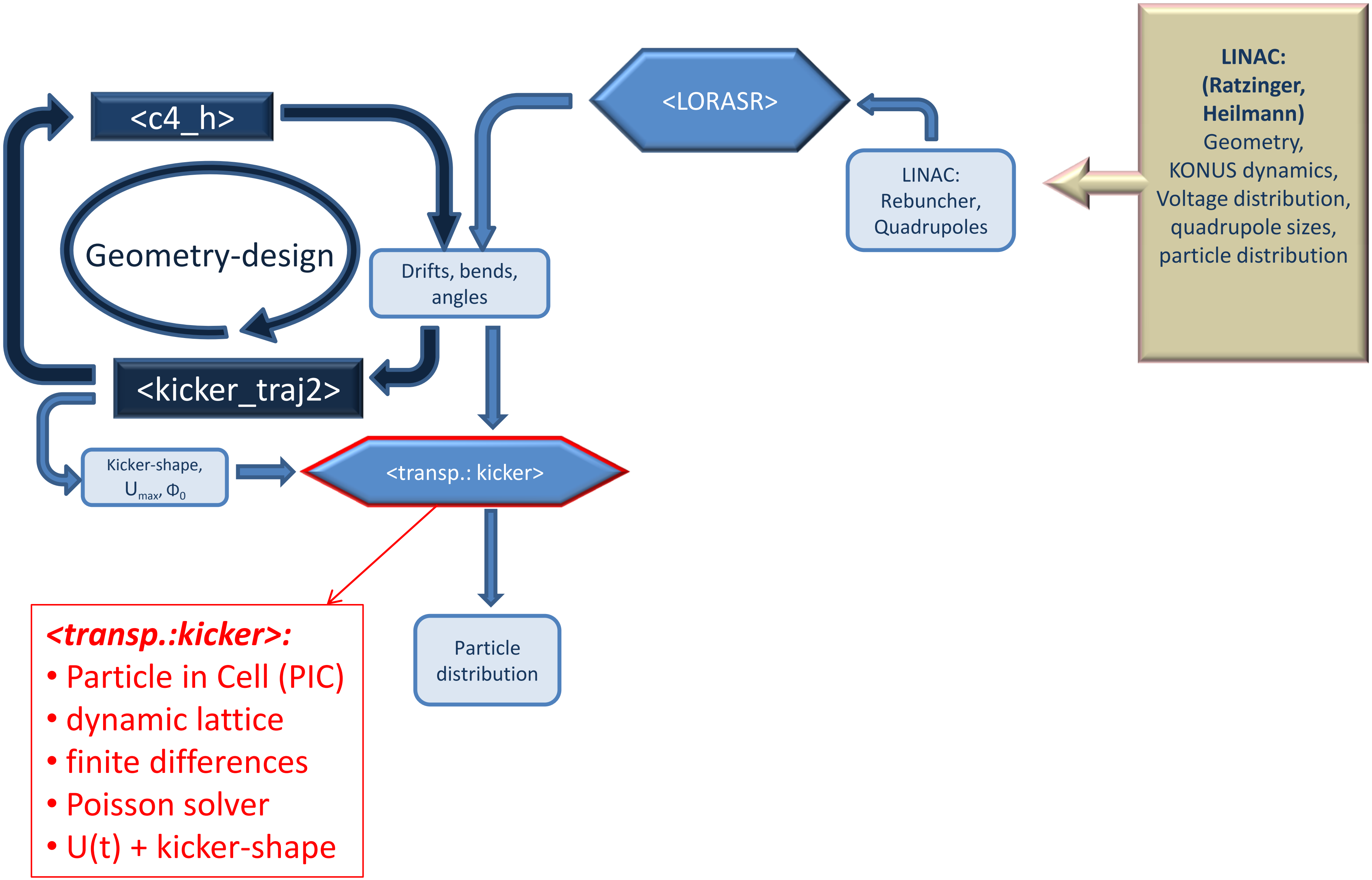
- trajectories, angles, distances
- magnetic fields, gradients
- shape of the dipoles

<kicker_traj2>: kicker properties

- max. deflection angles
- max. voltages
- shape of the plates


<c4_h>
Geometry-design
Drifts, bends, angles
<kicker_traj2>
Kicker-shape, U_{max}, Φ_0
<transp.: kicker>
<LORASR>
LINAC: Rebuncher, Quadrupoles
LINAC: (Ratzinger, Heilmann) Geometry, KONUS dynamics, Voltage distribution, quadrupole sizes, particle distribution

Bunch Compressor: Design / Optimization Cycles



<c4_h>

Geometry-design

Drifts, bends, angles

<kicker_traj2>

<LORASR>

LINAC: Rebuncher, Quadrupoles

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

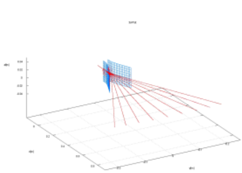
Kicker-shape, U_{max}, Φ_0

<transp.: kicker>

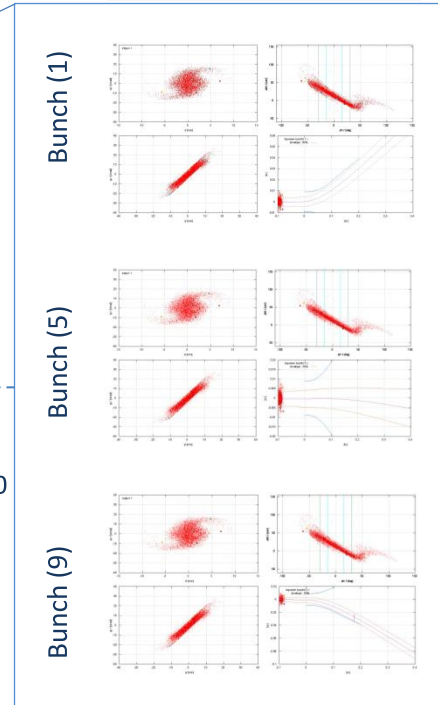
Particle distribution

<transp.:kicker>:

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

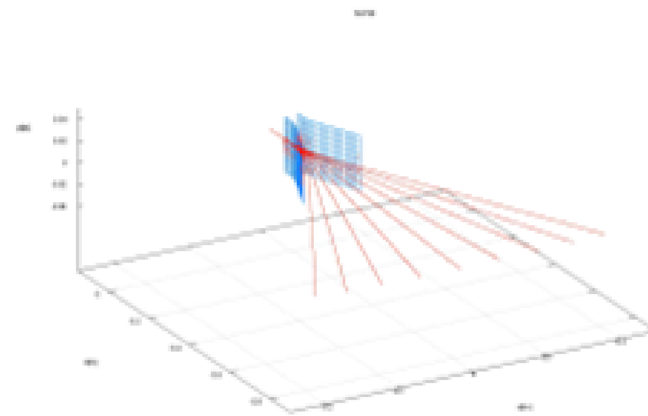


L	= 20*cm*
U_{max}	= 250*kV*
f	= 5*MHz*
d_{min}	= 18*mm*
α_1	= 29.5*deg*
α_2	= 11.5*deg*
a	= 1.2m^{-1}
I	= 150*mA*
$N_{particle}$	≈ 10k
N_{grid}	= 60x60x60
$\Delta x_{stepsize}$	= 1*mm*
$\Delta t_{calc+plot}$	≈ 7*s*



Analytical estimations:

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



Technical realization?

L = 20*cm*
U_{max} = 250*kV*
f = 5*MHz*
d_{min} = 18*mm*
α_1 = 29.5*deg*
α_2 = 11.5*deg*
a = 1.2m^{-1}

I = 150*mA*
$N_{particle}$ ≈ 10k
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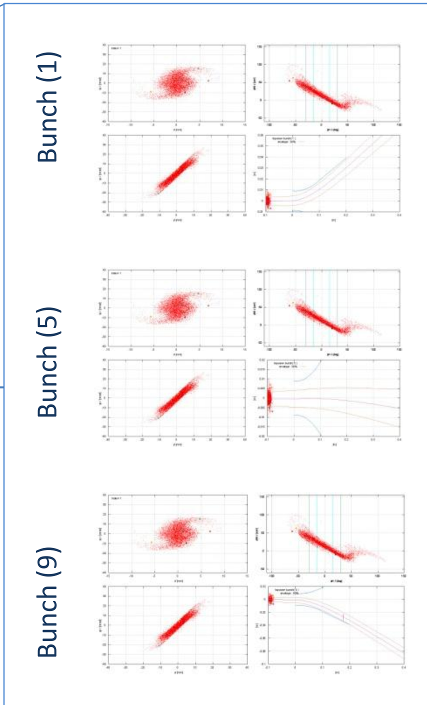
$\Delta x_{stepsize}$ = 1*mm*
$\Delta t_{calc+plot}$ ≈ 7*s*



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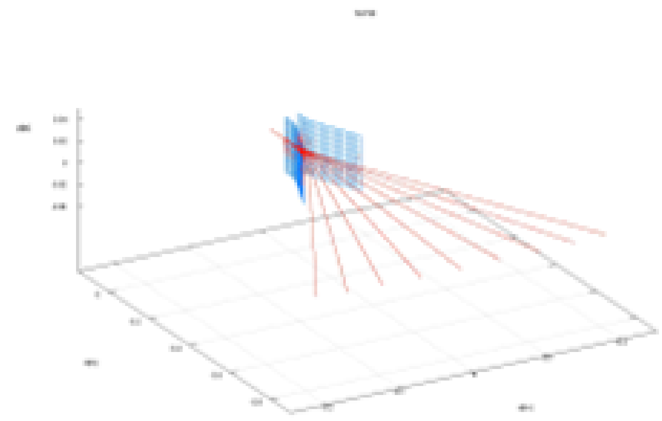

Scaled Model (analytical):

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**

Analytical estimations:

- RLC-Resonator
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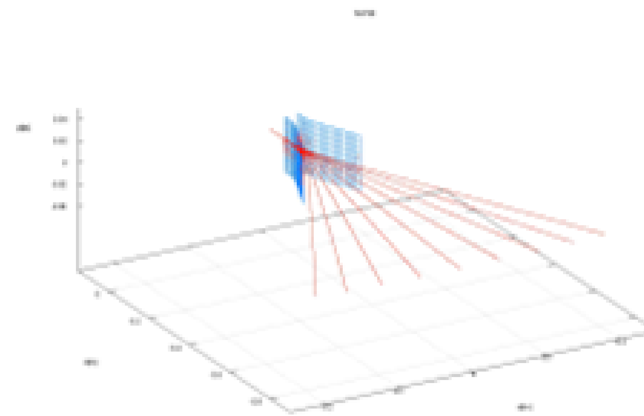

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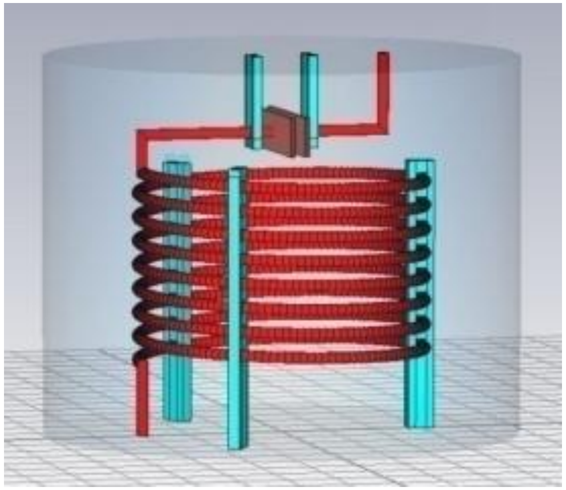
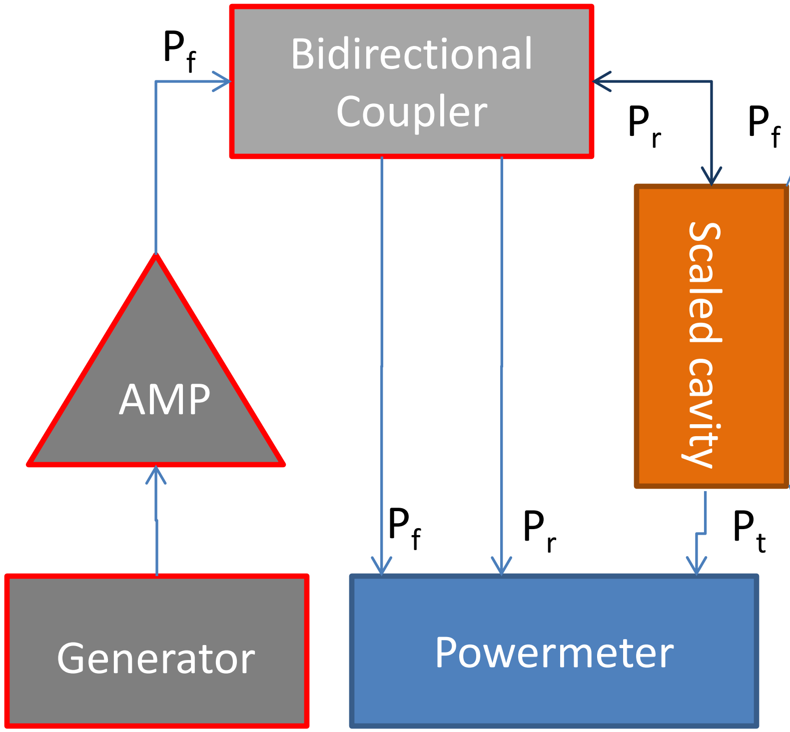
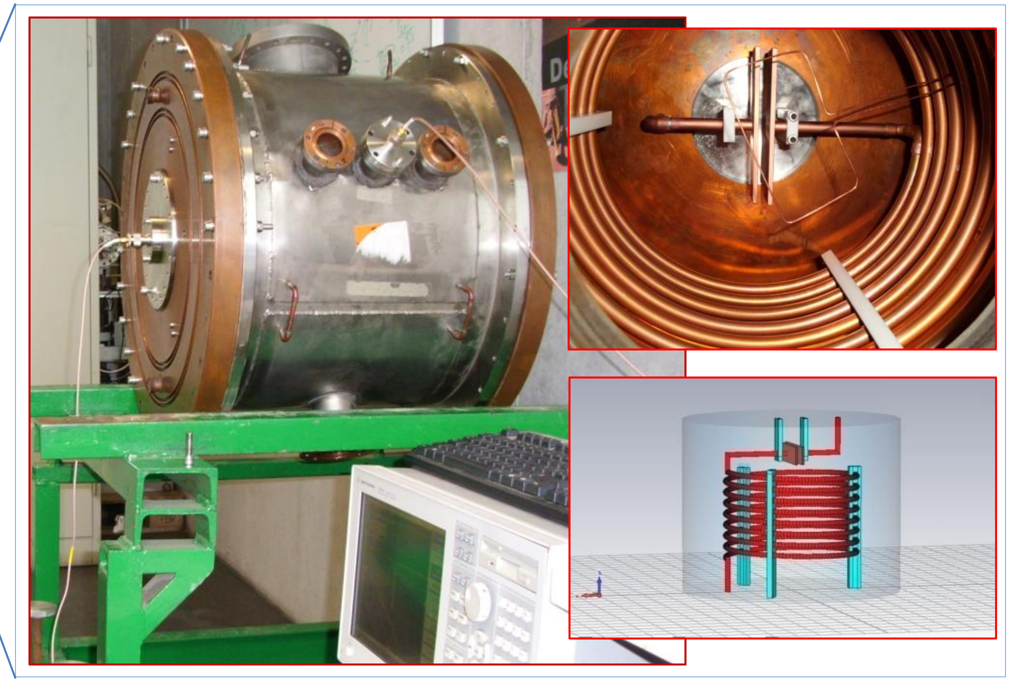
Frequency	**9.09**	**MHz**
Intrinsic Quality Factor	**2986**	
Shunt impedance	**4.4**	**MΩ**
Power losses @ 250kV	**14.8**	**kW**

Numerical estimation:

- 3D Cavity designs with CST Studios







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

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

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

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

Perturbation Capacitor method
=> shunt impedance

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

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

Measurement at scaled kicker 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

IAP

Outlines:

