HELMHOLTZ
ZENTRUM BERLIN
für Materialien und Energie

Space Charge Effects in cascaded HGHG-FELs

Lutz Hein

Verteidigung der Diplomarbeit

Gliederung

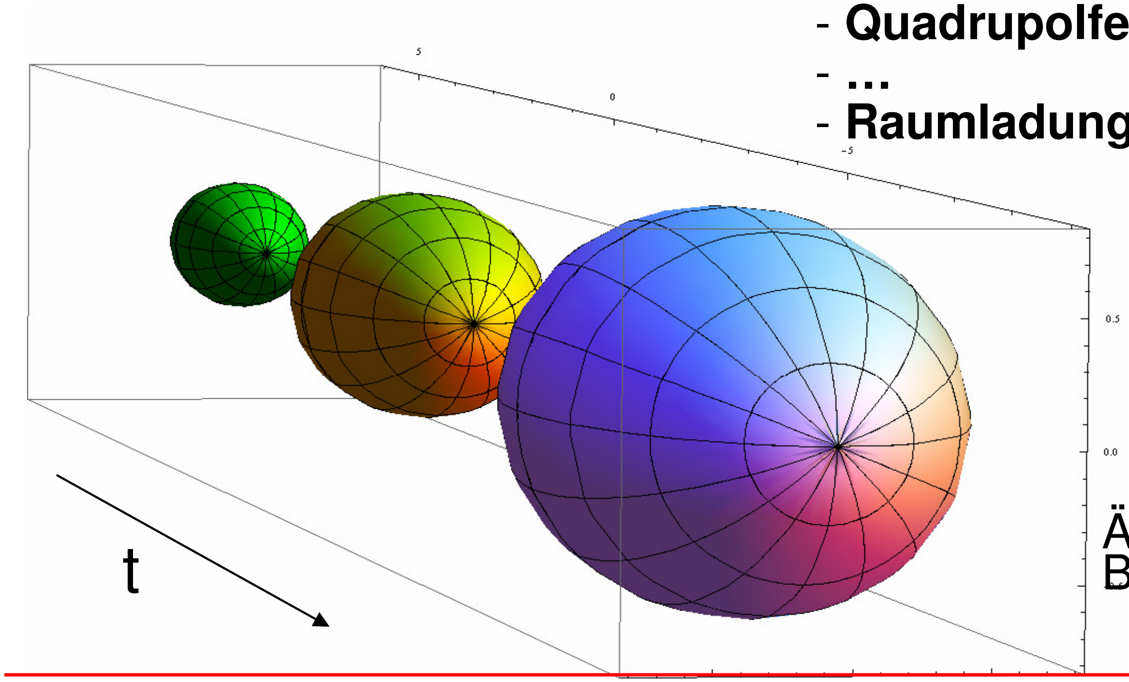
- Motivation
- Physikalische Grundlagen
  - FEL - Physik
  - Raumladung
- Programm P12
- FEL – Genesis1.3 & Simulation FLASH II / STARS
- Zusammenfassung
- Ausblick

Motivation

Die Lichtqualität eines FELs ist stark abhängig von den Eigenschaften des verwendeten Elektronenbunches.

Die Entwicklung eines Elektronenbunches kann beeinflusst werden durch:

- **Dipolfelder**
- **Quadrupolfelder**
- **…**
- **Raumladungseffekte**



Änderung des Bunches

Motivation

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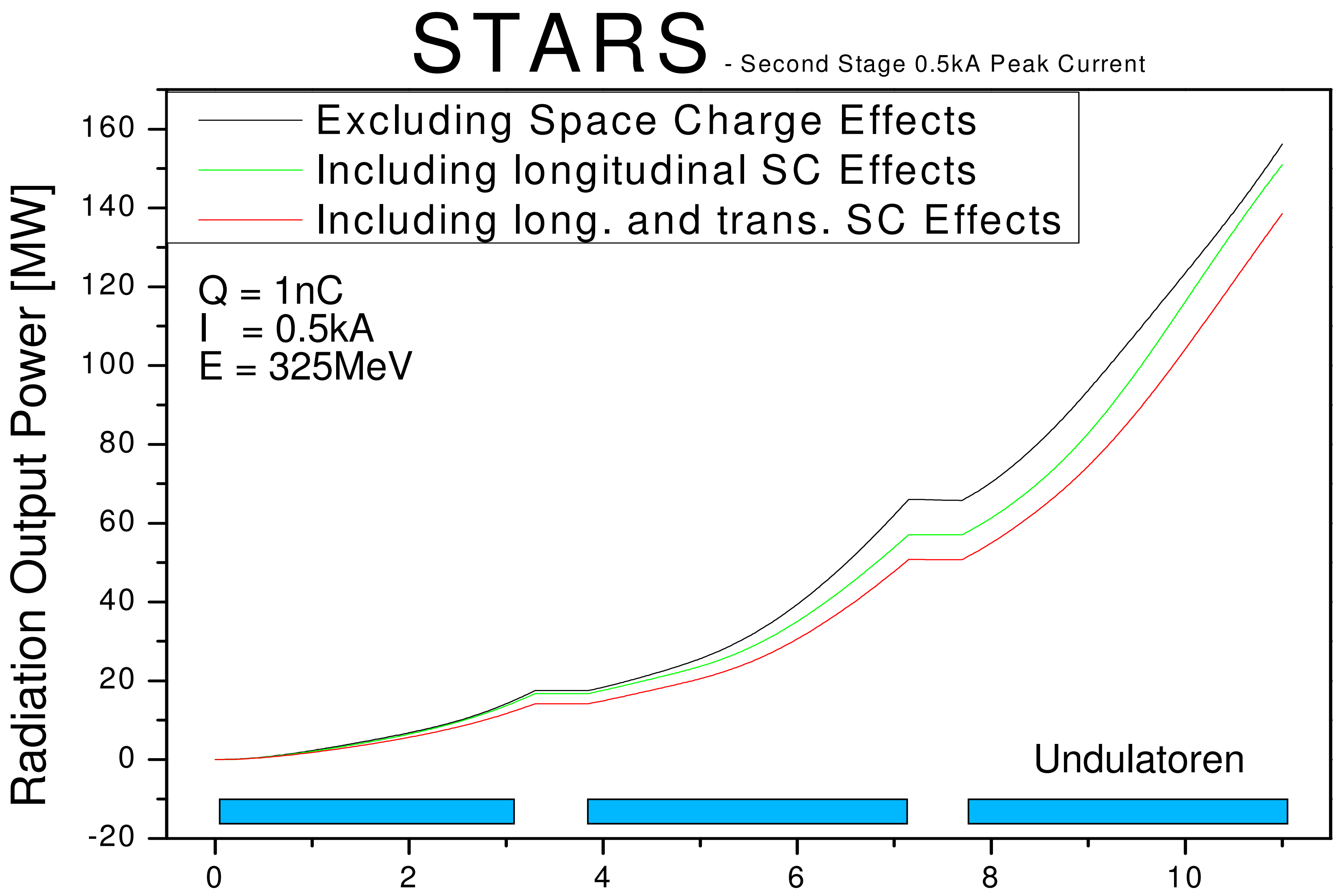
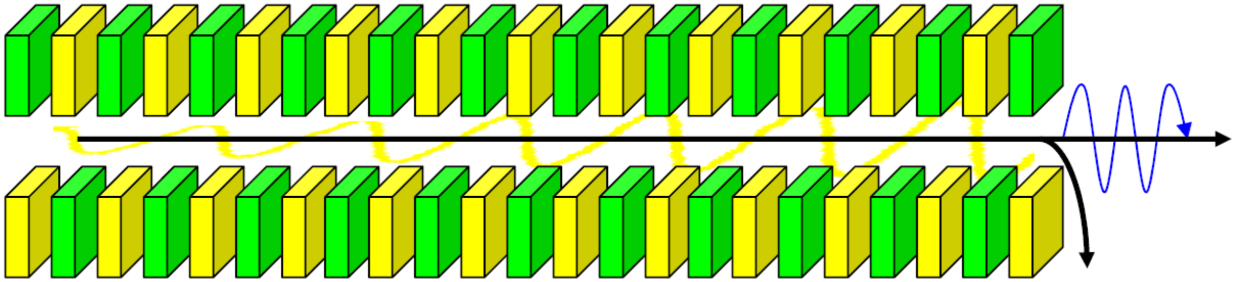
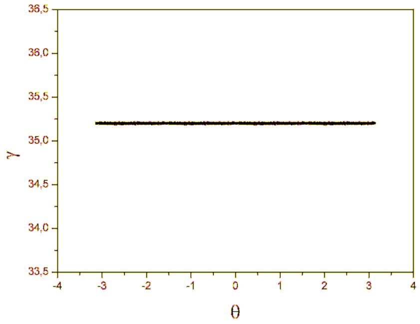


FEL – Physik I

Prinzip:

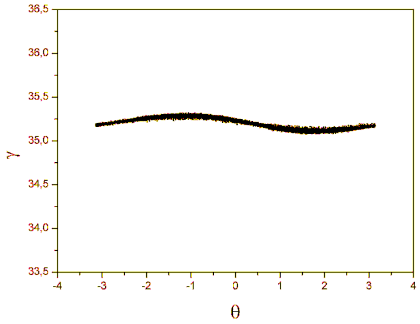


HighGain - MODUS

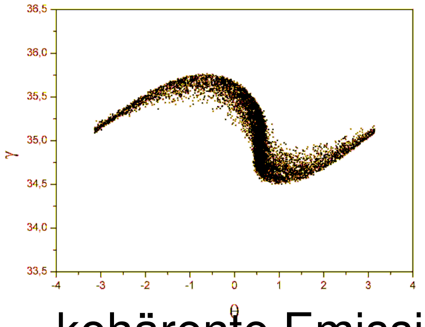


Shot Noise

Energie-modulation

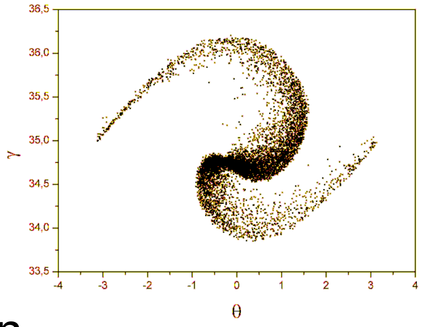


Dichtemodulation
Microbunching

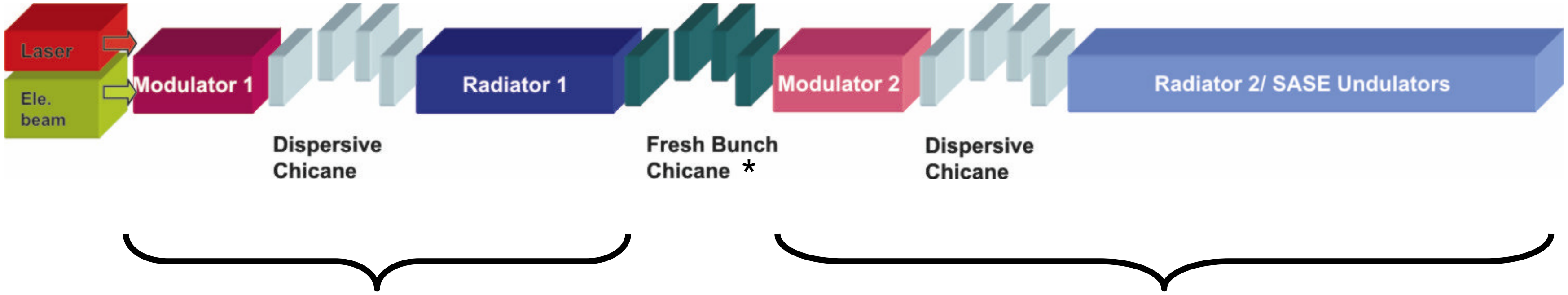


kohärente Emission

Sättigung



FLASH II: High-Gain Harmonic Generation FEL^{+}



STAGE 1

STAGE 2

200nm SEED → 40nm Abstrahlung

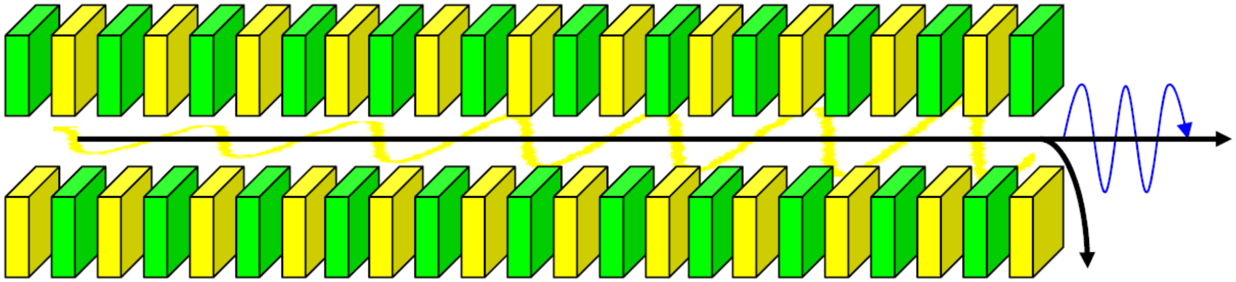
40nm SEED → 8nm Abstrahlung

+„Theory of high gain harmonic generation: an analytical estimate“,
Li Hua Yu, NIM A483(2003)

*„High-gain harmonic generation of soft X-rays with the ‚fresh bunch‘ technique“,
Li-Hua Yu, NIM A393(1997)

FEL – Physik III

Prinzip:



Pierce-Parameter: $$\varrho = \frac{1}{\gamma}\left[\left(\frac{K_{rms}\lambda_u f_B}{8\pi}\right)^2 \frac{I_{Peak}}{I_A \sigma^2}\right]^{\frac{1}{3}}$$

Verstärkungslänge $L_{Gain} \sim \frac{\lambda_u}{\varrho}$

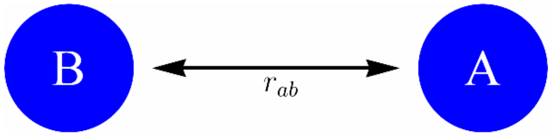
Spektrum $\frac{\Delta\lambda}{\lambda} \sim \varrho$

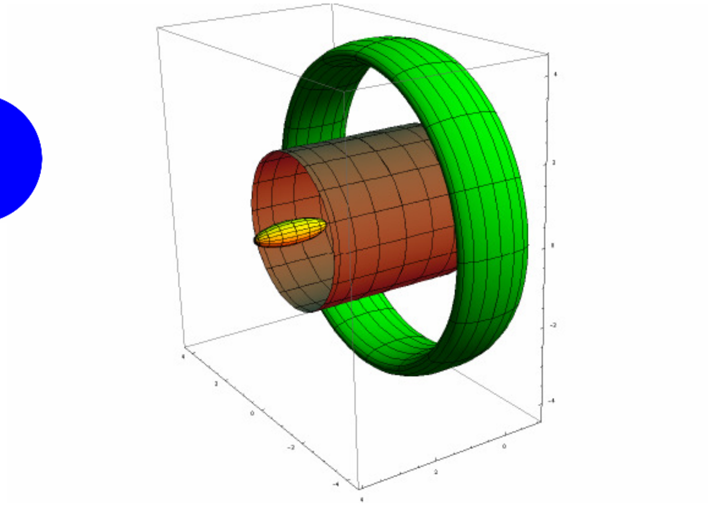
Sättigungsintensität $P_{sat} \sim \varrho$