○ **FRANZ:**

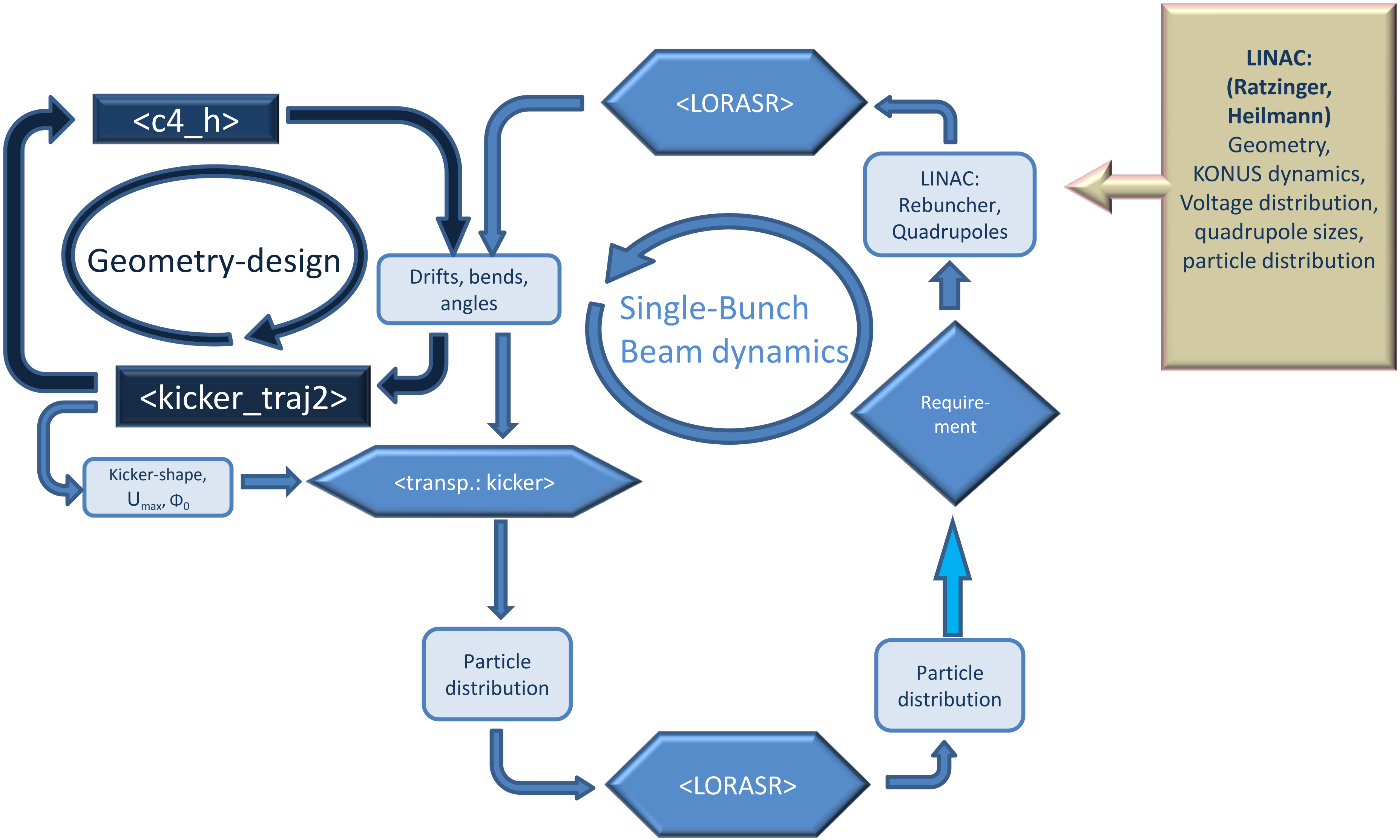
- Overview & Status

○ **Bunch Compressor: Design & Optimization**

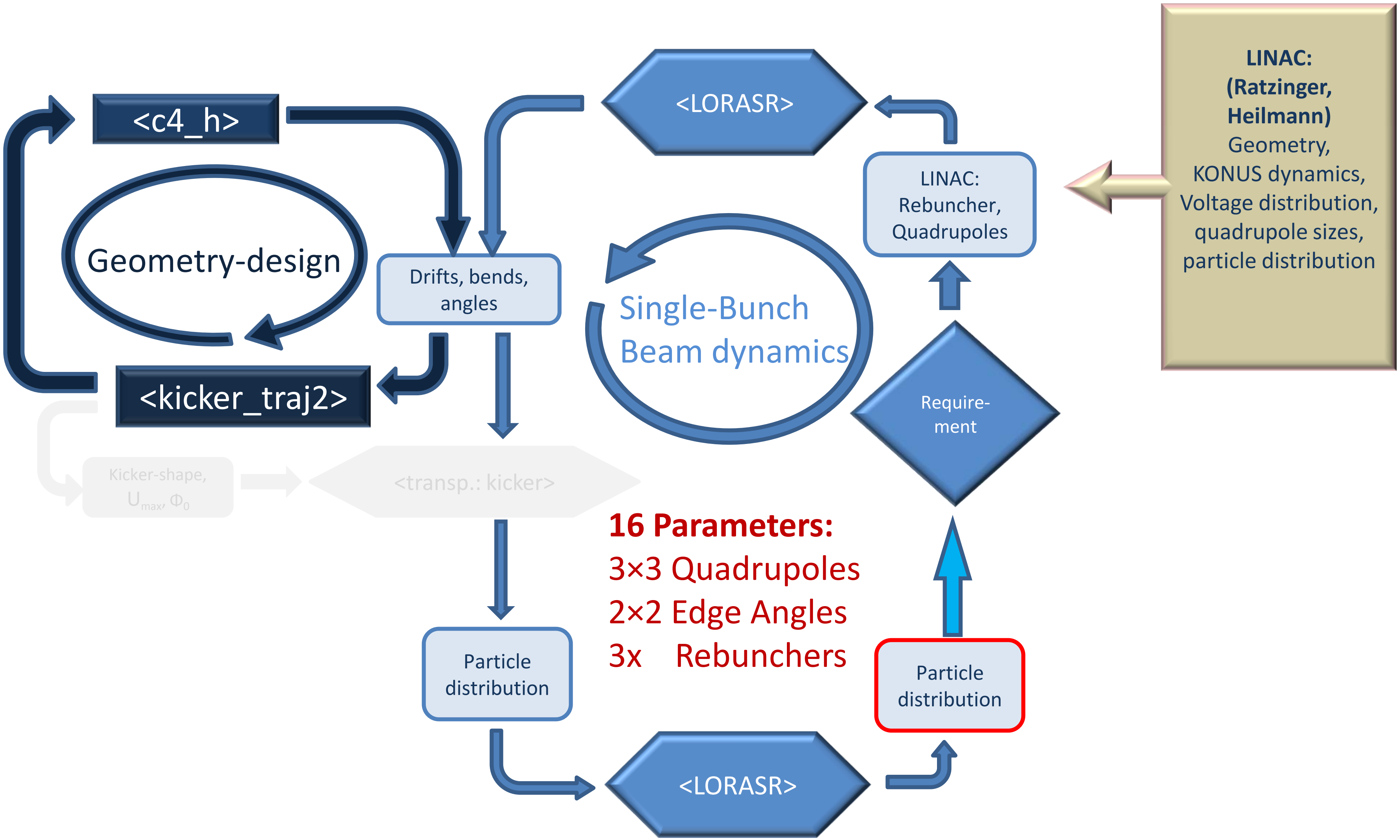
- Concepts: Geometry
- 5MHz Kicker
- Single Bunch Beam Dynamics
- Merging Scenario
- Rebuncher Cavities
- Magnet Design
- Beam Dynamics with Realistic Field Distributions

○ **Outlook**

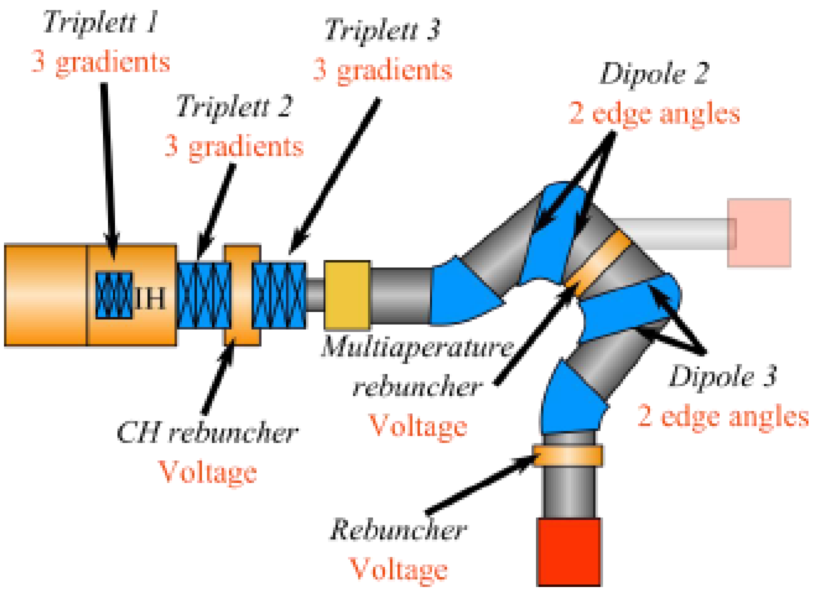
Bunch Compressor: Design / Optimization Cycles



Bunch Compressor: Design / Optimization Cycles



- 3 Triplets provide transversal focussing in the linac
- Transversal focussing in the bunch compressor works via edge and weak focussing
- Two rebunchers are needed for longitudinal focussing

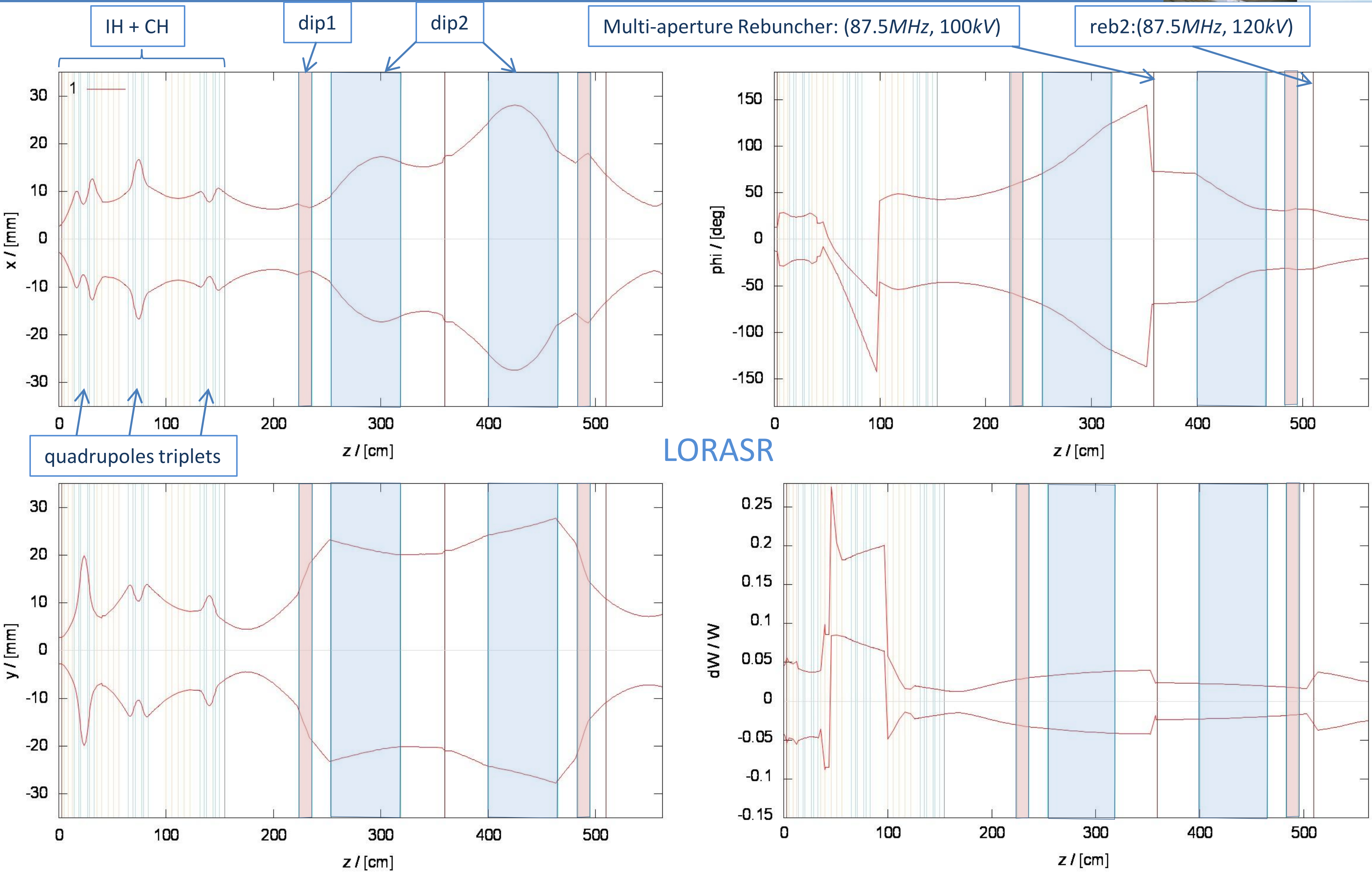


16 parameters for every trajectory: 1 calculation ⇒ several minutes

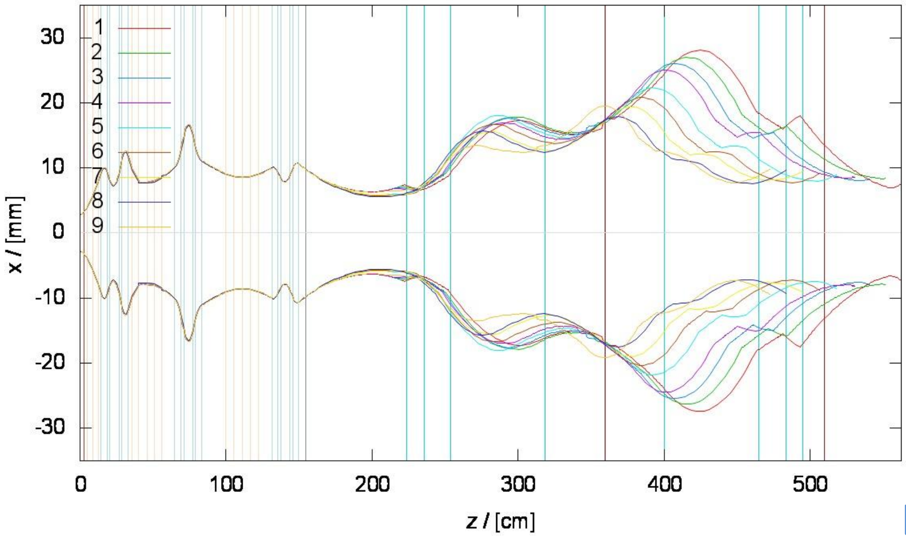
⇒ "brute force" solution unworkable!

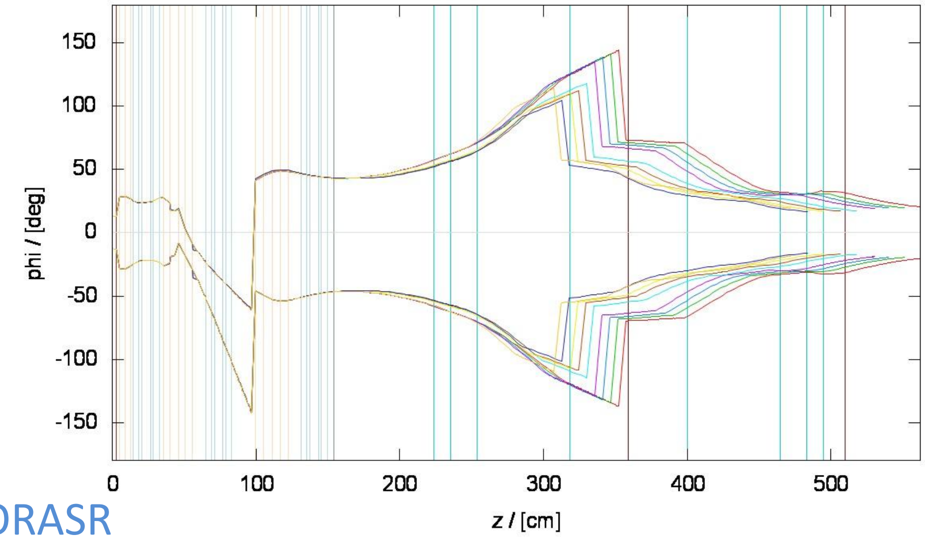
⇒ "smart" algorithm like "Particle Swarm"- Optimization (PSO)