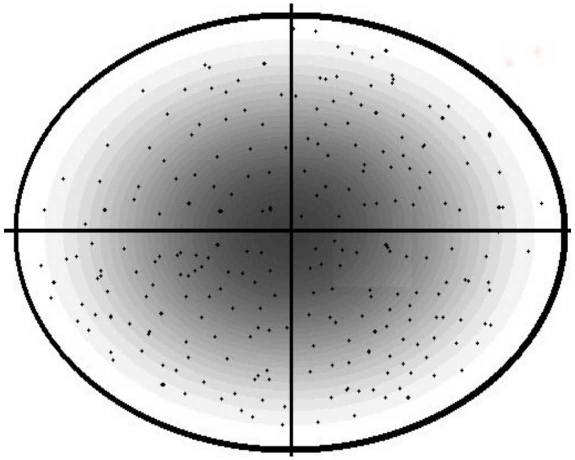
Überblick – Raumladungseffekte

Raumladung

Einzelteilchen | **Mit der Umgebung** | **Als Kollektiv**







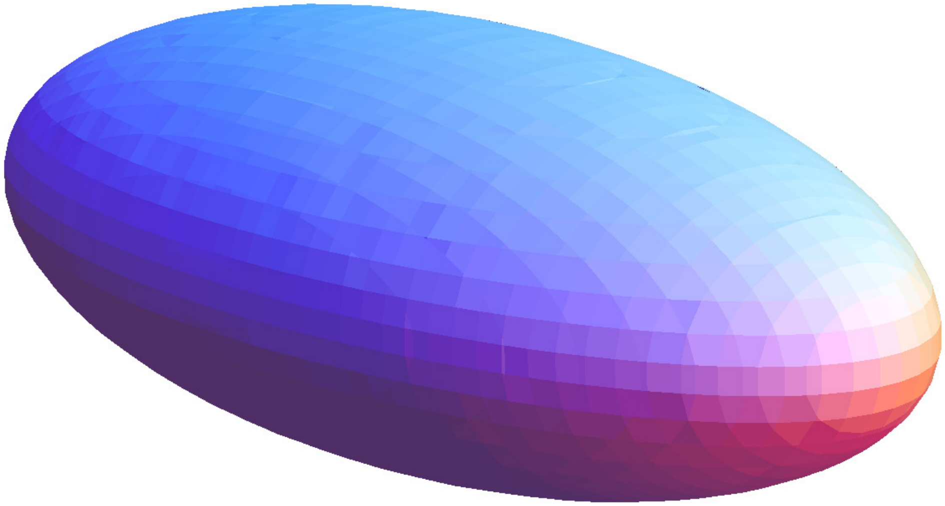
- Touschek – Streuung

- Wake-fields

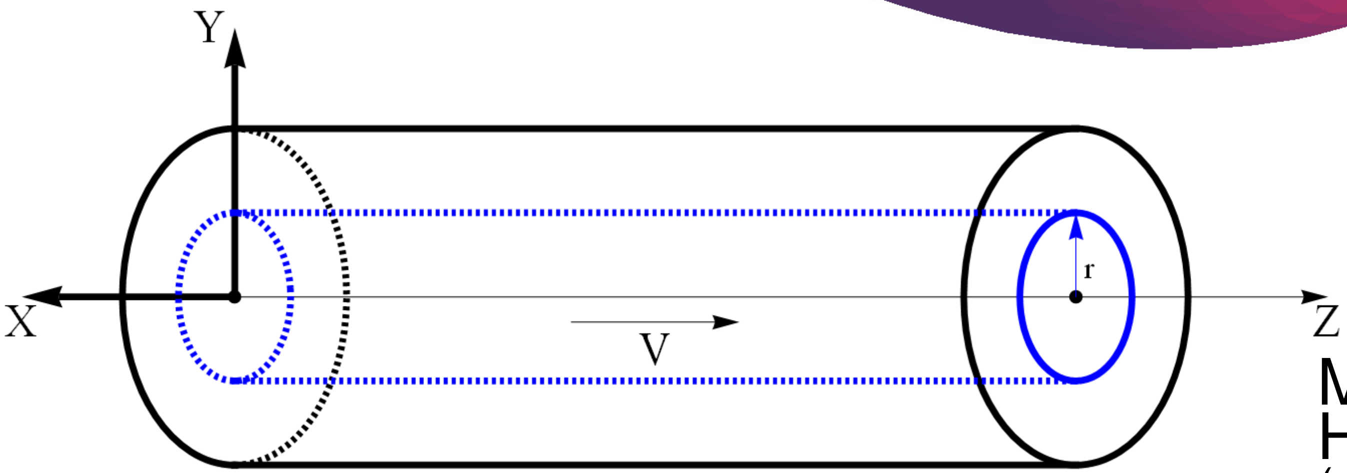
- Kollektive Selbstwechselwirkung

Raumladung - Modell

3D-Ellipsoid*



2D-Ellipse⁺



Modell für
HGHG-FELs
(→keine longitudinale Raumladung)

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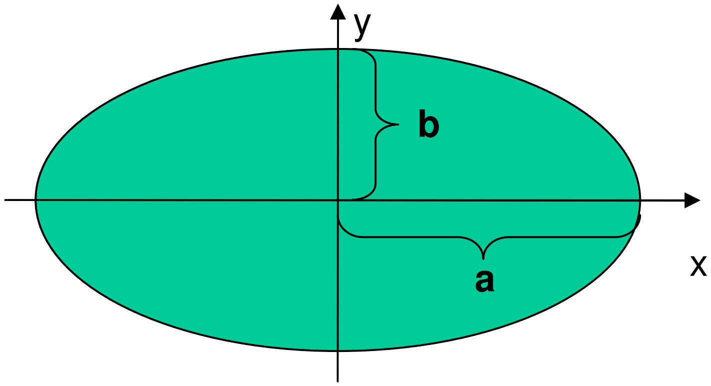
[*] „Foundations of potential theory“, O.D. Kellogg, 1976

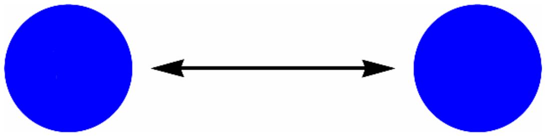
[+] „Space charge fields of elliptical symmetrical beams“, M.R.Shubaly, NIM 13:19-21,1975

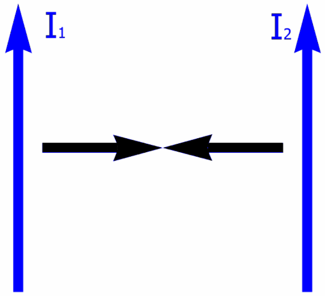
Raumladung – Uniforme Verteilung I



$$\rho(\vec{r}) = \frac{I}{A_0 \cdot \beta \cdot c}$$

$$\vec{E} = \frac{I}{\pi \epsilon_0 (a+b) \beta c} \cdot \left(\frac{x}{a}, \frac{y}{b}, 0\right) \qquad \vec{B} = \frac{\mu_0 I}{\pi (a+b)} \cdot \left(-\frac{y}{b}, \frac{x}{a}, 0\right)$$

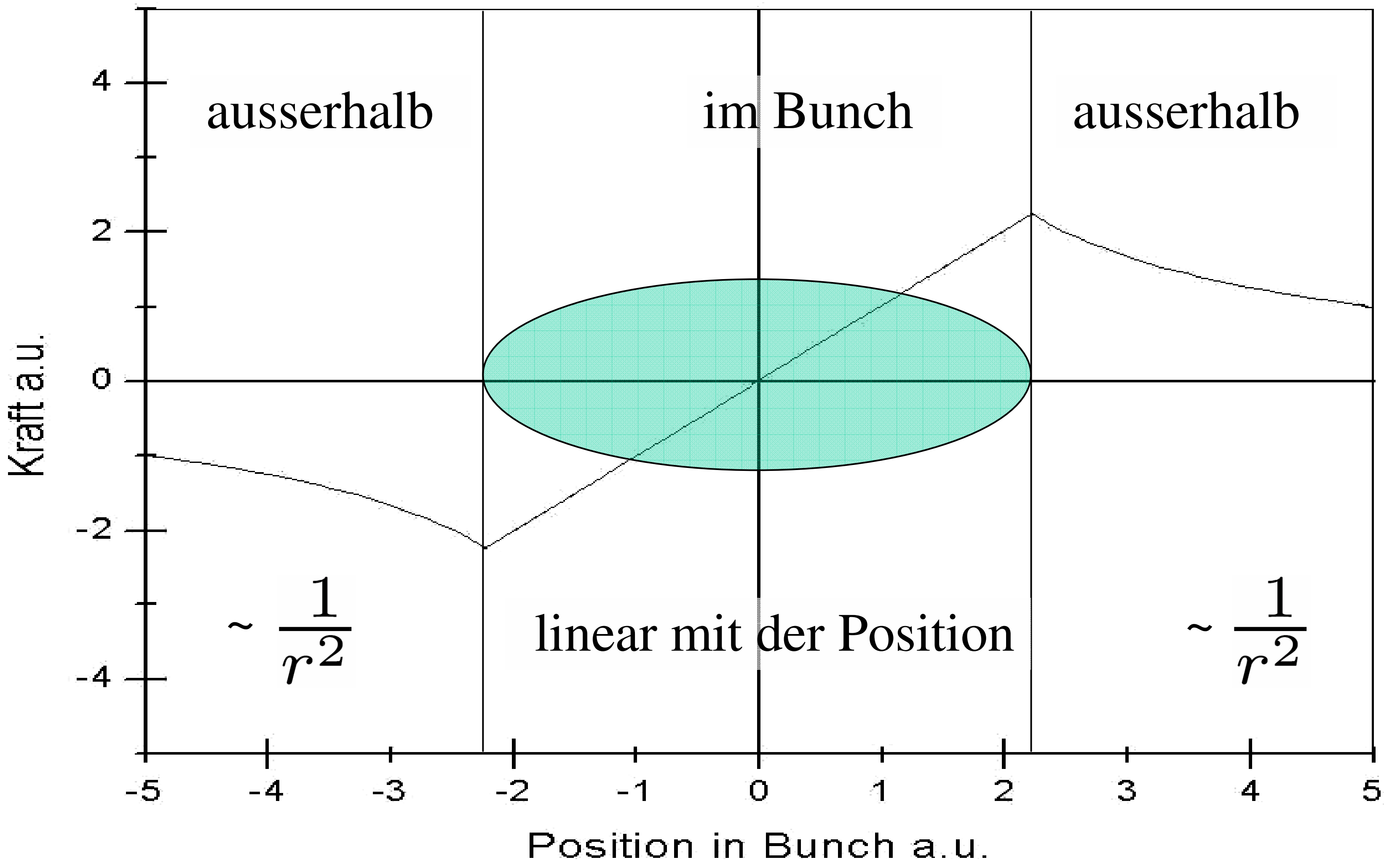




Mit der Näherung $\vec{\beta} \cdot c \approx \vec{v}_s$

$$\vec{F}_L = \frac{eI}{\pi \epsilon_0 \beta c \gamma^2 \cdot (a+b)} \cdot \left(\frac{x}{a}, \frac{y}{b}, 0\right)$$