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



Bunch Compressor: Envelopes(95%) – all bunches





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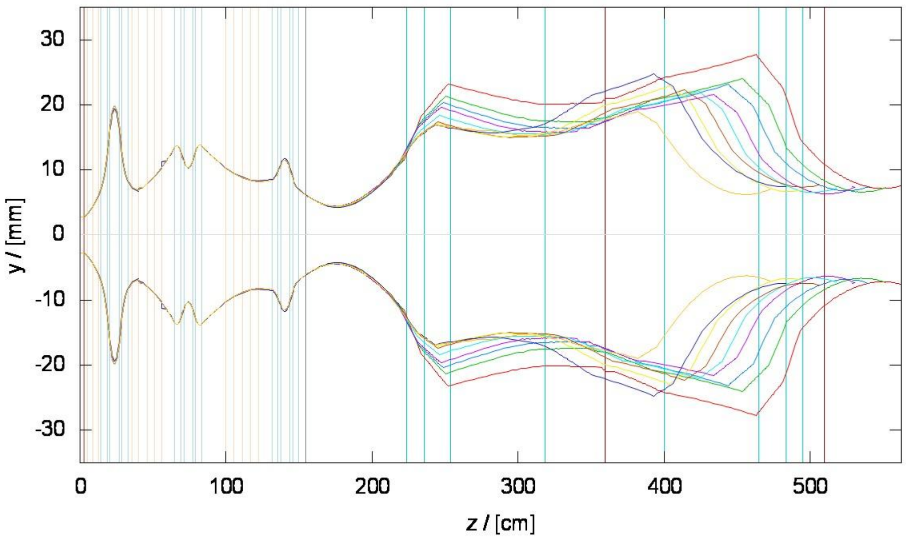
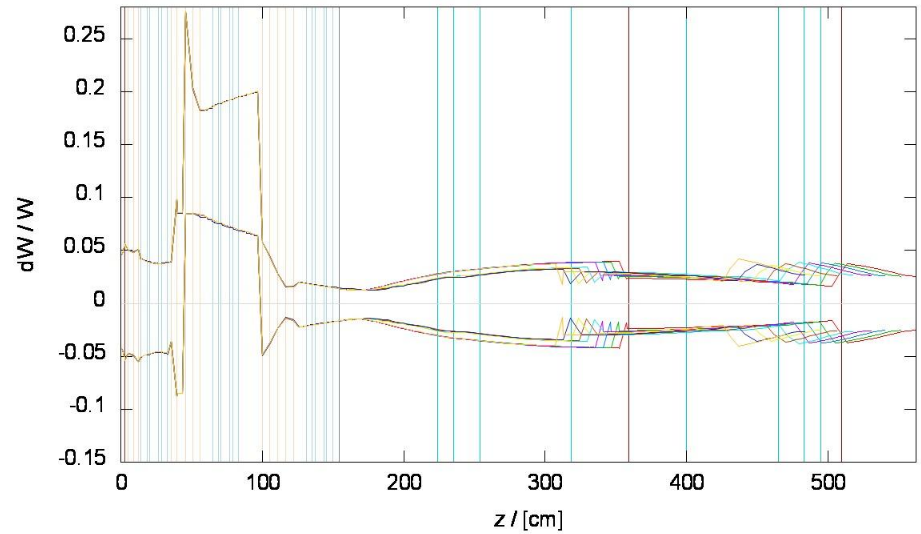
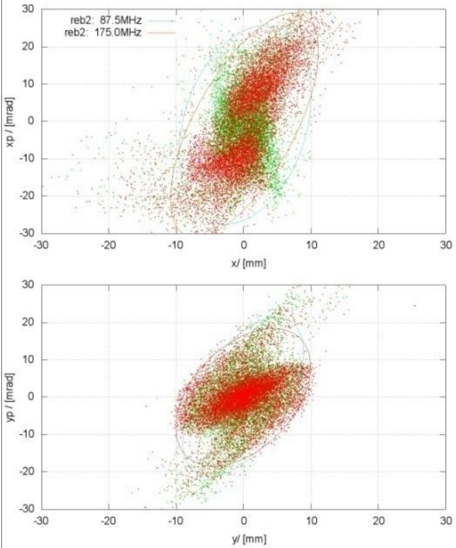
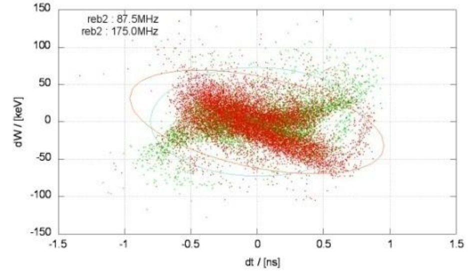




Single Bunch Projections at the Target

Bunch(1)

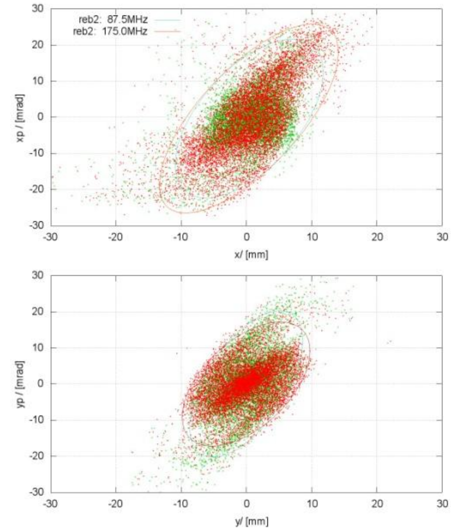


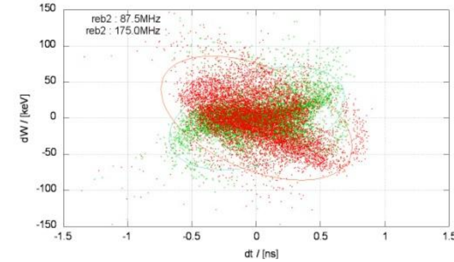


Rebuncher(2)

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)

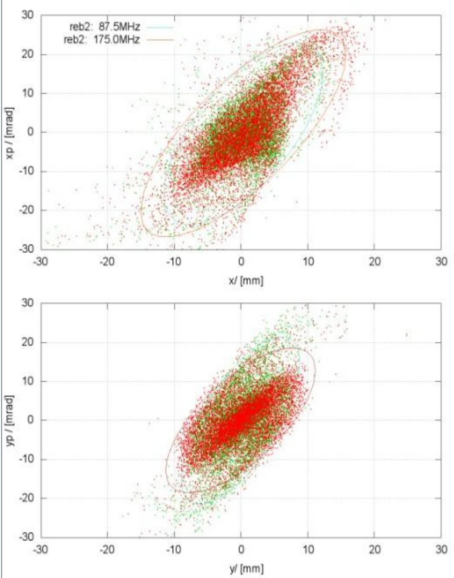


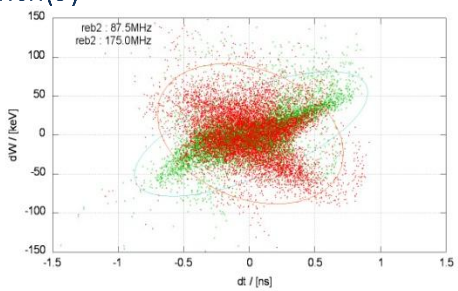


Rebuncher(2)

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:

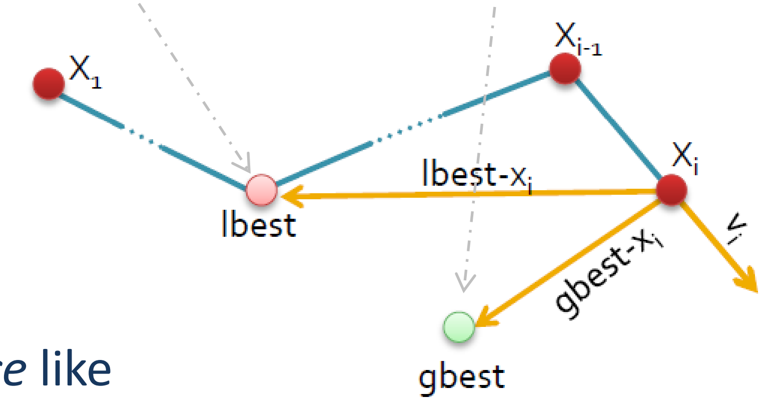
- N_{bunch} = 9
- ΔT = 50-100*ns* => $\Delta T \approx 1$*ns*
- $A_{(beam\ at\ target)}$ < $3x3cm^2$
- $I_{(per\ pulse)}$ ≈ 8*A*
- ΔW < ± 5%

- N points in ***search space*** (e.g. in $\Re^{16}$)
  - "position" ***x*** = set of parameter in $\Re^{16}$
  - "velocity" ***v*** = change of the position in one iteration
- Initialize ***x*** and ***v*** with random values
- ***Iteration***:

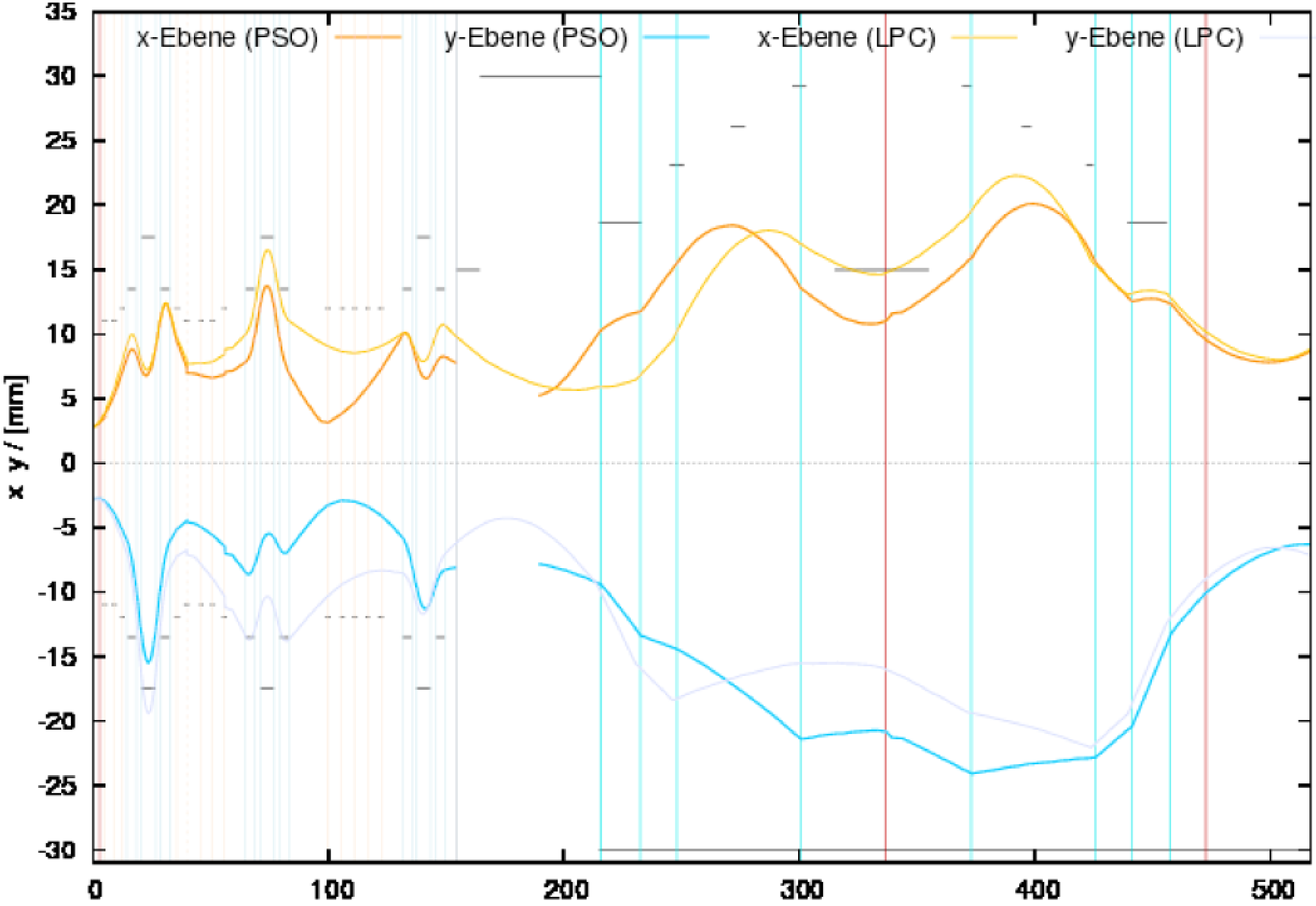
$$\vec{x}_{i+1} = \vec{x}_i + \vec{v}_{i+1} \quad \Leftarrow \quad \vec{v}_{i+1} = \omega \vec{v}_i + c_1 \underline{A} \cdot (\vec{x}_{best,local} - \vec{x}_i) + c_2 \underline{B} \cdot (\vec{x}_{best,global} - \vec{x}_i)$$

  - empirical parameters: $\omega = 0.25..\ 0.75$, $c_1=2$, $c_2=2$
  - random diagonal matrix: A , B
- ***Collective Memory*** :
  - Local best result on path in search space
  - Global best result in all iterations
- Collective movement of the ***x***´s in *search space* like

fish swarm chasing a bait



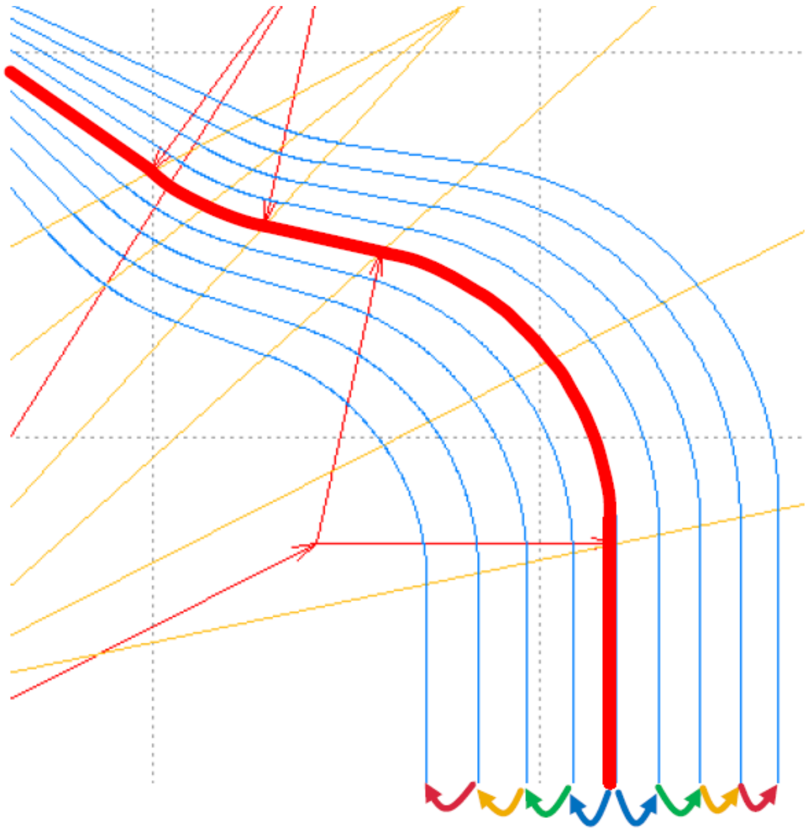
Optimization of the central trajectory

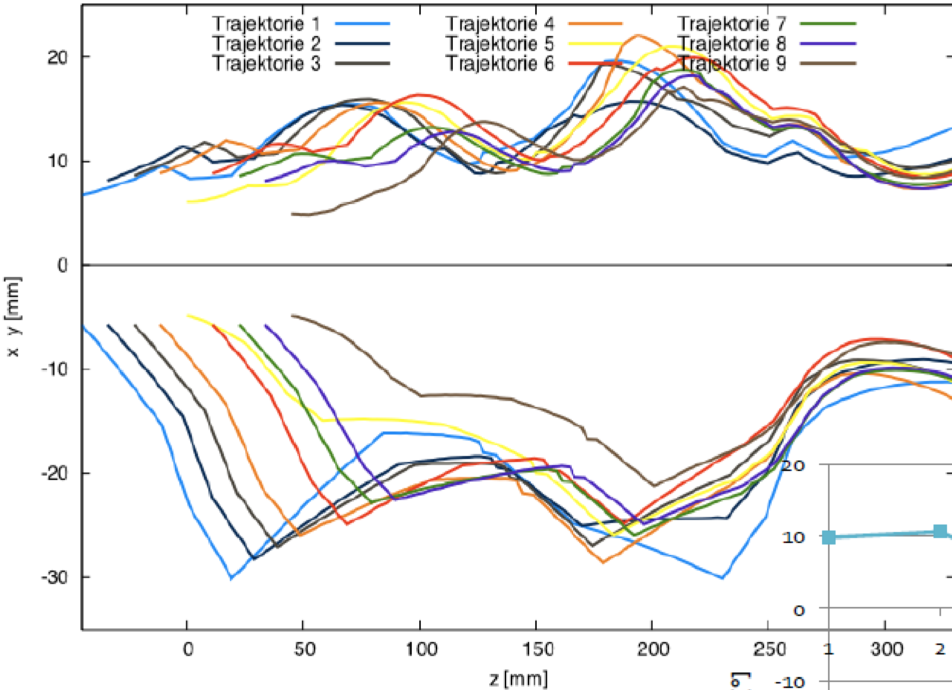


1,7 cm

1,3 cm

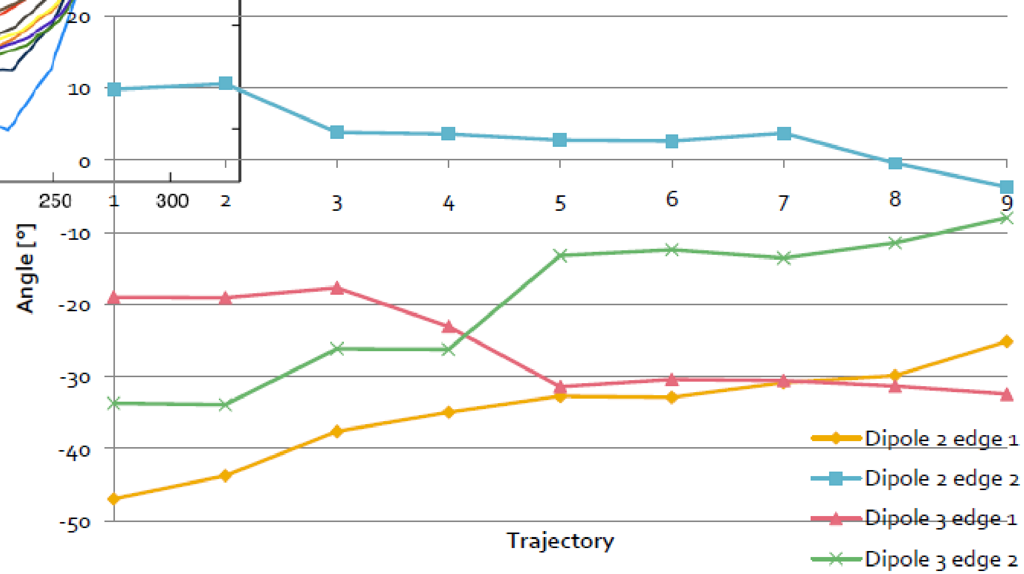
- Optimize one trajectory using a *global* optimization algorithm (like PSO)
- Repeat for adjacent trajectories:
  - Use solution for neighbouring trajectory as a starting point for a local optimization algorithm





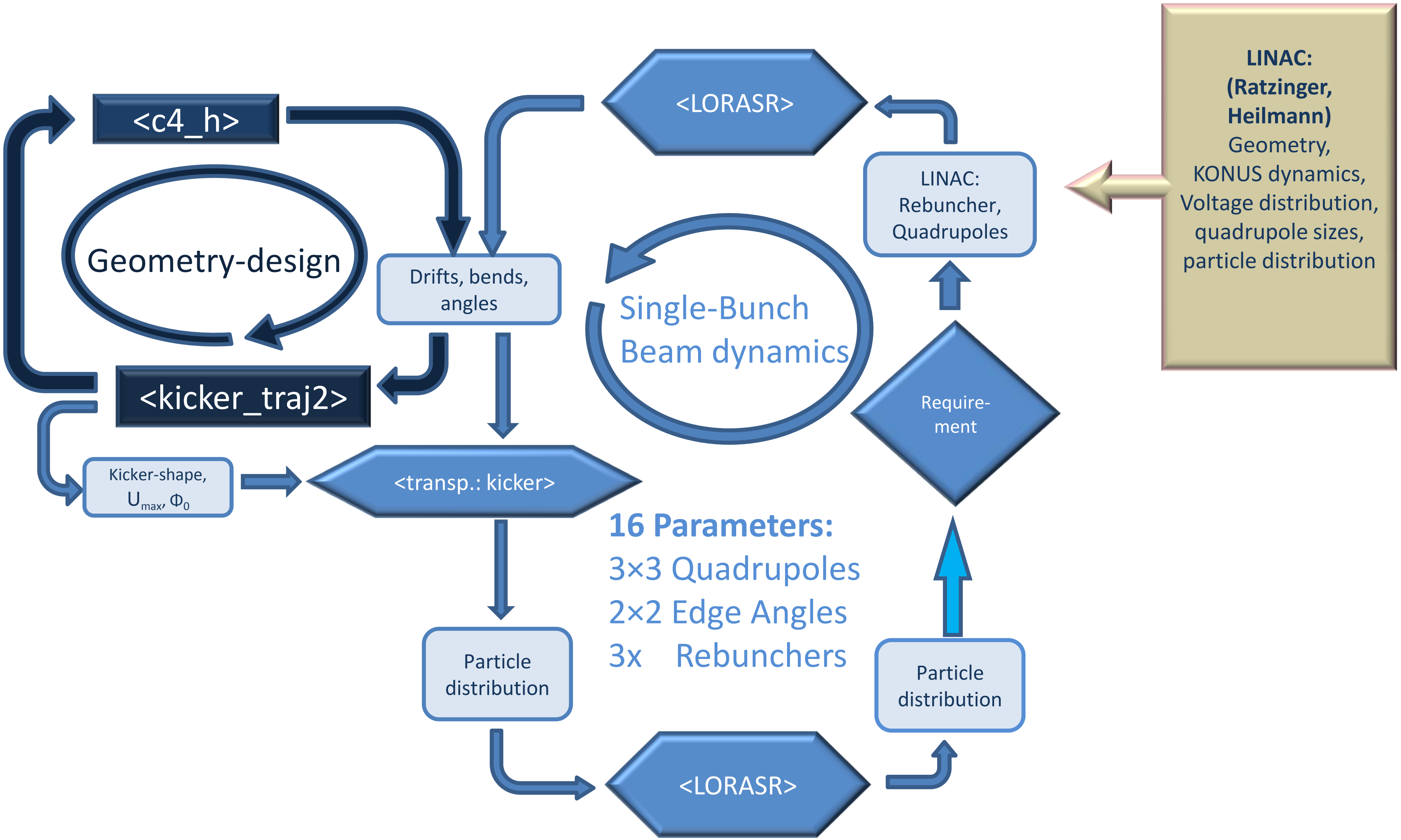
Transverse beam dynamics:
Longest trajectory => hardest to optimize

Longitudinal beam dynamics:
Shortest trajectory => hardest to optimize

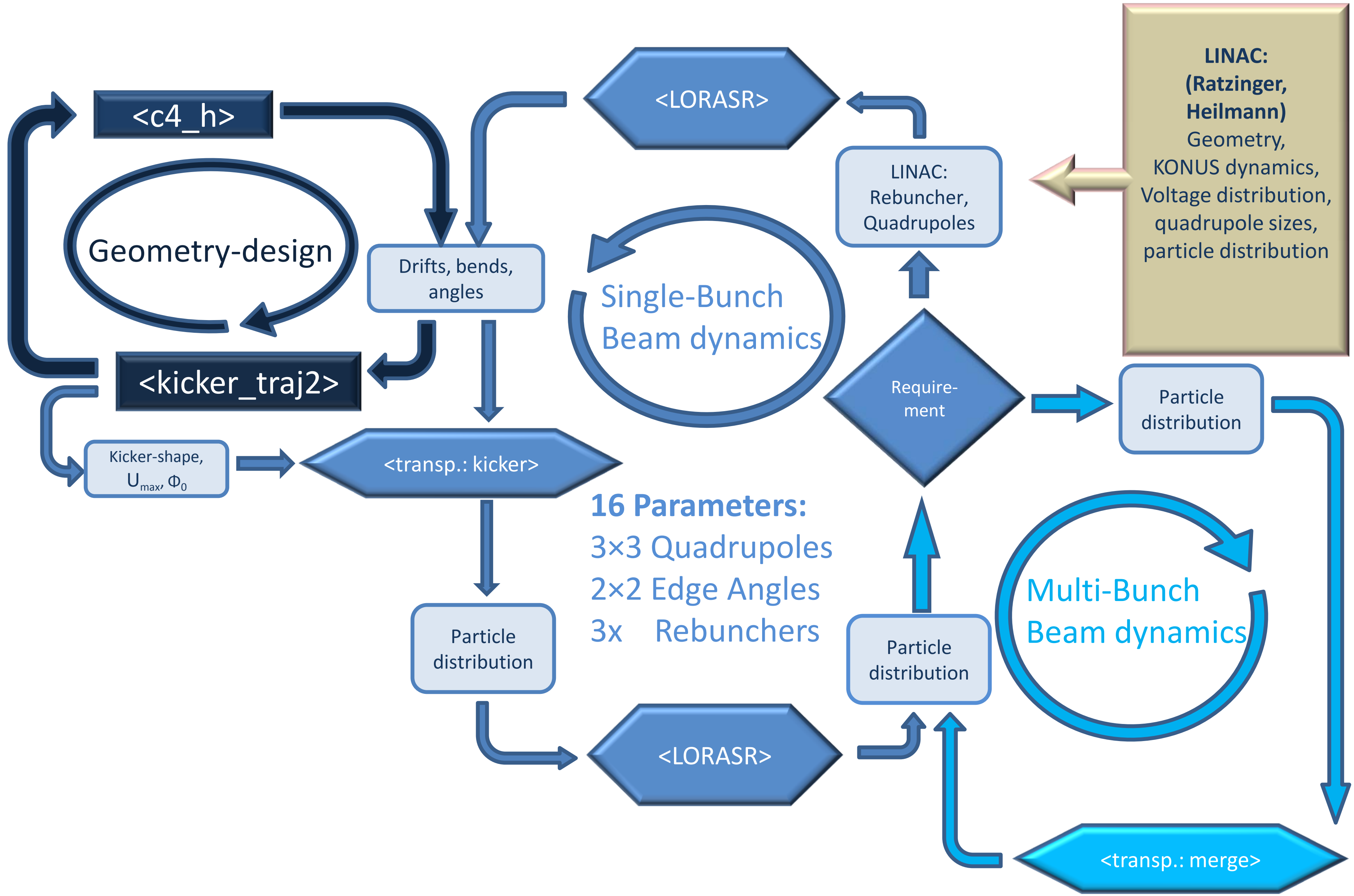


Result vectors near by each other

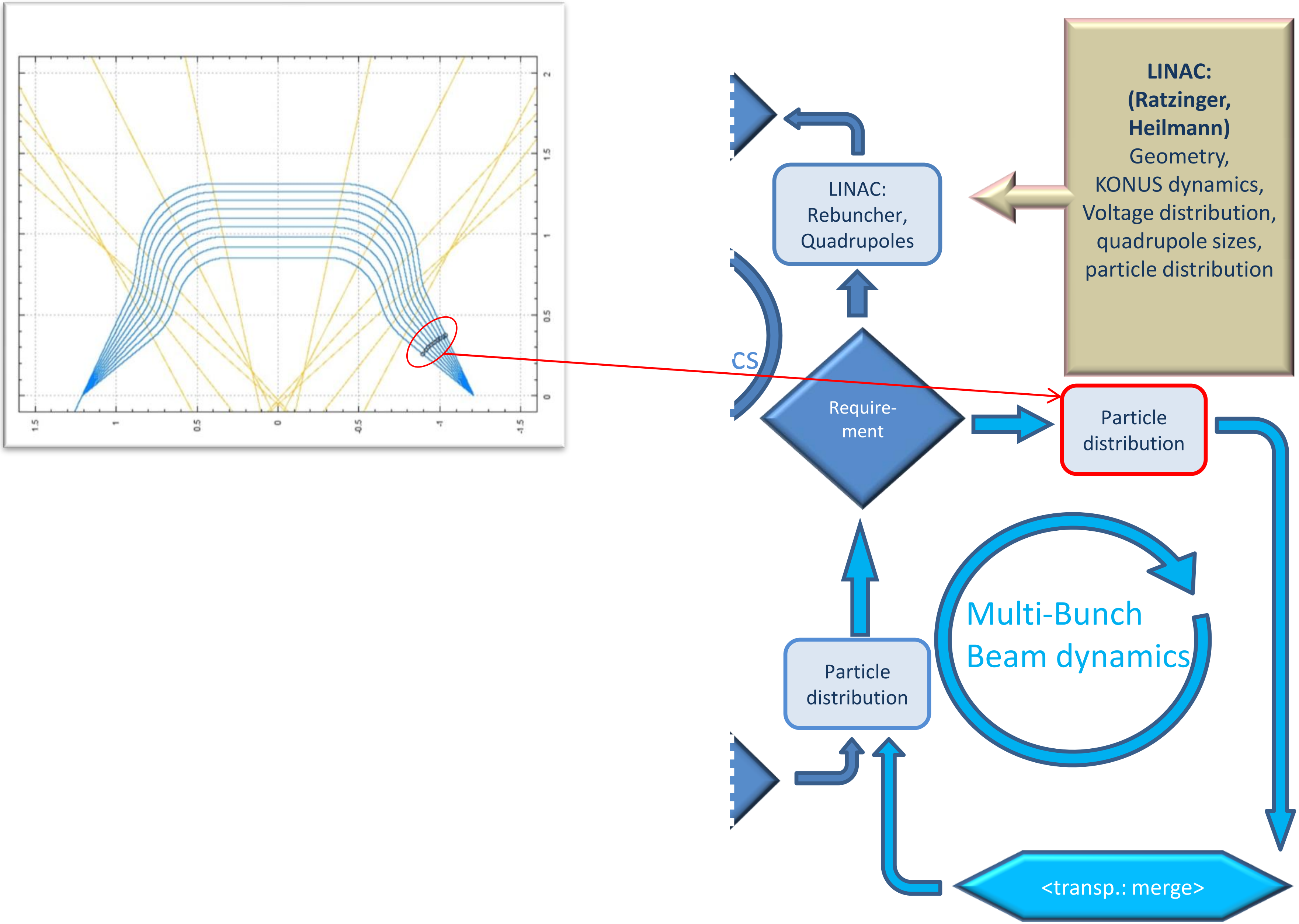
Bunch Compressor: Design / Optimization Cycles



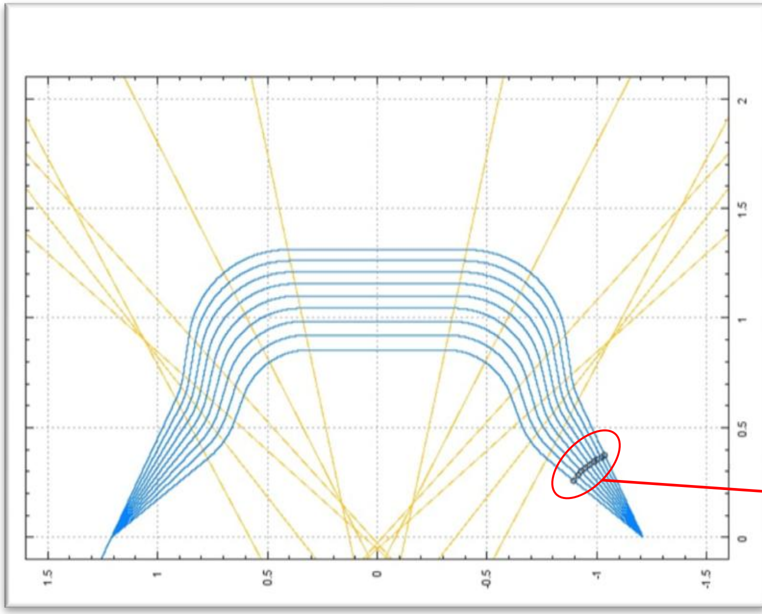
Bunch Compressor: Design / Optimization Cycles