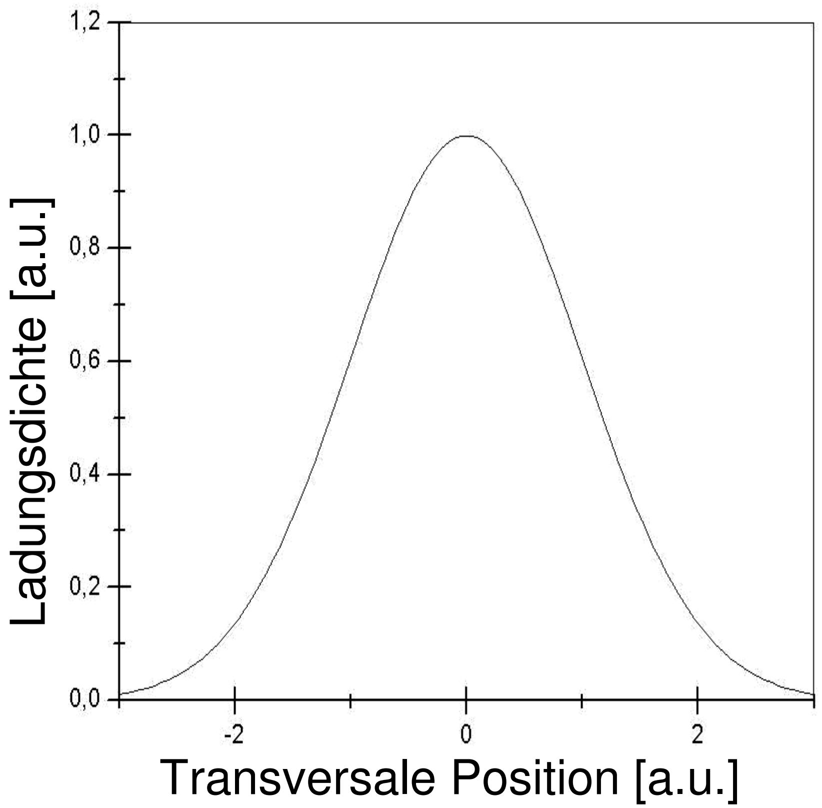
Raumladung – Uniforme Verteilung II



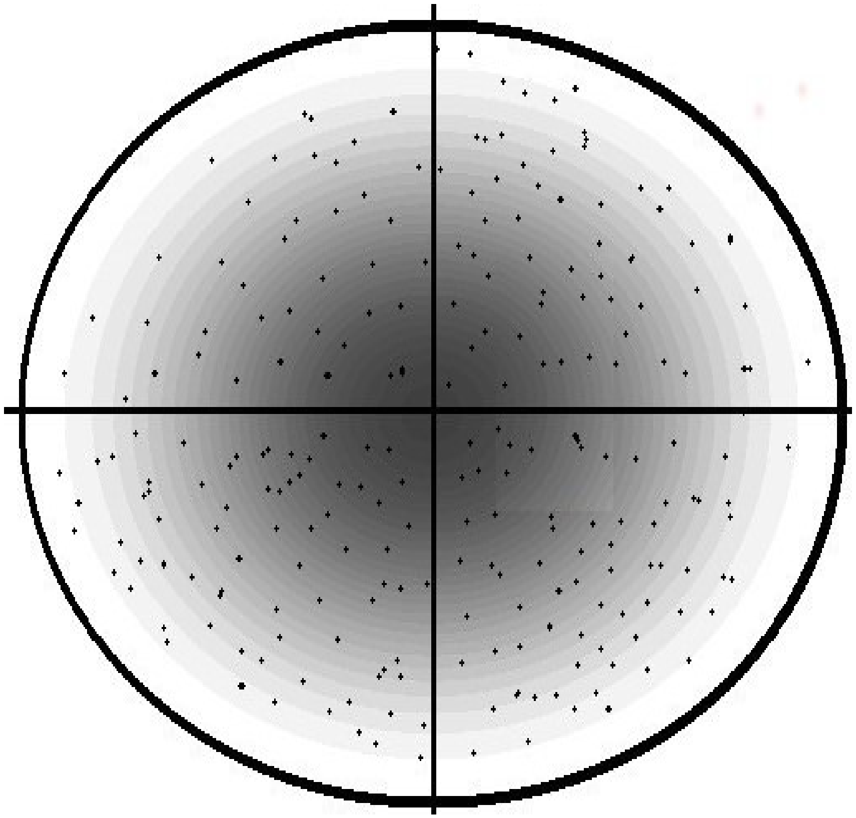
Raumladung – Gauß-Verteilung I

Annahmen:

- Gauss-Verteilung
- rotationssymmetrisch



Querschnitt des Bunches



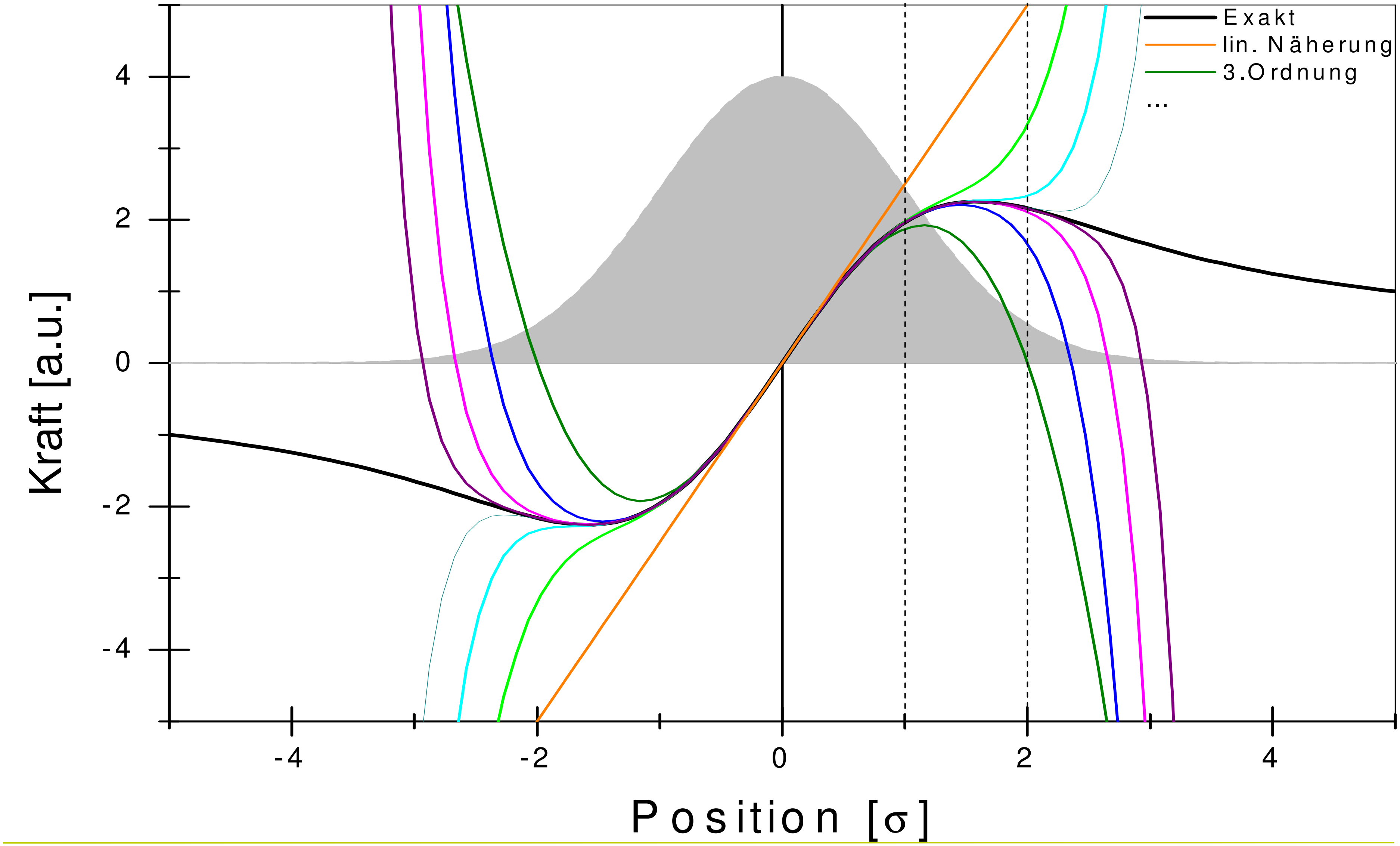
Raumladung – Gauß-Verteilung II

$$\left.\rho(r) = \frac{I}{\beta\cdot c}\cdot\frac{1}{2\pi\sigma^2}\cdot e^{-\frac{r^2}{2\cdot\sigma^2}}\right\}\text{Ladungsverteilung}$$

$$\left.\begin{aligned}\vec{E} &= E_r = \frac{I}{2\pi\epsilon_0\beta c}\cdot\frac{1}{r}\left(1-e^{-\frac{r^2}{2\sigma^2}}\right)\\ \vec{B} &= B_\phi = \frac{I}{2\pi\epsilon_0 c^2}\cdot\frac{1}{r}\left(1-e^{-\frac{r^2}{2\sigma^2}}\right)\end{aligned}\right\}\text{Felder}$$