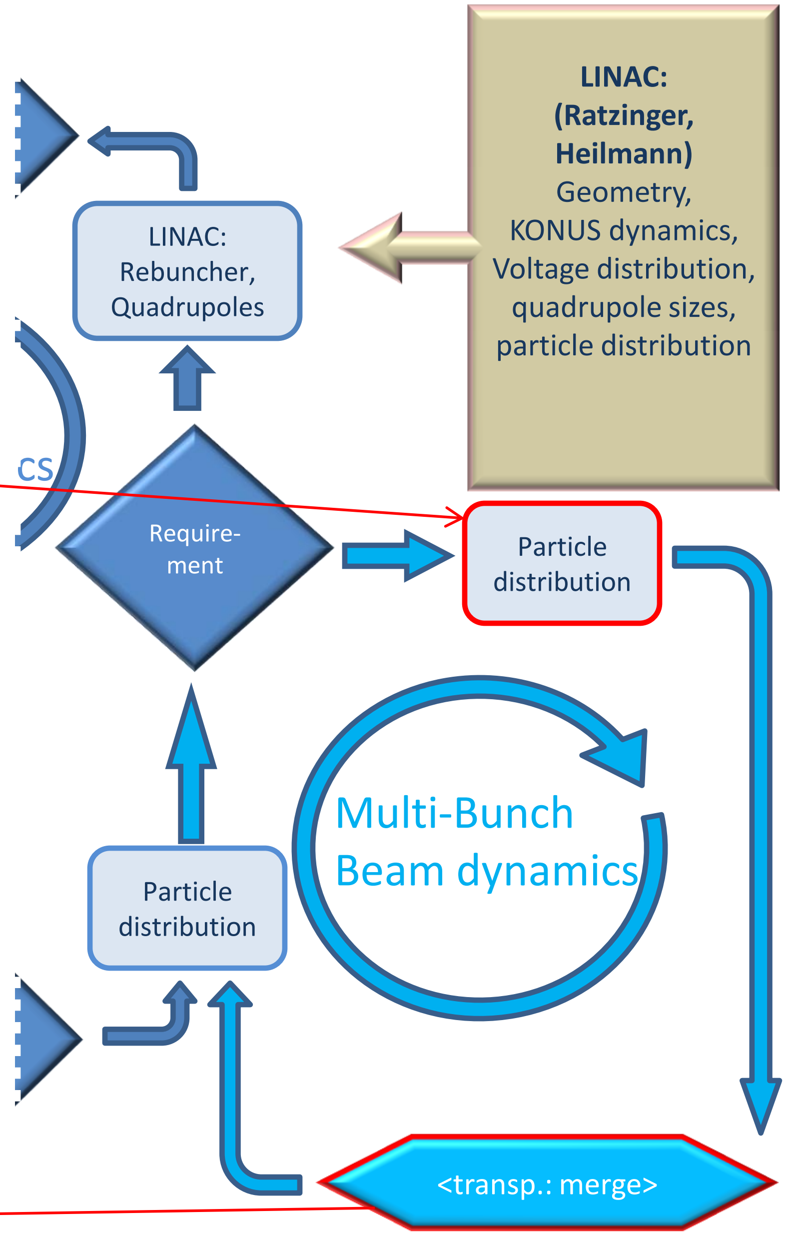


Bunch Compressor: Design / Optimization Cycles



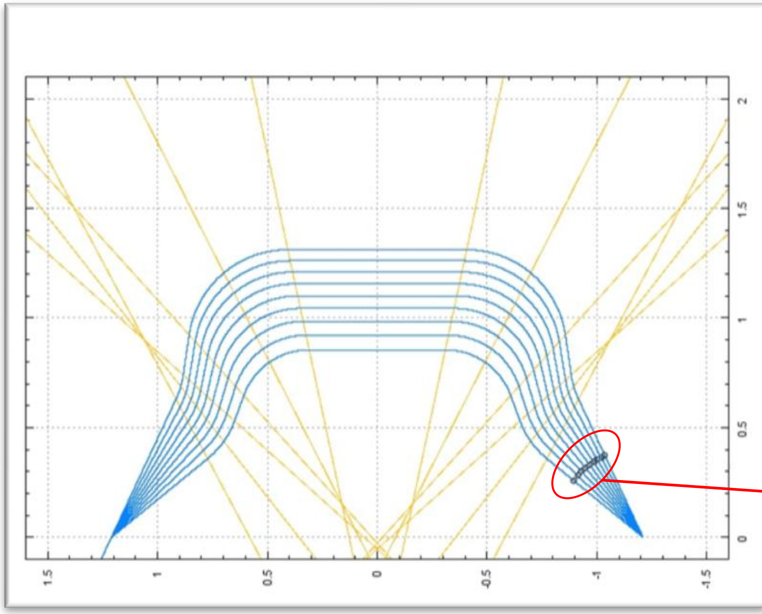
Bunch Compressor: Design / Optimization Cycles

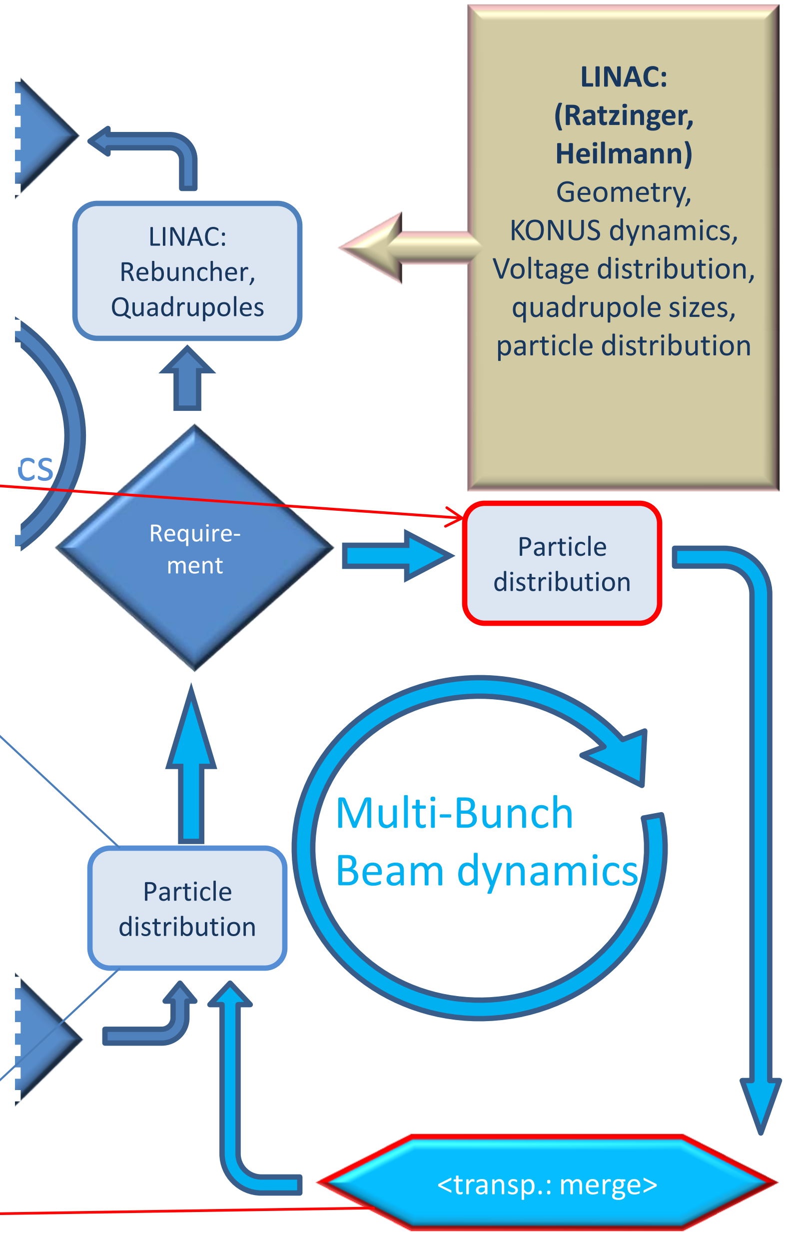




<transp.:merge>:
- Particle in Cell (PIC)
- dynamic lattice
- finite differences
- Poisson solver

Bunch Compressor: Design / Optimization Cycles





L = 35*cm*

I = 9x150*mA*

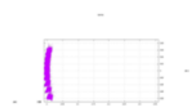
$N_{particle}$ ≈ 90k

N_{grid} = 100x100x100

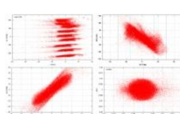
$\Delta x_{stepsize}$ = 1*mm*

$\Delta t_{calc+plot}$ ≈ 50*s*

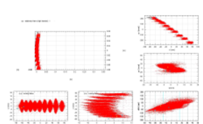
merge



Projections at target

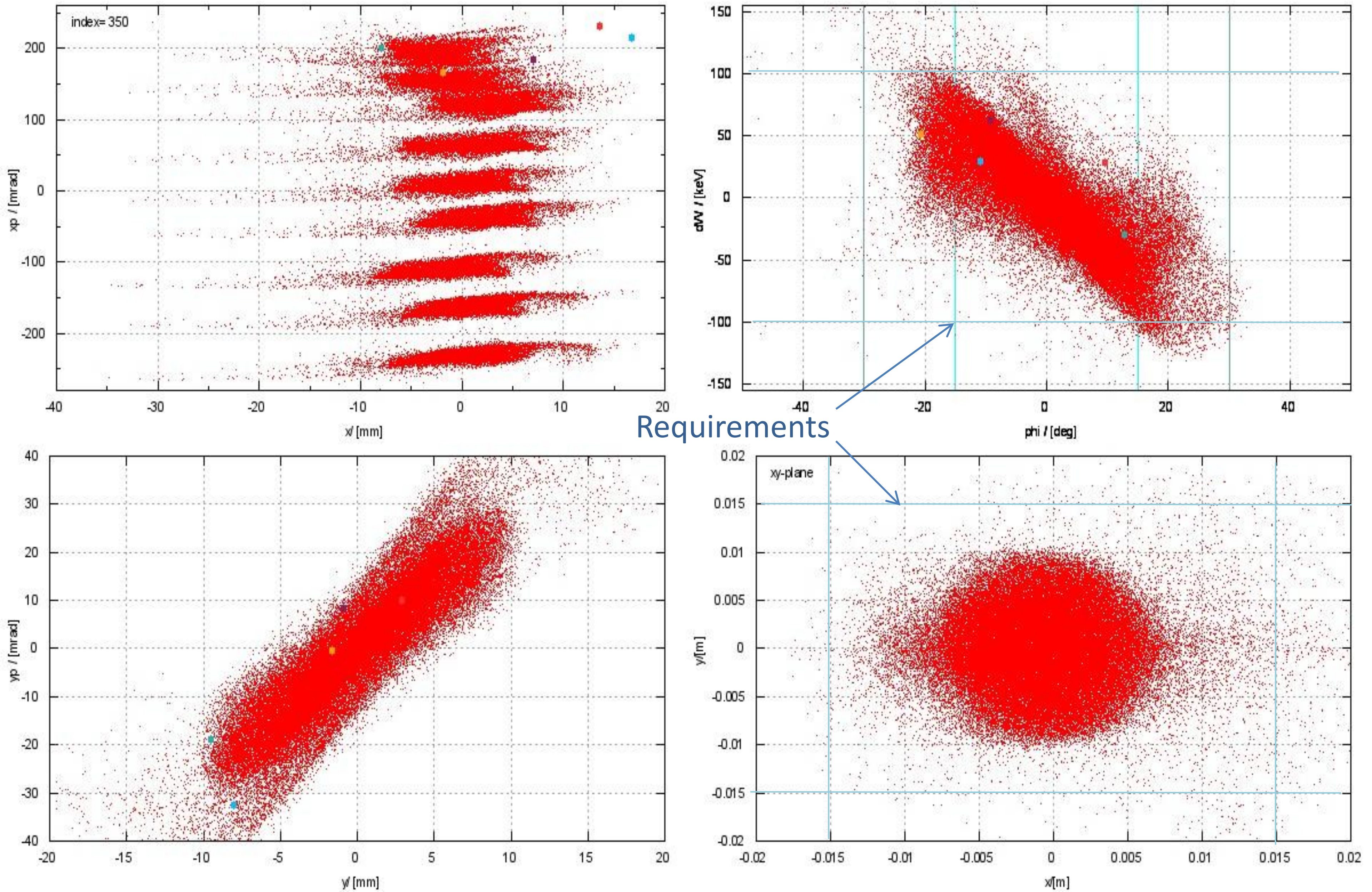


projections



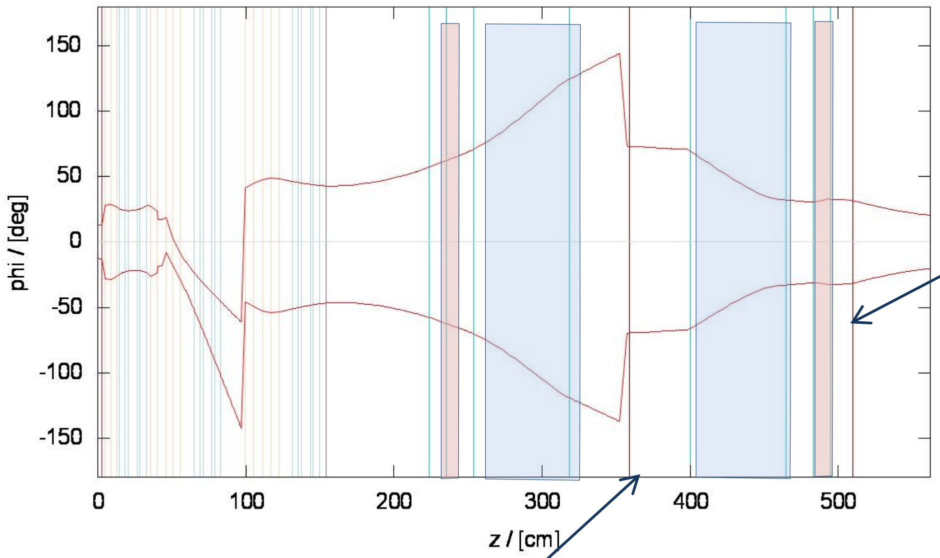
<transp.:merge>:

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


index= 350
xp / [mrad]
x/ [mm]
dW / [keV]
phi / [deg]
Requirements
yp / [mrad]
y/ [mm]
xy-plane
y/[m]
x/[m]

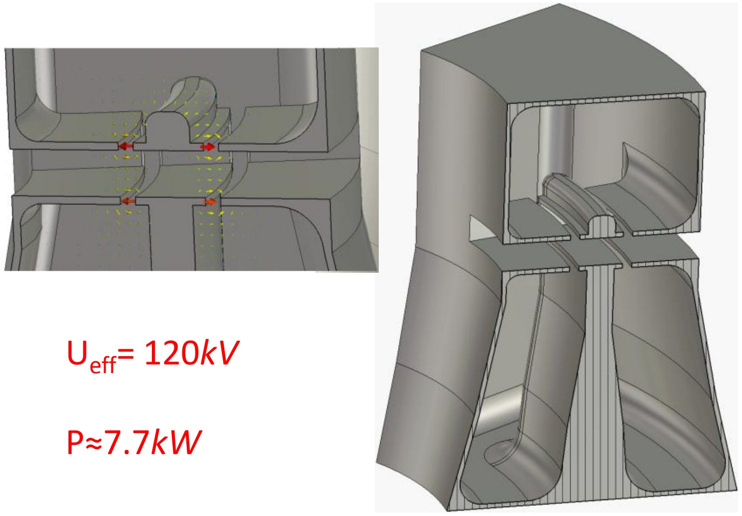
Outlines:

- FRANZ:
  - Overview & Status
- **Bunch Compressor: Design & Optimization**
  - Concepts: Geometry
  - 5MHz Kicker
  - Single Bunch Beam Dynamics
  - Merging Scenario
  - Rebuncher Cavities
  - Magnet Design
  - Beam Dynamics with Realistic Field Distributions
- **Outlook**



©D. Noll

@175MHz



U_{eff}= 120kV

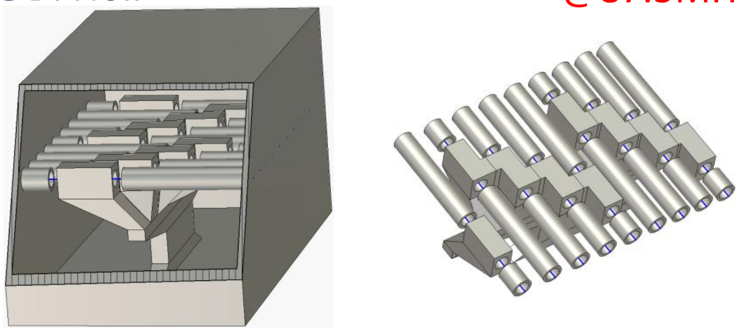
P≈7.7kW

$R_p \approx 1.9M\Omega$

Broad-Gap-Rebuncher

©D. Noll

@87.5MHz



U_{eff}= 100-140kV, P≈11kW, $R_p \approx 1.3M\Omega$

Multi-Aperture-Rebuncher

- λ/4-Cavity
- longitudinal Beam Dynamics
- Energy variation of the final Pulse

Outlines:

○ **FRANZ:**

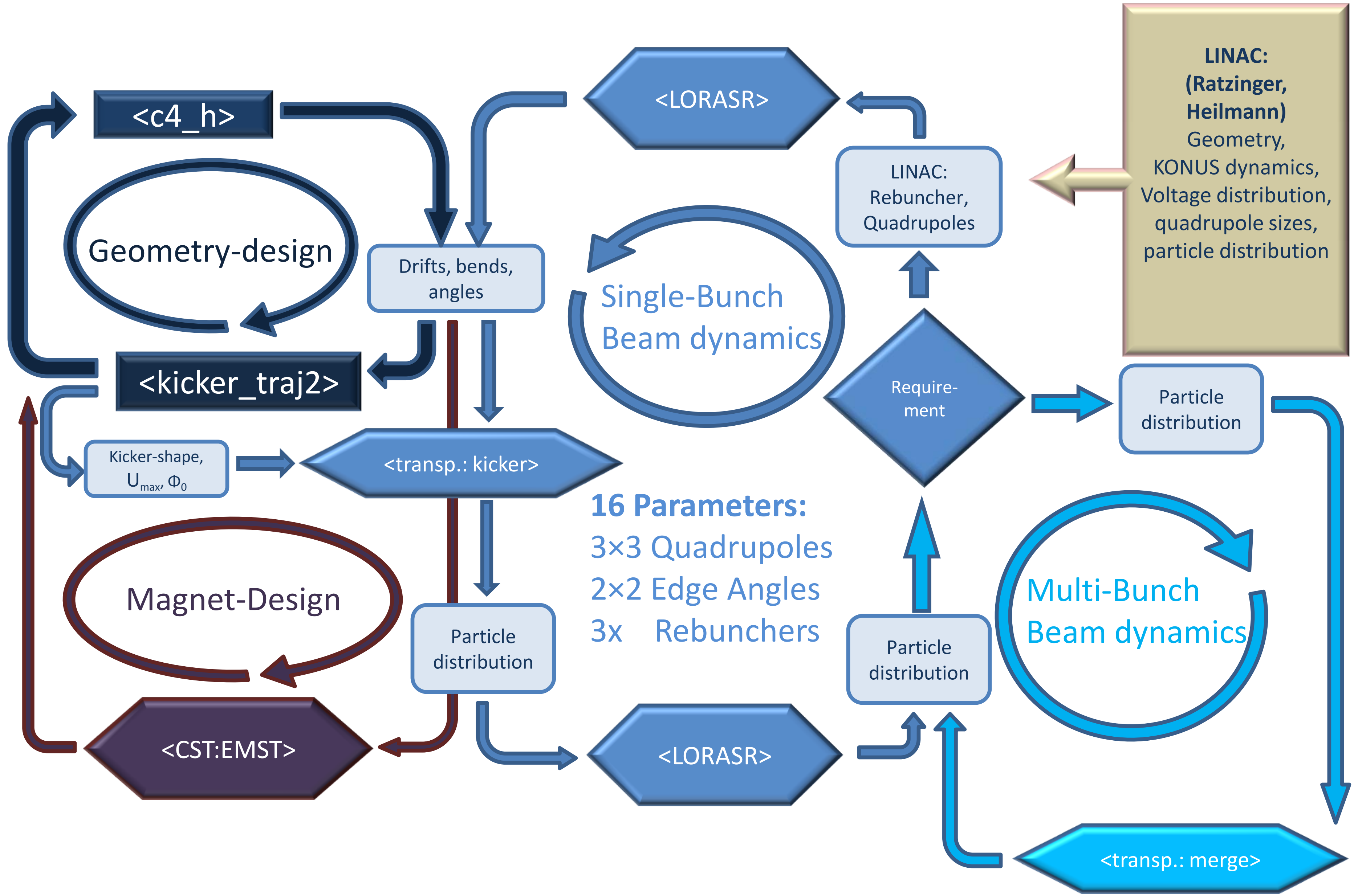
- Overview & Status

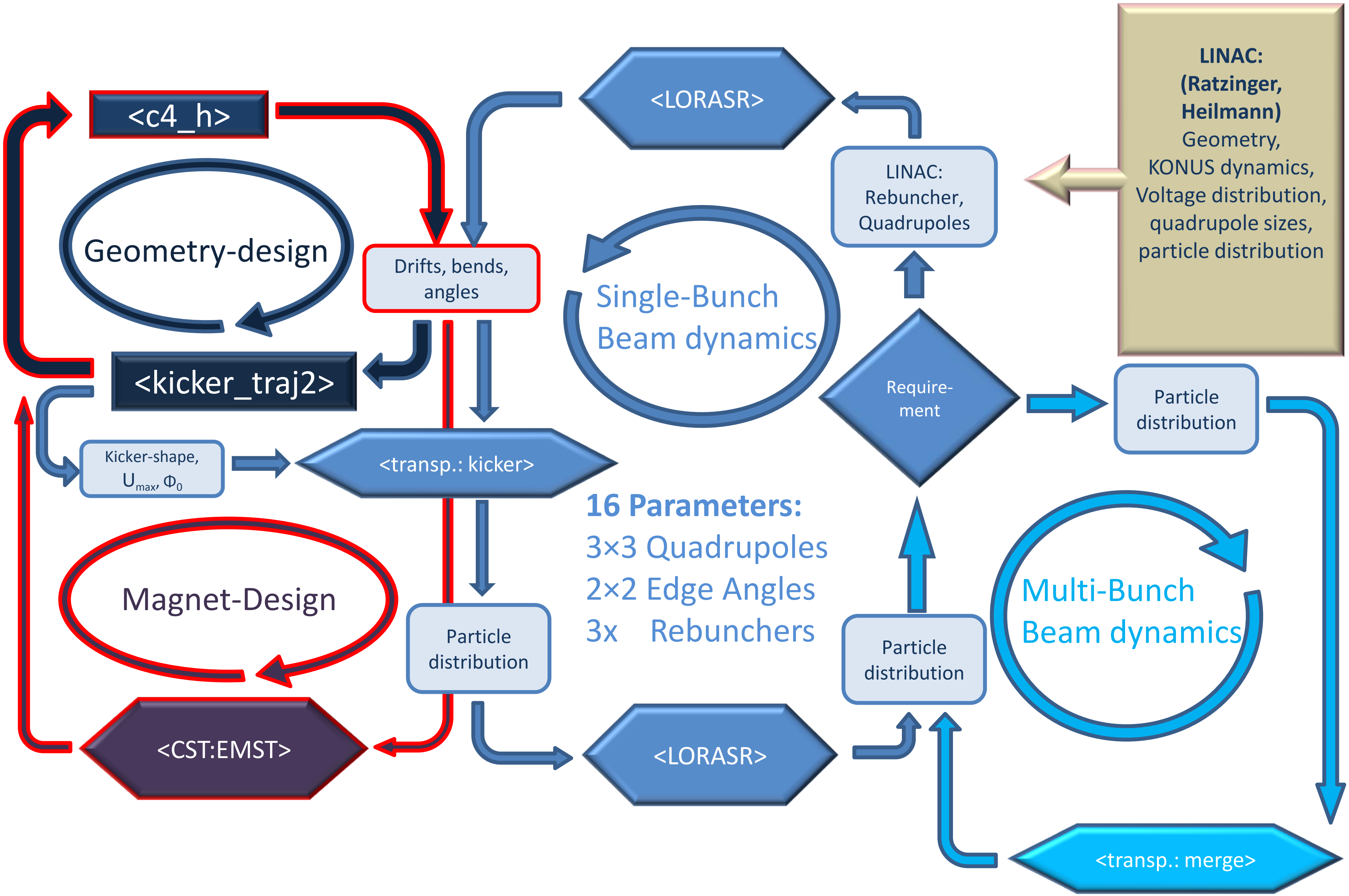
○ **Bunch Compressor: Design & Optimization**

- Concepts: Geometry
- 5MHz Kicker
- Single Bunch Beam Dynamics
- Merging Scenario
- Magnet Design
- Beam Dynamics with Realistic Field Distributions

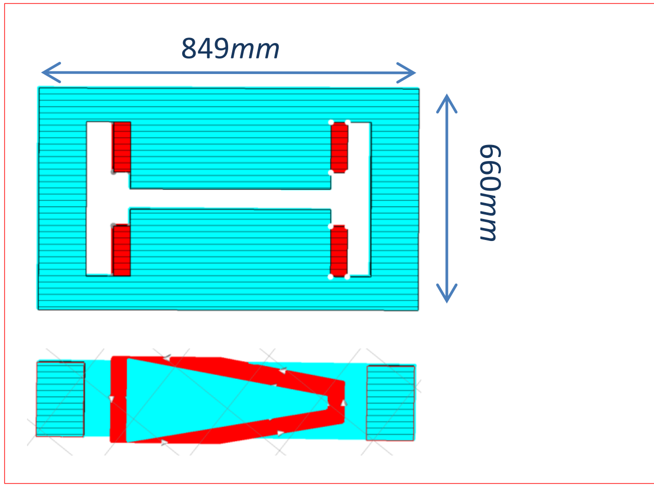
○ **Outlook**

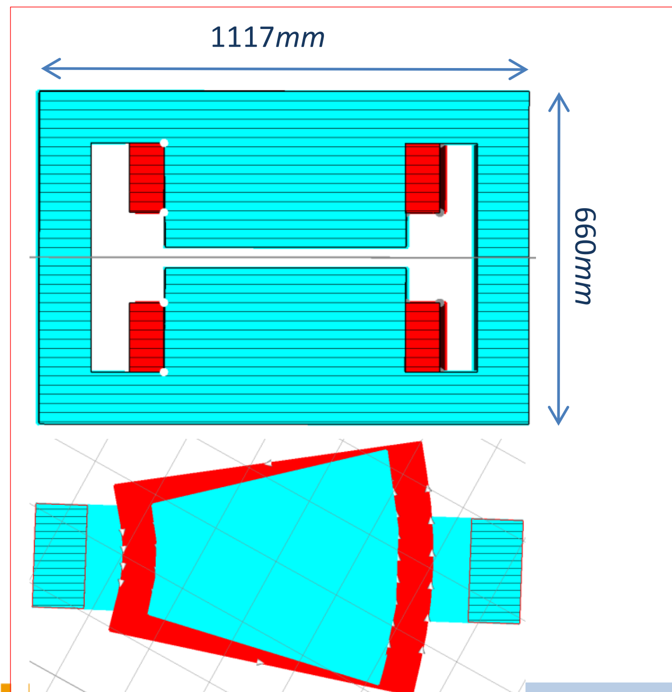
Bunch Compressor: Design / Optimization Cycles



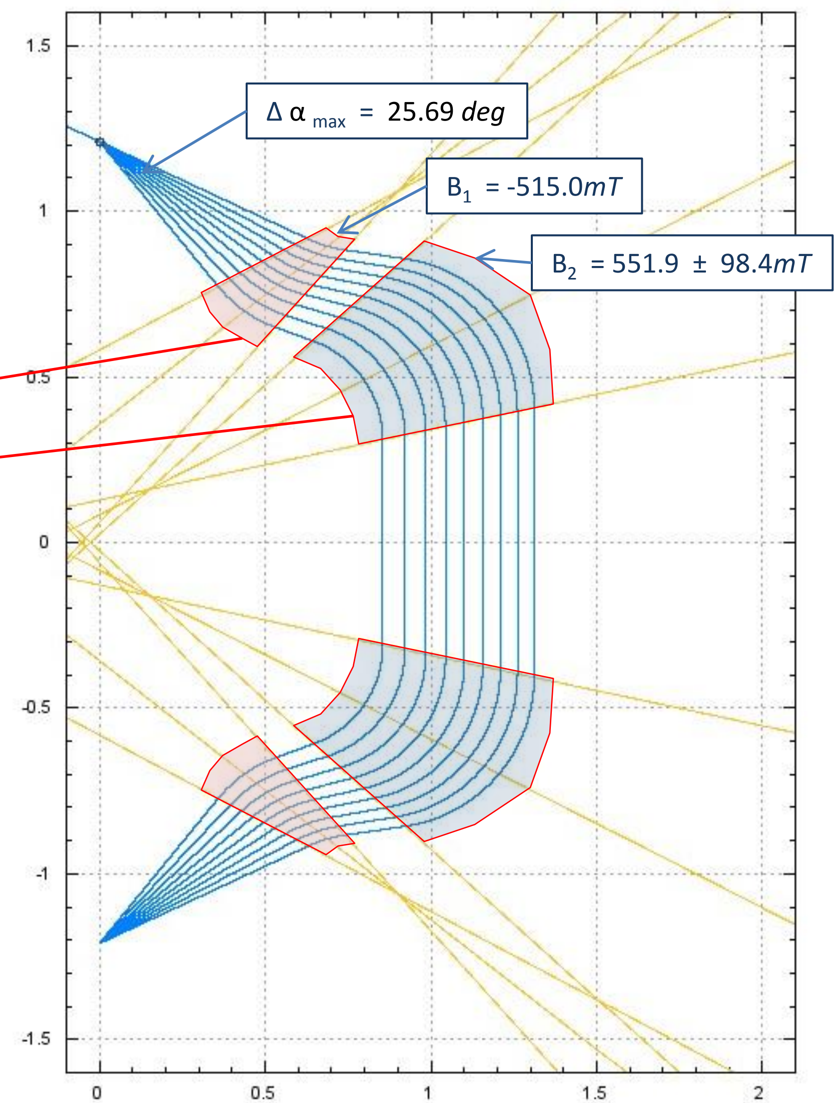

<c4_h>
Geometry-design
Drifts, bends, angles
<kicker_traj2>
Kicker-shape, U_{max}, Φ_0
<transp.: kicker>
Magnet-Design
Particle distribution
<CST:EMST>
<LORASR>
Single-Bunch Beam dynamics
LINAC: Rebuncher, Quadrupoles
Require-ment
LINAC: (Ratzinger, Heilmann) Geometry, KONUS dynamics, Voltage distribution, quadrupole sizes, particle distribution
Particle distribution
16 Parameters:
3×3 Quadrupoles
2×2 Edge Angles
3x Rebunchers
Particle distribution
<LORASR>
Multi-Bunch Beam dynamics
<transp.: merge>

Preliminary Magnet Design



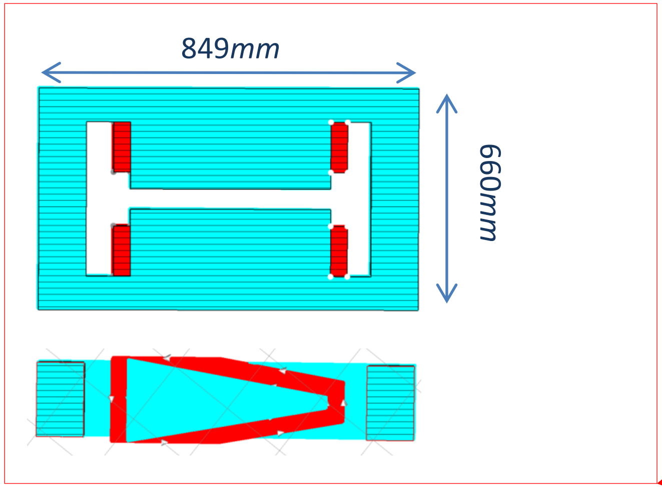


Geometry: g9_5x

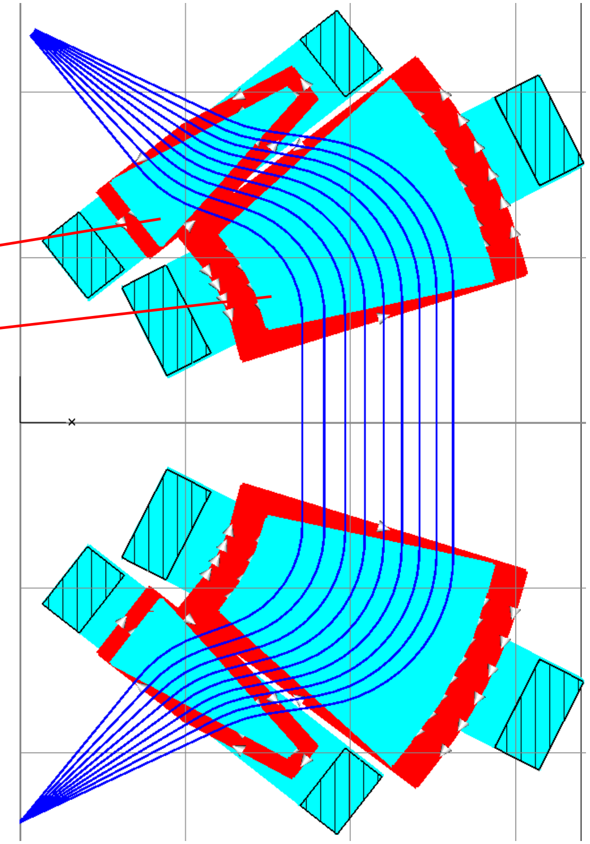


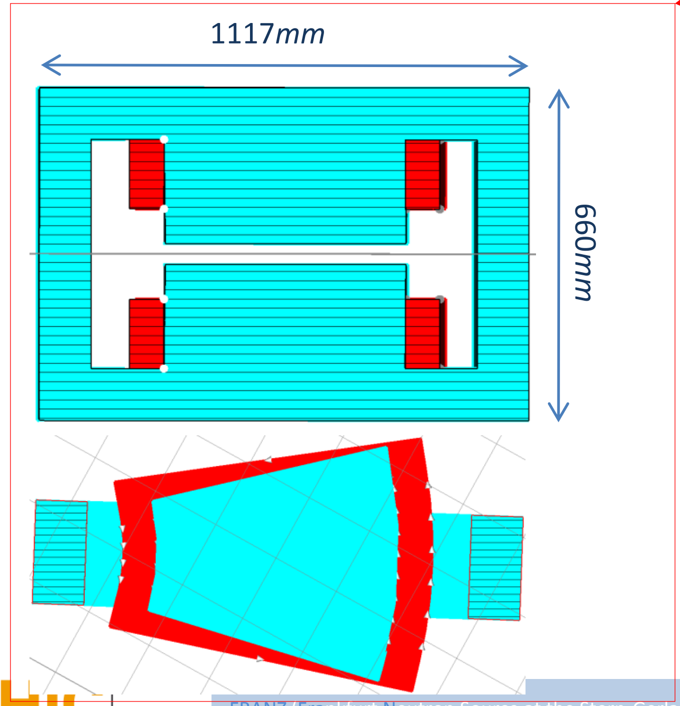
Preliminary Magnet Design

Geometry: g9_5x

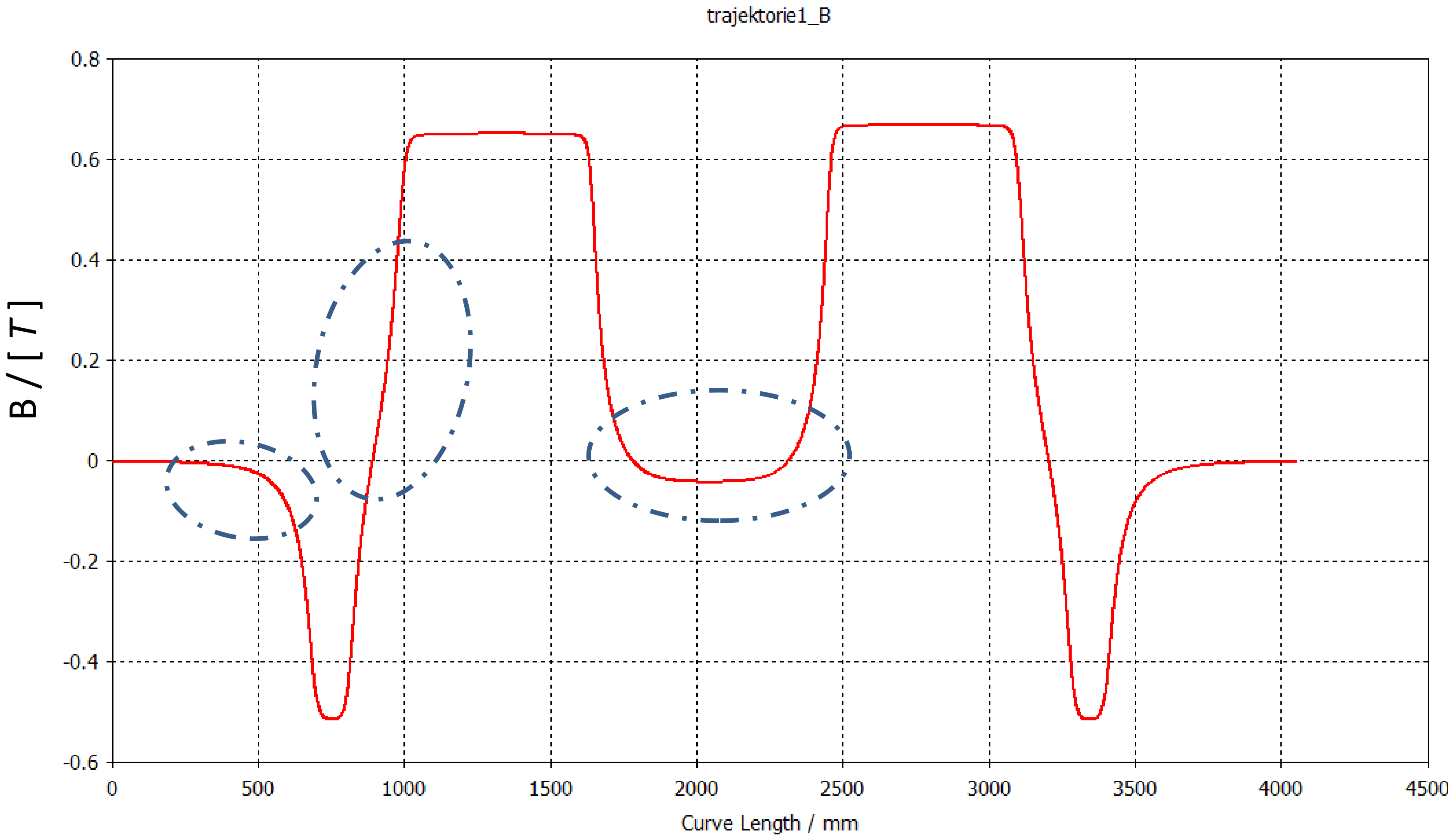


Dipole(1)	
B_1/[mT]	515
g/[mm]	60
N·I/[A]	10420
A_{coil}/[mm^2]	50×150
A_{wind}/[mm^2]	7×7
N	153
I/[A]	68



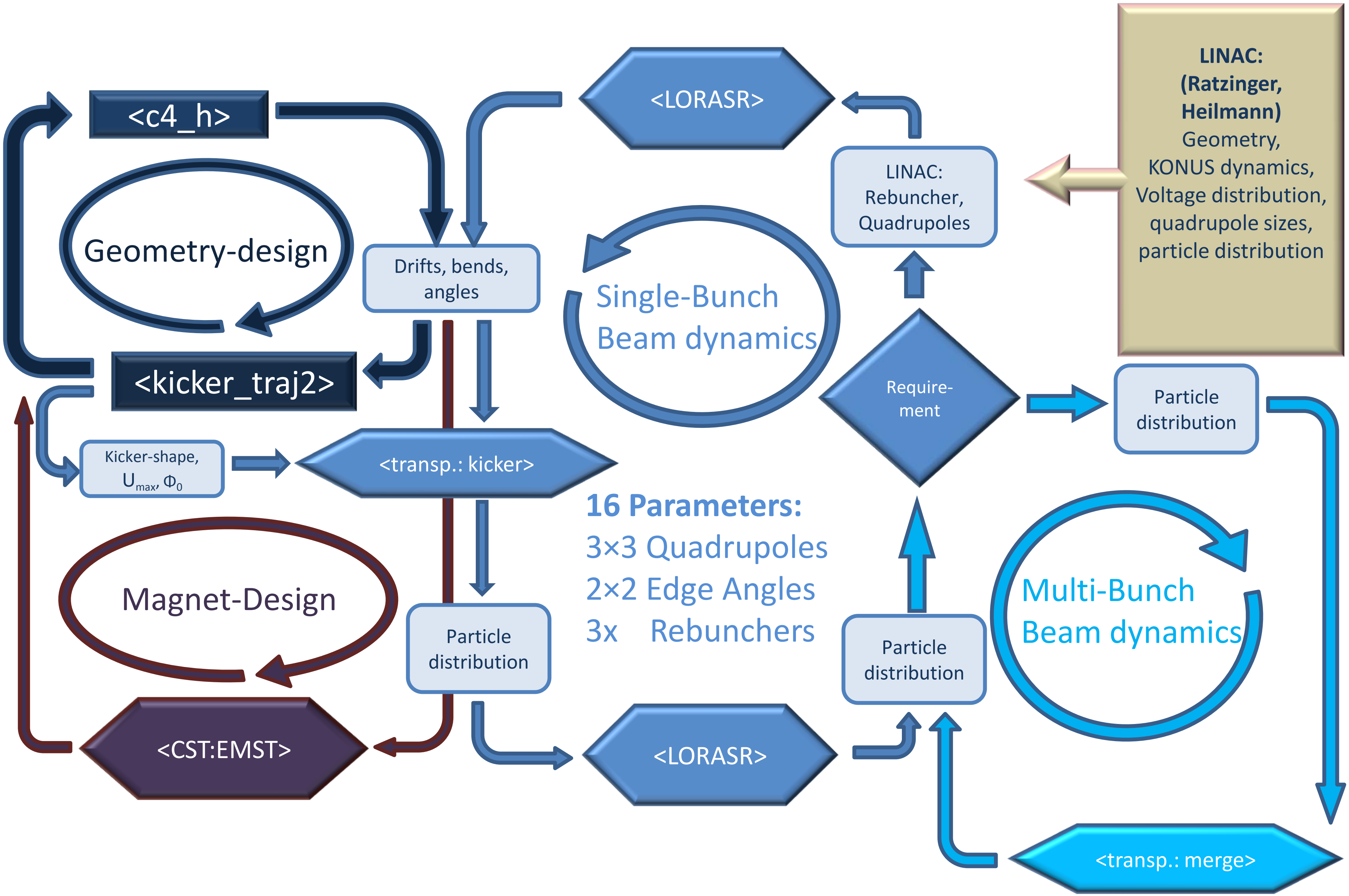


Dipole(2)	
B_2/[mT]	650
g/[mm]	60
N·I/[A]	60476
A_{coil}/[mm^2]	100×200
A_{wind}/[mm^2]	7×7
N	408
I/[A]	148



- large fringing field
- Connected fringing field region

=> Effects of fringing fields on beam dynamics?


<c4_h>
Geometry-design
Drifts, bends, angles
<kicker_traj2>
Kicker-shape, U_{max}, Φ_0
<transp.: kicker>
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16 Parameters:
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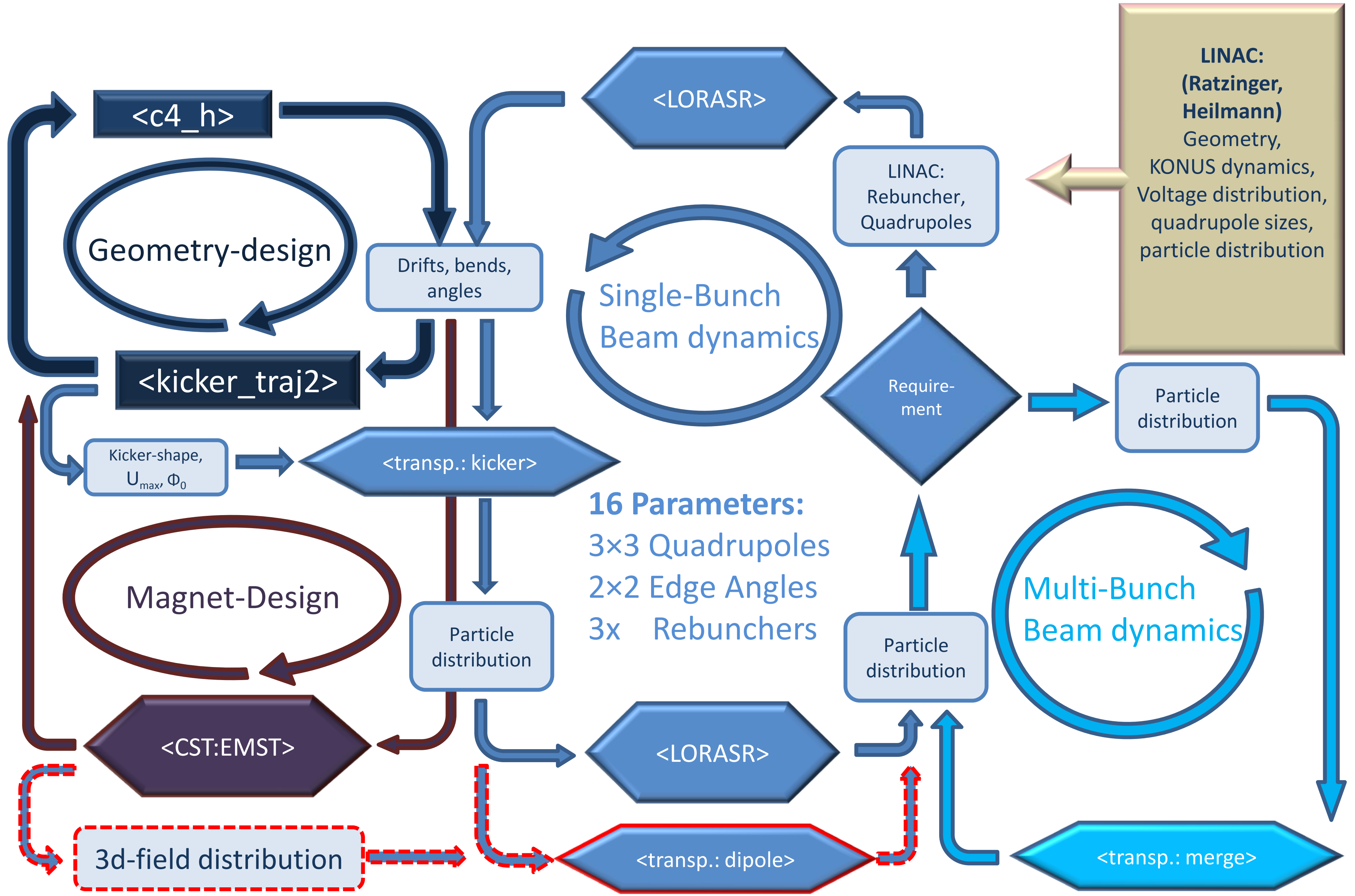
Particle distribution
Multi-Bunch Beam dynamics
<transp.: merge>

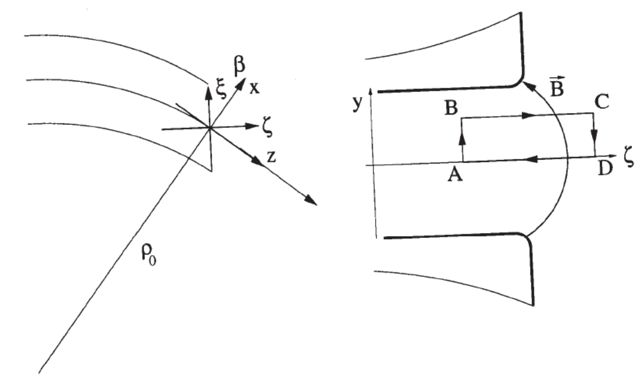
Bunch Compressor: Design / Optimization Cycles



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

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

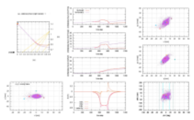
$$y' = y'_0 + \underbrace{k_y\left(\phi, \frac{g}{\rho_0}, K\right) \cdot y_0}_{\Delta y'}$$



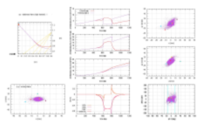
Parameters of the first dipole:

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]

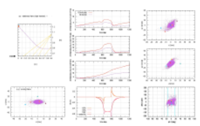
Comparison with realistic field distribution:



0mA: real field dist. vs. matrix

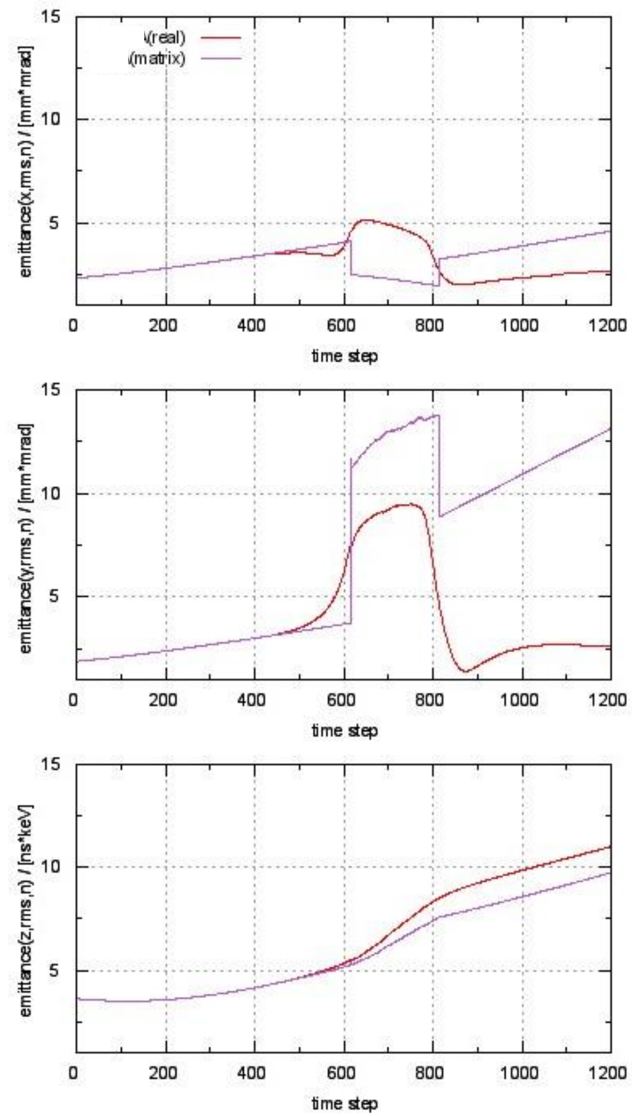


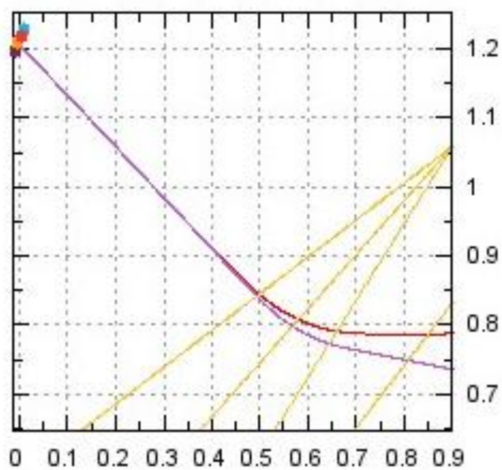
150mA: real field dist. vs. matrix

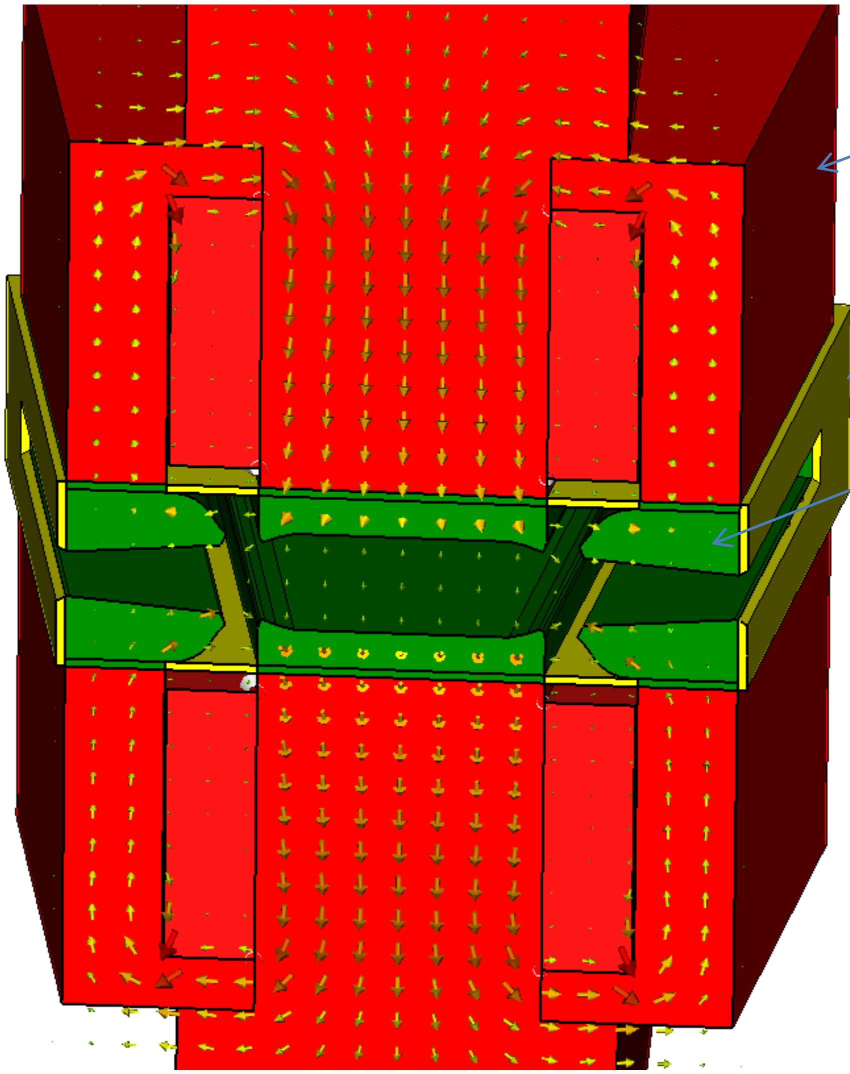


real field dist.: 0mA vs. 150mA

- 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.