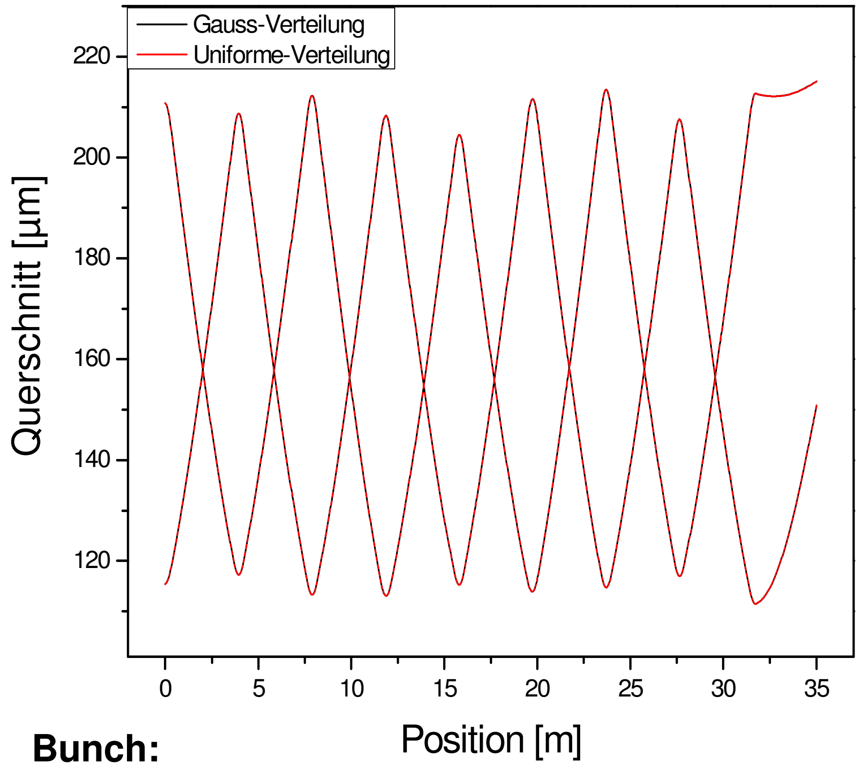
$$\left.\begin{aligned}\vec{F} &= \frac{eI}{2\pi\epsilon_0\beta c\gamma^2}\cdot\frac{\vec{r}}{r^2}\left(1-e^{-\frac{r^2}{2\sigma^2}}\right)\\ \vec{F} &\approx \frac{eI}{2\pi\epsilon_0\beta c\gamma^2}\cdot\frac{\vec{r}}{2\sigma^2}\end{aligned}\right\}\text{Kraft}$$

Raumladung – Gauß-Verteilung III



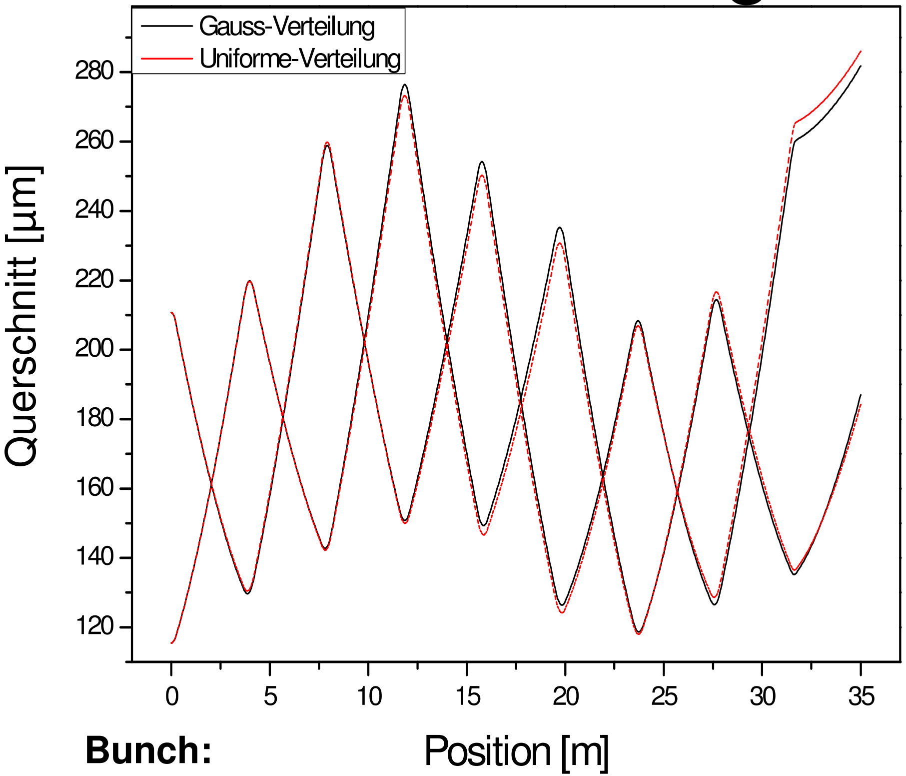
Uniforme Verteilung Vs. Gauss-Verteilung

Ohne Raumladung



Bunch:
Energy 230MeV
σ_x = 210 µm
σ_y = 115 µm

Mit Raumladung



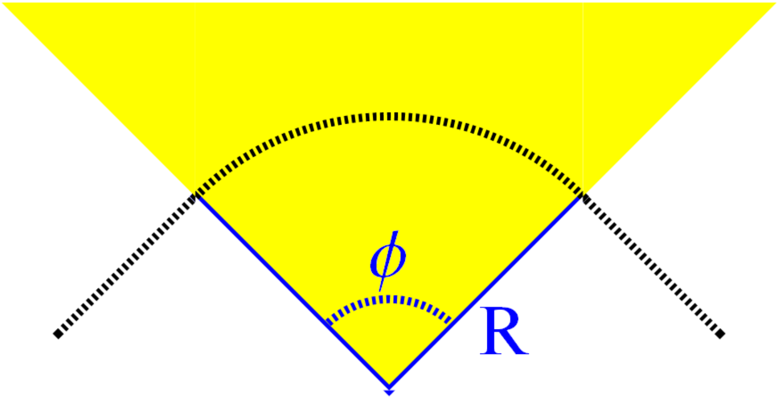
Bunch:
Energy 230MeV
σ_x = 210 µm
σ_y = 115 µm

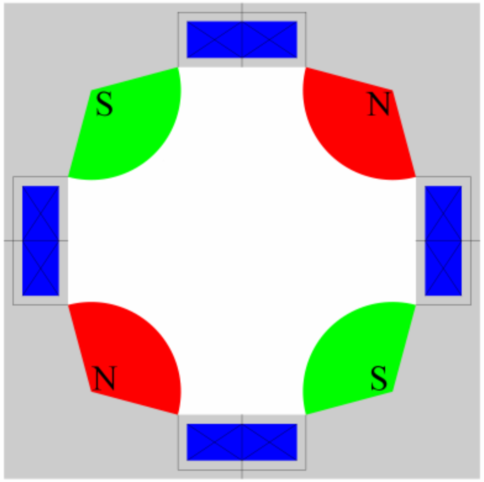
Simulation mit ASTRA (Teilchen-tracking).

Raumladung – Lineare Optik I

Bewegungsgleichung ohne Raumladung:

$$
\begin{aligned}
x''(s) + (\frac{1}{R^2(s)} - k_x(s))x(s) &= \frac{1}{R(s)}\frac{\Delta p}{p} \\
y''(s) + k_y(s)y(s) &= 0
\end{aligned}
$$





Raumladung – Lineare Optik II

Bewegungsgleichung ohne Raumladung:

$$\begin{aligned} x''(s) + \left(\frac{1}{R^2(s)} - k_x(s)\right)x(s) &= \frac{1}{R(s)}\frac{\Delta p}{p} \\ y''(s) + k_y(s)y(s) &= 0 \end{aligned}$$

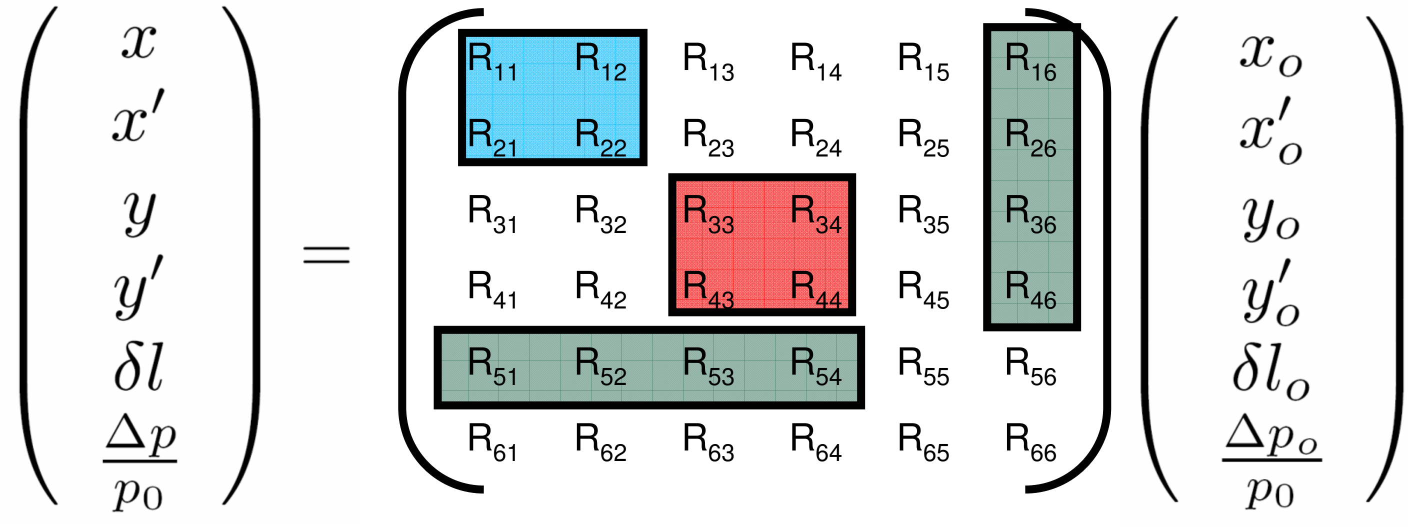
Bewegungsgleichung mit transversaler Raumladung:

$$\begin{aligned} x''(s) + \left(\frac{1}{R^2(s)} - (k_x(s) + k_{sc})\right)x(s) &= \frac{1}{R(s)}\frac{\Delta p}{p} \\ y''(s) + (k_y(s) - k_{sc})y(s) &= 0 \end{aligned}$$

Raumladung – Lineare Optik III

$$
\begin{aligned}
x''(s) + \left(\frac{1}{R^2(s)} - (k_x(s) + k_{sc})\right)x(s) &= \frac{1}{R(s)}\frac{\Delta p}{p} \\
y''(s) + (k_y(s) - k_{sc})y(s) &= 0
\end{aligned}
$$

Transfermatrix

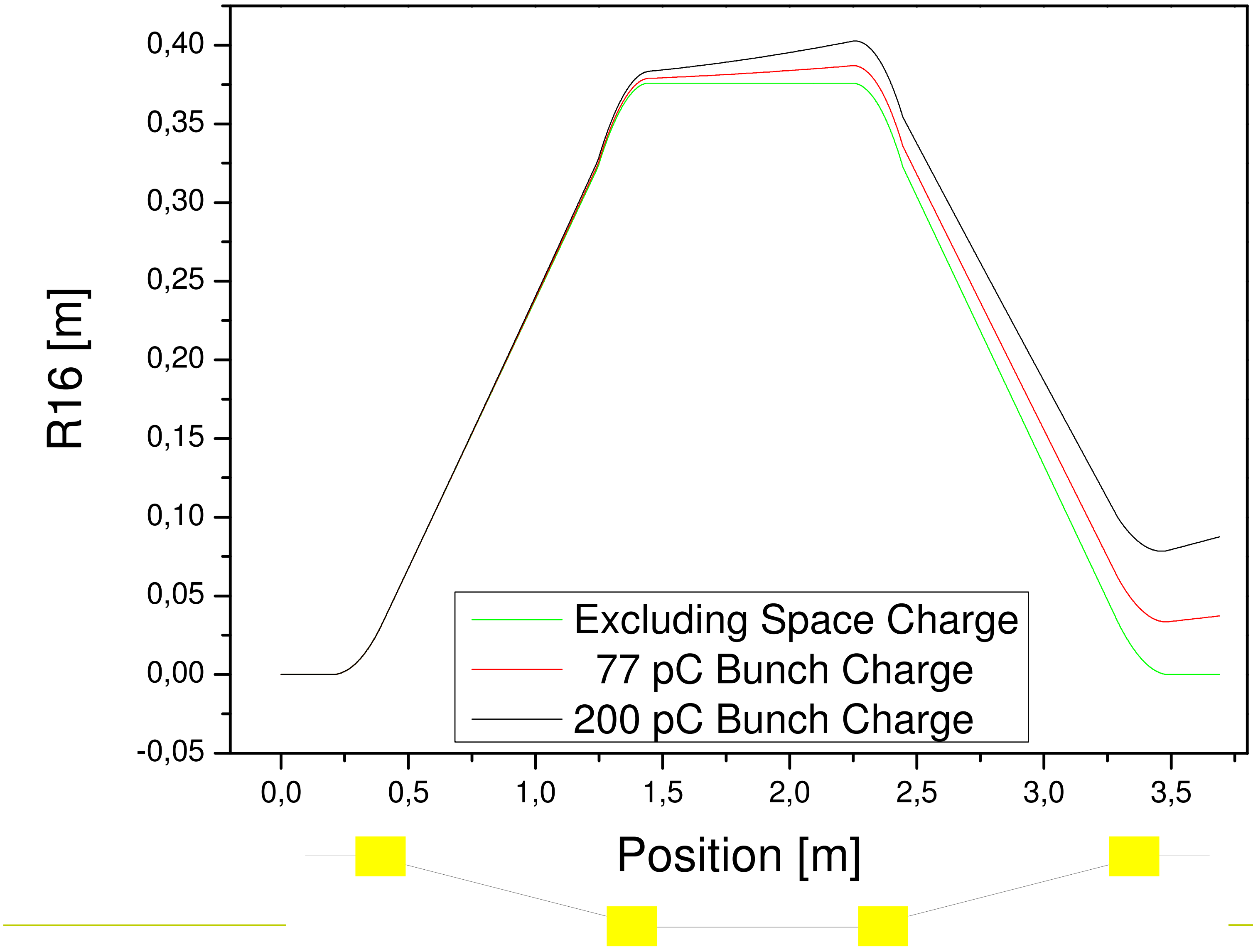


$$
\begin{pmatrix} x \\ x' \\ y \\ y' \\ \delta l \\ \frac{\Delta p}{p_0} \end{pmatrix}
=
\begin{pmatrix}
R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\
R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\
R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\
R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\
R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\
R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66}
\end{pmatrix}
\begin{pmatrix} x_o \\ x'_o \\ y_o \\ y'_o \\ \delta l_o \\ \frac{\Delta p_o}{p_0} \end{pmatrix}
$$

Endvektor

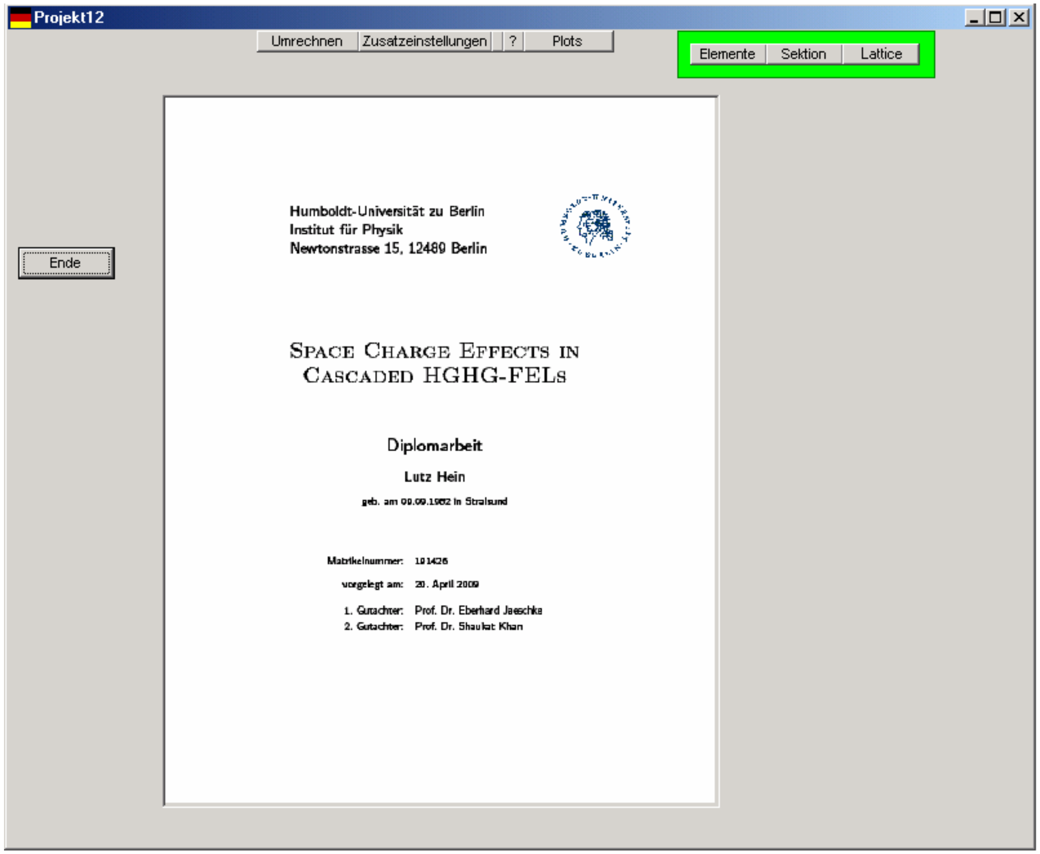
Eingangsvektor

Raumladung – Dispersion



Bunch:
energy 6,5MeV
σ_x = 0,7 mm
σ_y = 0,1 mm
σ_z = 6,0 mm

Programm P12 - Nutzerprogramm



Humboldt-Universität zu Berlin
Institut für Physik
Newtonstrasse 15, 12489 Berlin