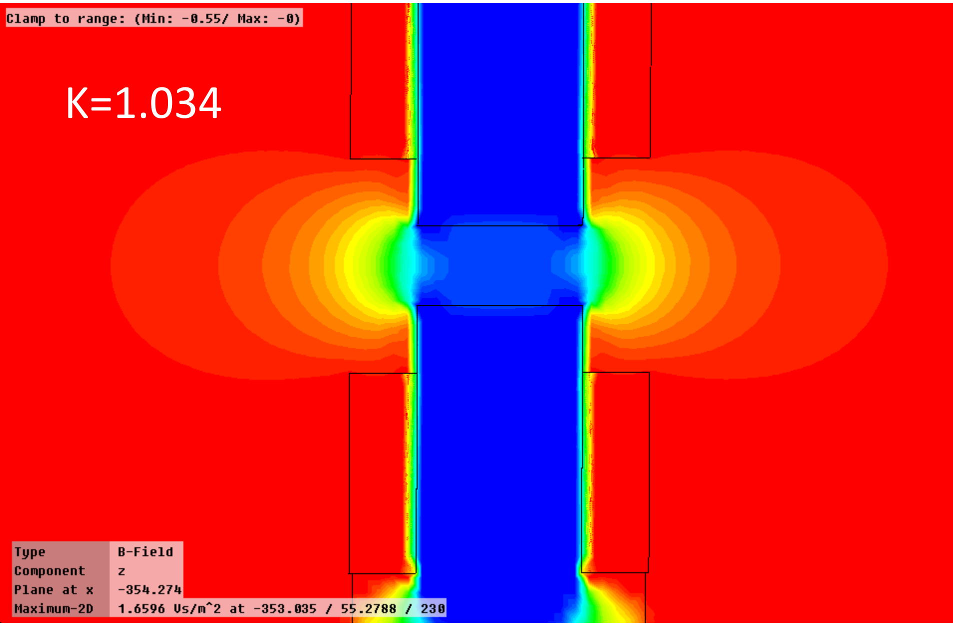
Iron: $\mu_{r,max}$=13k, B_s= 1.6T

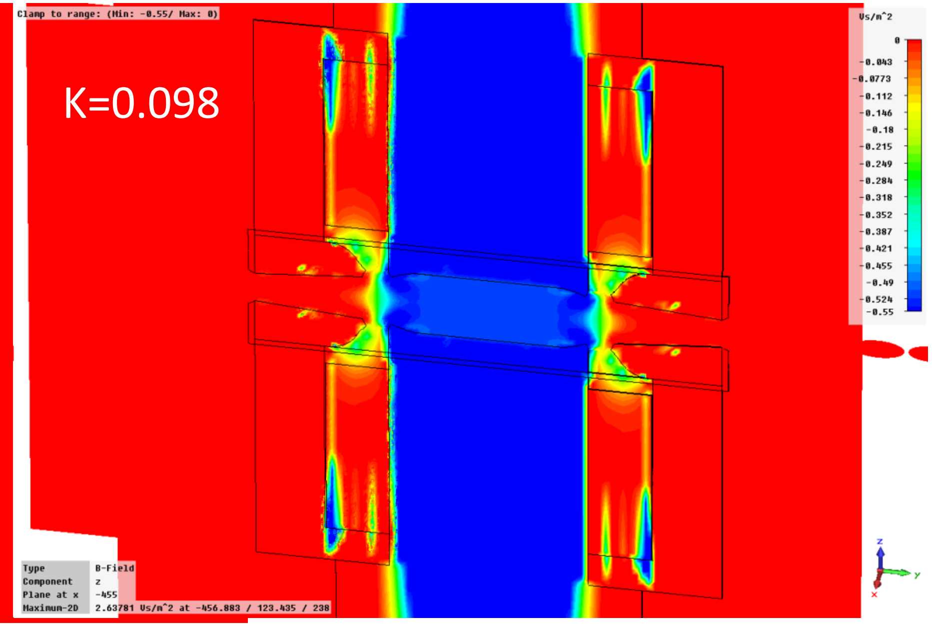
Non magnetic vacuum chamber

Vacoflux50: $\mu_{r,max}$=15k, B_s=2.2T

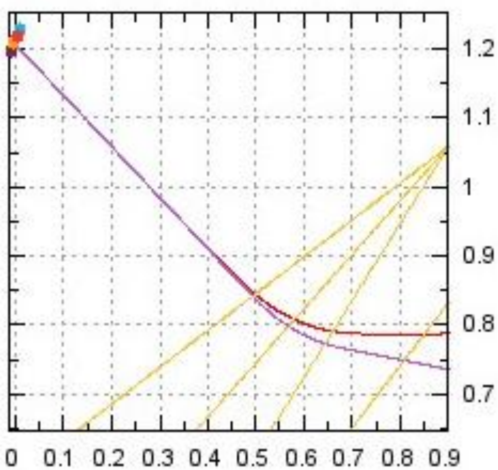
⇒ Modular pole face

⇒ Additional return yoke

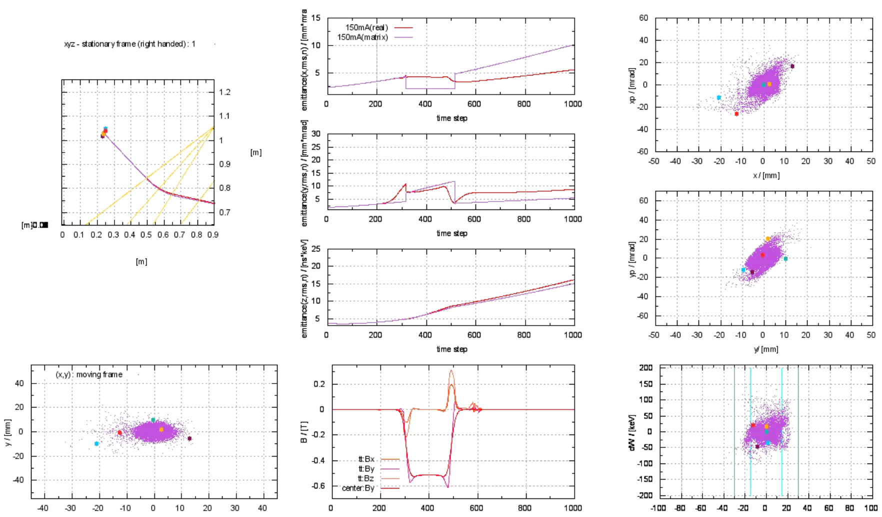




Without additional return yoke



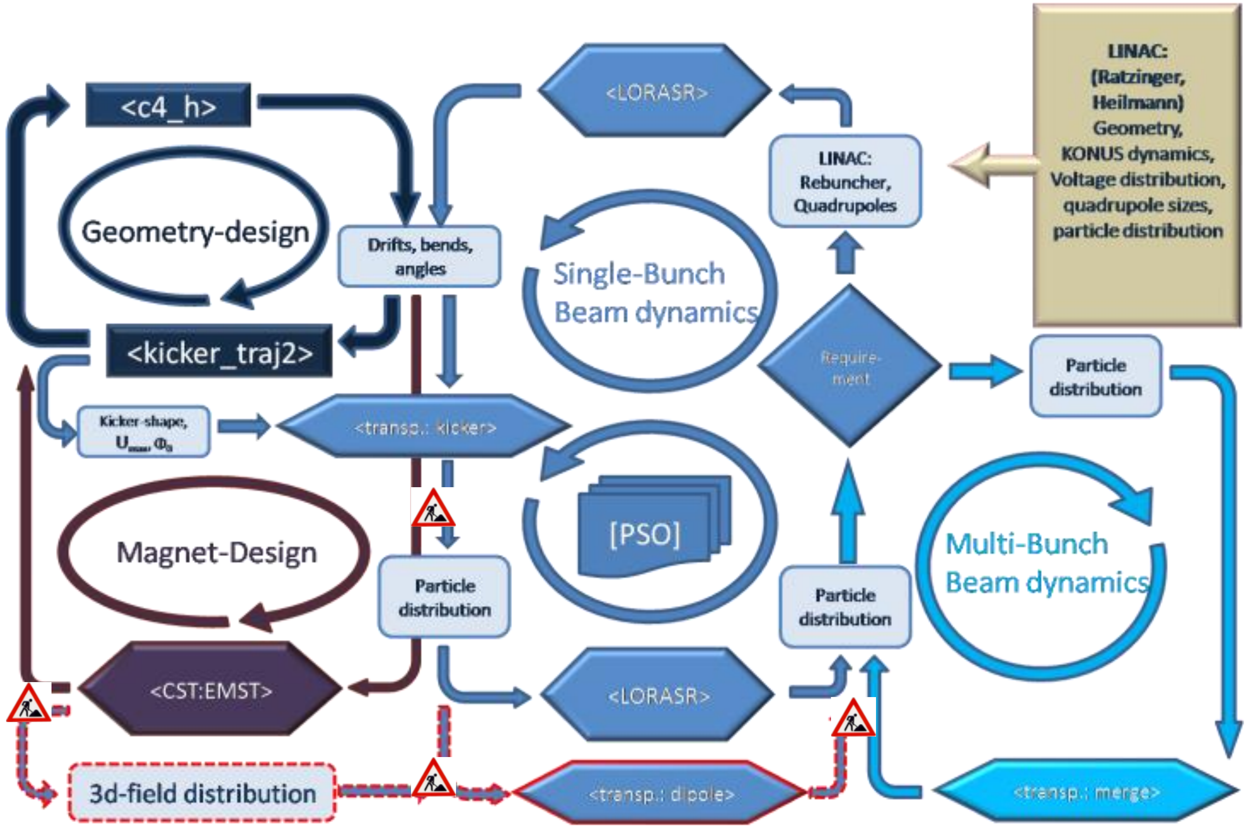
Center motion



Transport: paraxial approach vs. realistic field

Summery

- 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
- “Smart” Algorithm for **multi dimensional optimization** applied on Bunch Compressor
- **Code Development**: space charge dominated transport in realistic external Fields
- 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



Outlook:

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

Thank you for your attention.

on behalf of:

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

IAP, Goethe University Frankfurt

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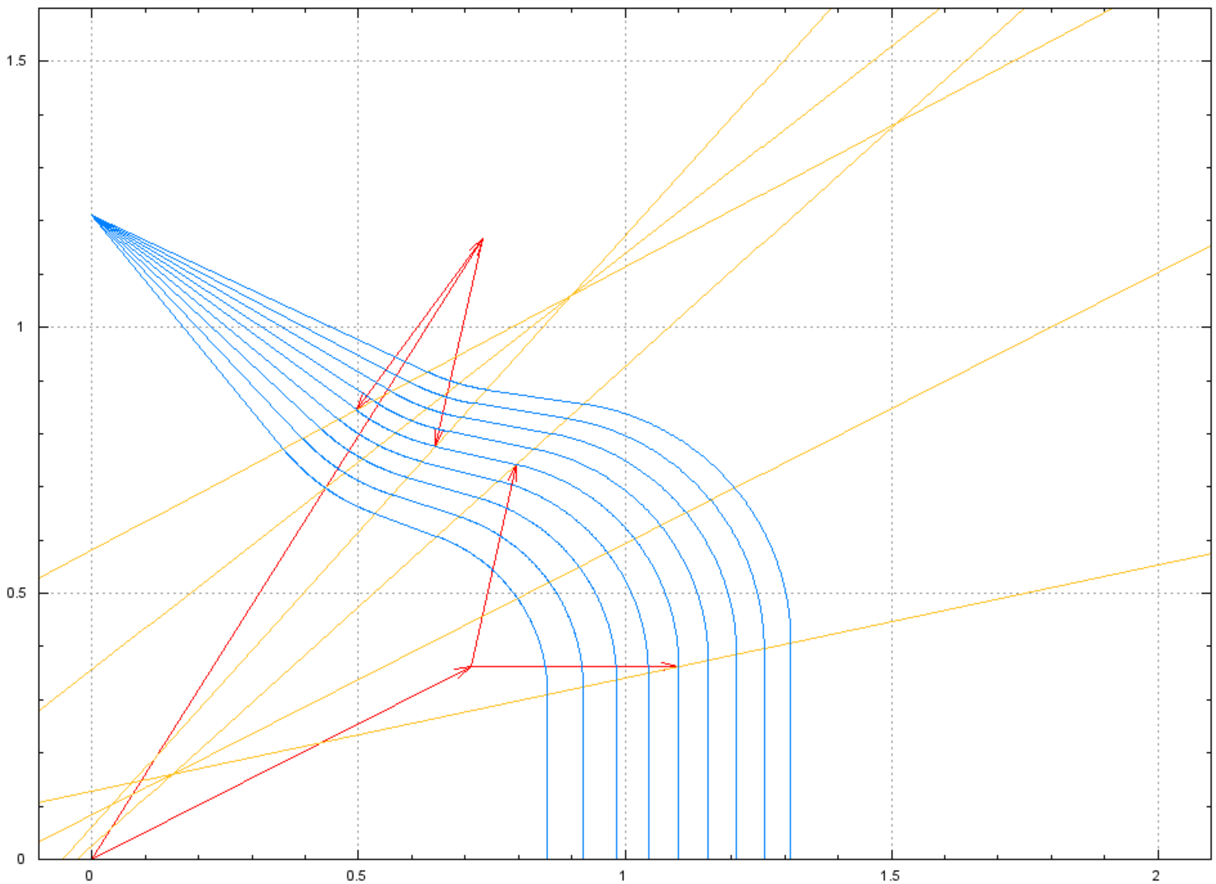
Franz Käppeler(FZK)
R. Reifarth (GSI / U. Frankfurt)
M. Heil (GSI)

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

Bunch Compressor: geometrical parameters

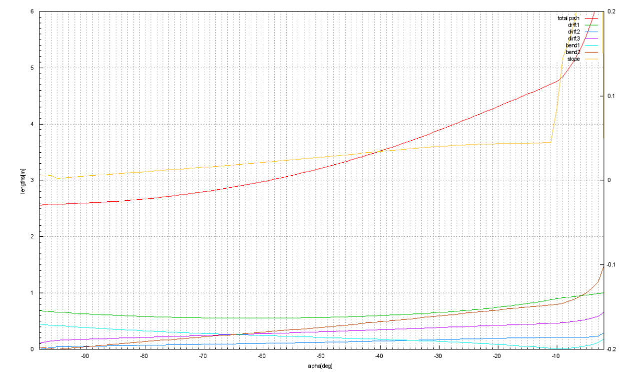


g9_5x

B_1 = -0.51497[T]

α_{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