SPACE CHARGE EFFECTS IN
CASCADED HGHG-FELs

Diplomarbeit

Lutz Hein

geb. am 09.09.1982 in Stralsund

Matrikelnummer: 191426
vorgelegt am: 20. April 2009
1. Gutachter: Prof. Dr. Eberhard Jaeschke
2. Gutachter: Prof. Dr. Shaukat Khan

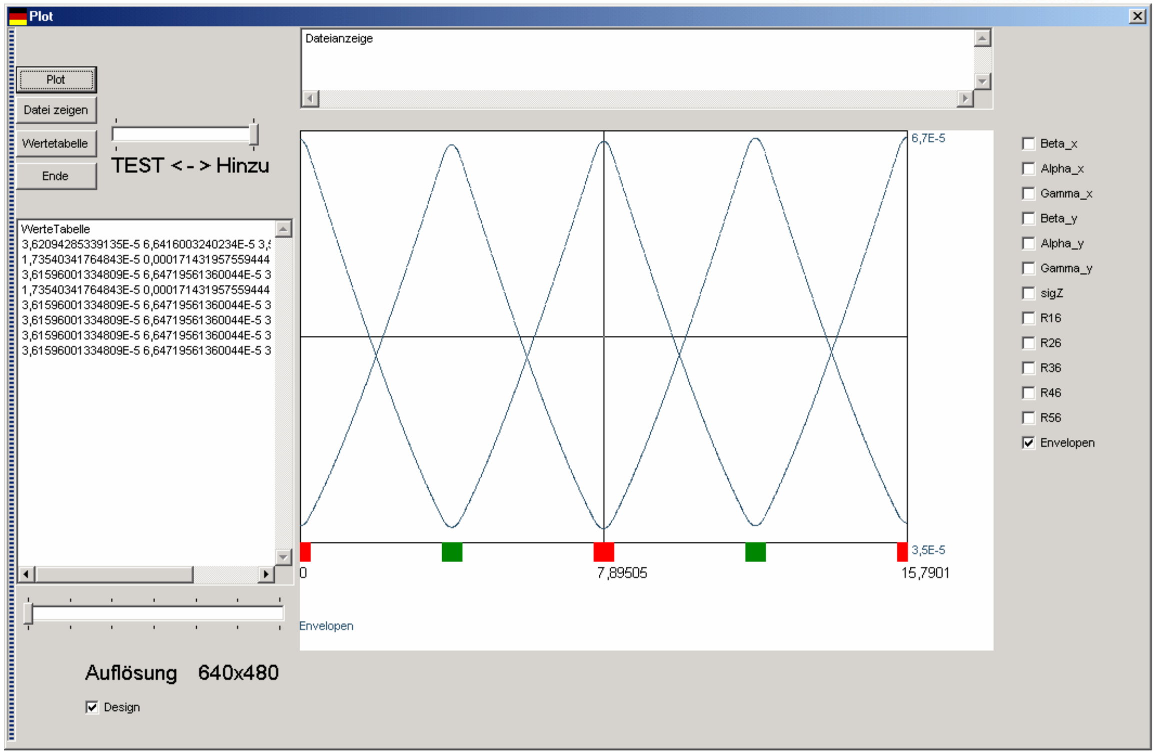
- Erstellung von Lattices
- Schnelle Analysen

- Lineare Optik
- Raumladungseffekte
- Undulatorfokusierung
- Auswertungsprogramme

Programm P12

Besonderheiten

- Transfermatrizen Output
- Entwicklung der Parameter
- Selektive Auswahl berücksichtigter Effekte
- Undulatorbesonderheiten
- Genesis1.3 Output.lat
- Benutzerfreundlichkeit durch optische Oberflächen
- Auswertungsprogramme
- …



WerteTabelle

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1,73540341764843E-5 0,000171431957559444
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1,73540341764843E-5 0,000171431957559444
3,61596001334809E-5 6,64719561360044E-5 3
3,61596001334809E-5 6,64719561360044E-5 3
3,61596001334809E-5 6,64719561360044E-5 3
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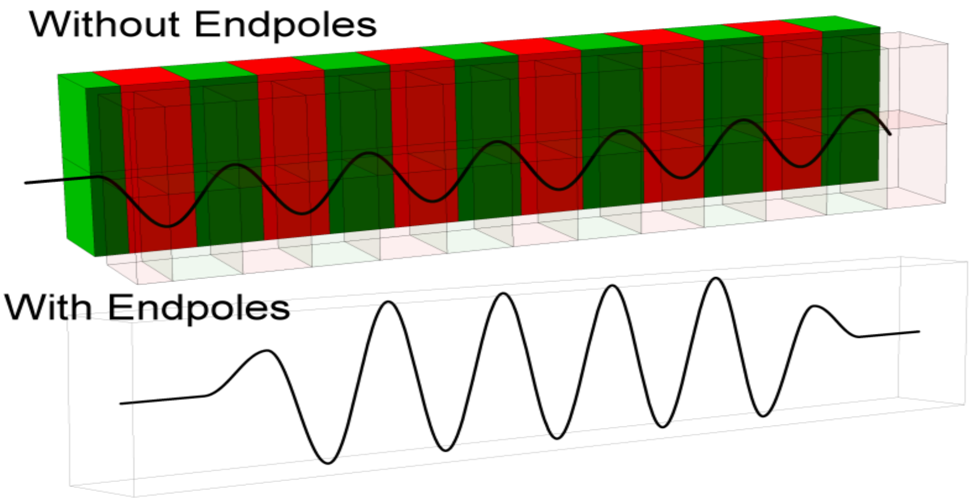
```

☐ Beta_x
☐ Alpha_x
☐ Gamma_x
☐ Beta_y
☐ Alpha_y
☐ Gamma_y
☐ sigZ
☐ R16
☐ R26
☐ R36
☐ R46
☐ R56
☑ Envelopen

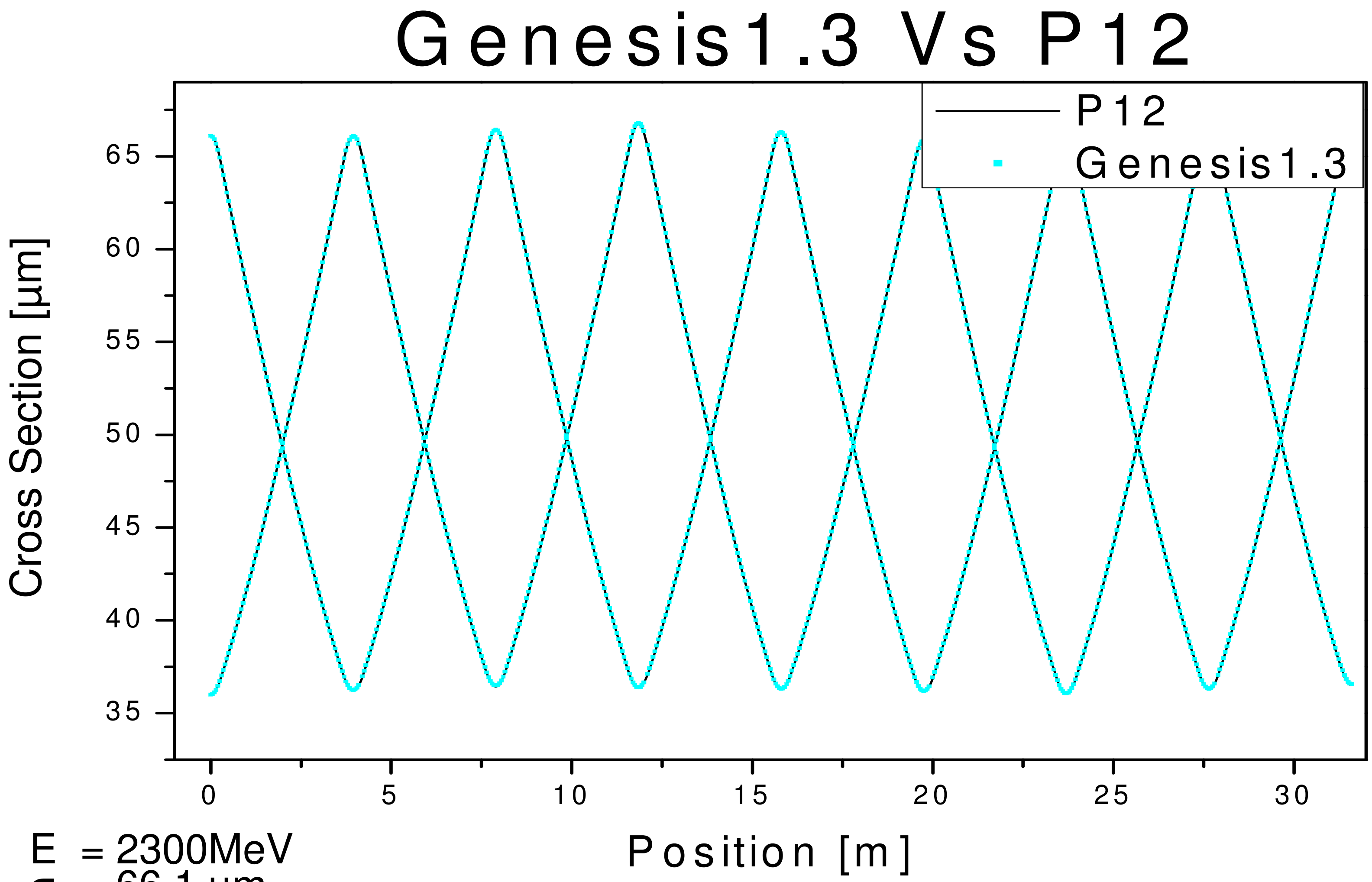
Auflösung 640x480

☑ Design



Vergleich: P12 Vs Genesis1.3 & ASTRA

Ohne Raumladung



E = 2300MeV

σx = 66,1 µm

σy = 36,0 µm

Vergleich: P12 Vs Genesis1.3 & ASTRA

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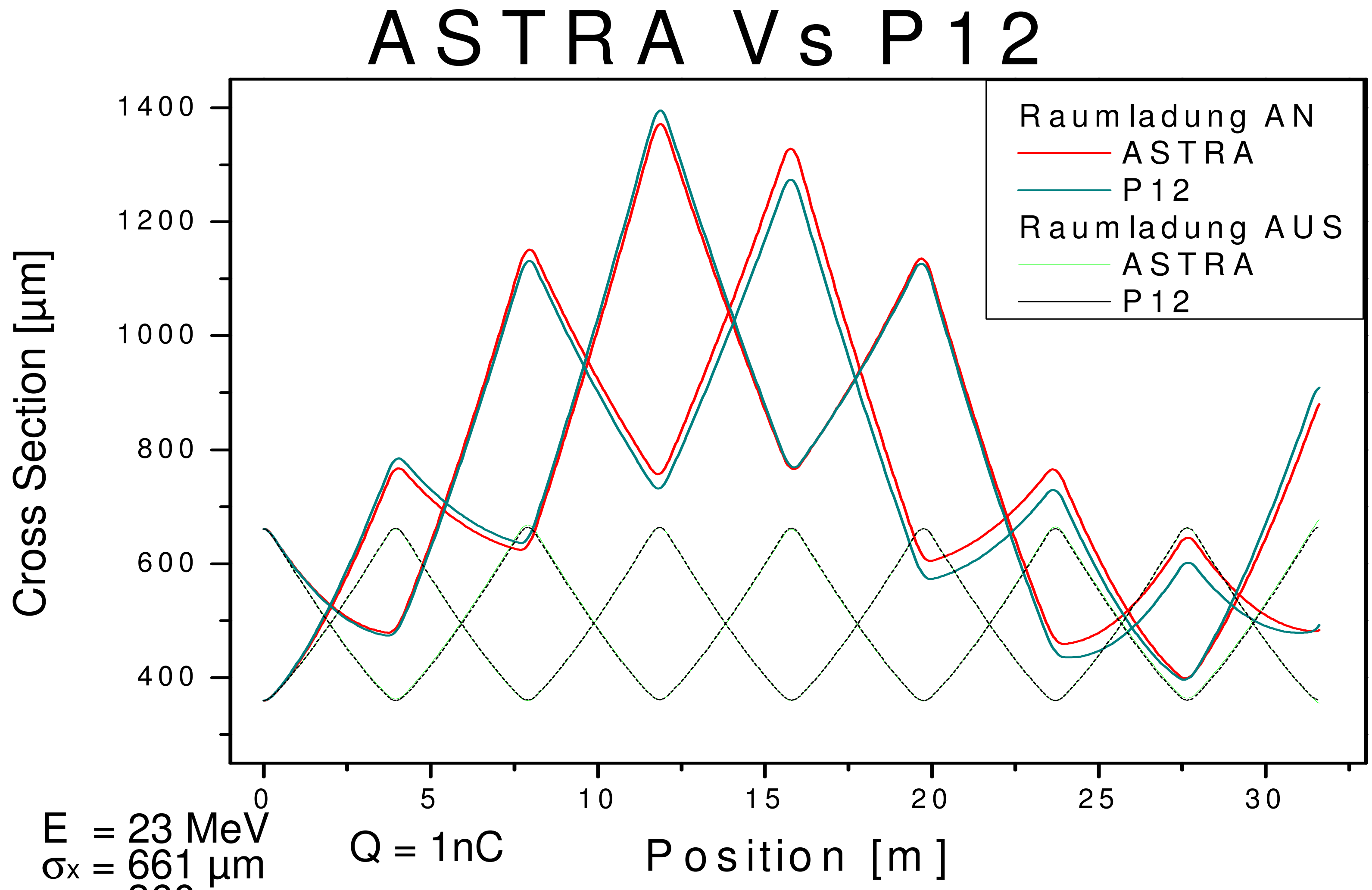
Mit Raumladung



E = 23 MeV
σ_x = 661 µm
σ_y = 360 µm

Q = 1nC

FEL – Genesis1.3 I

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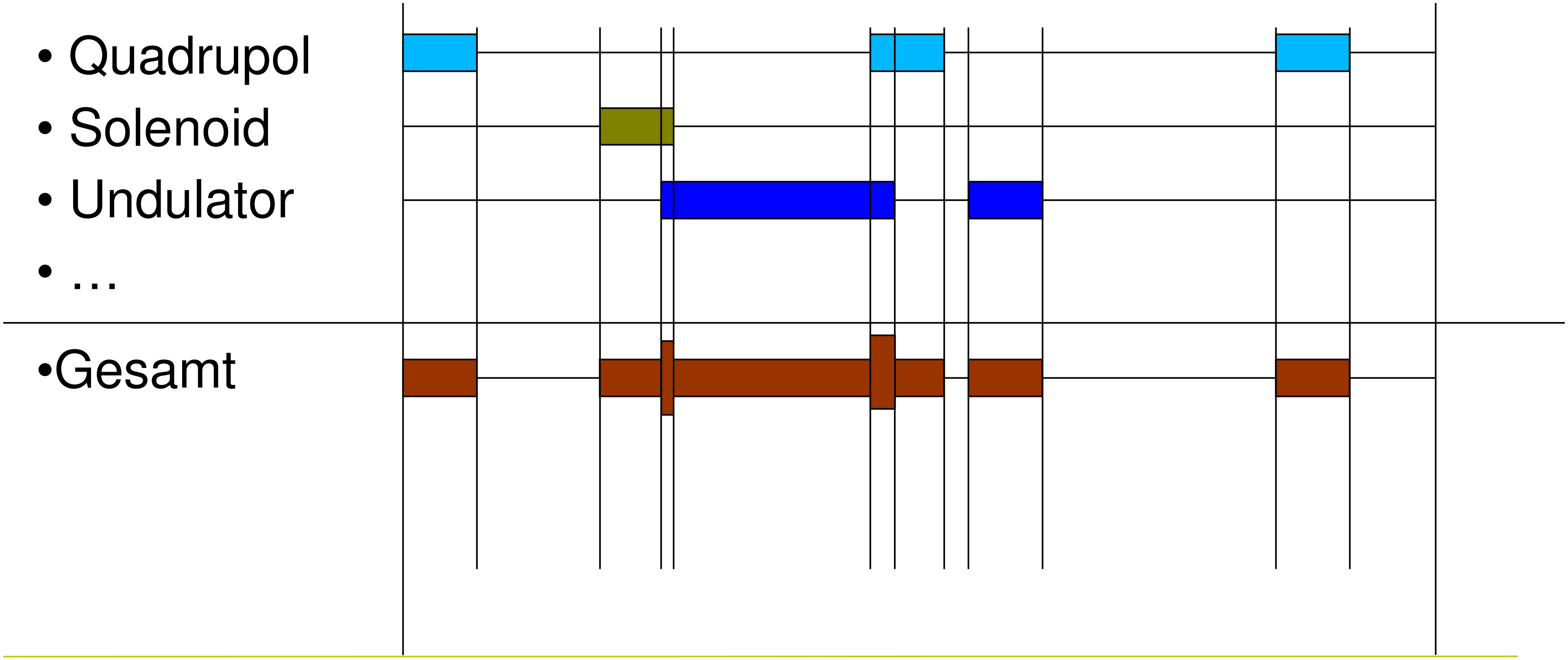
* Programm von Sven Reiche

Genesis 1.3 – Optikberechnung

`track.f`

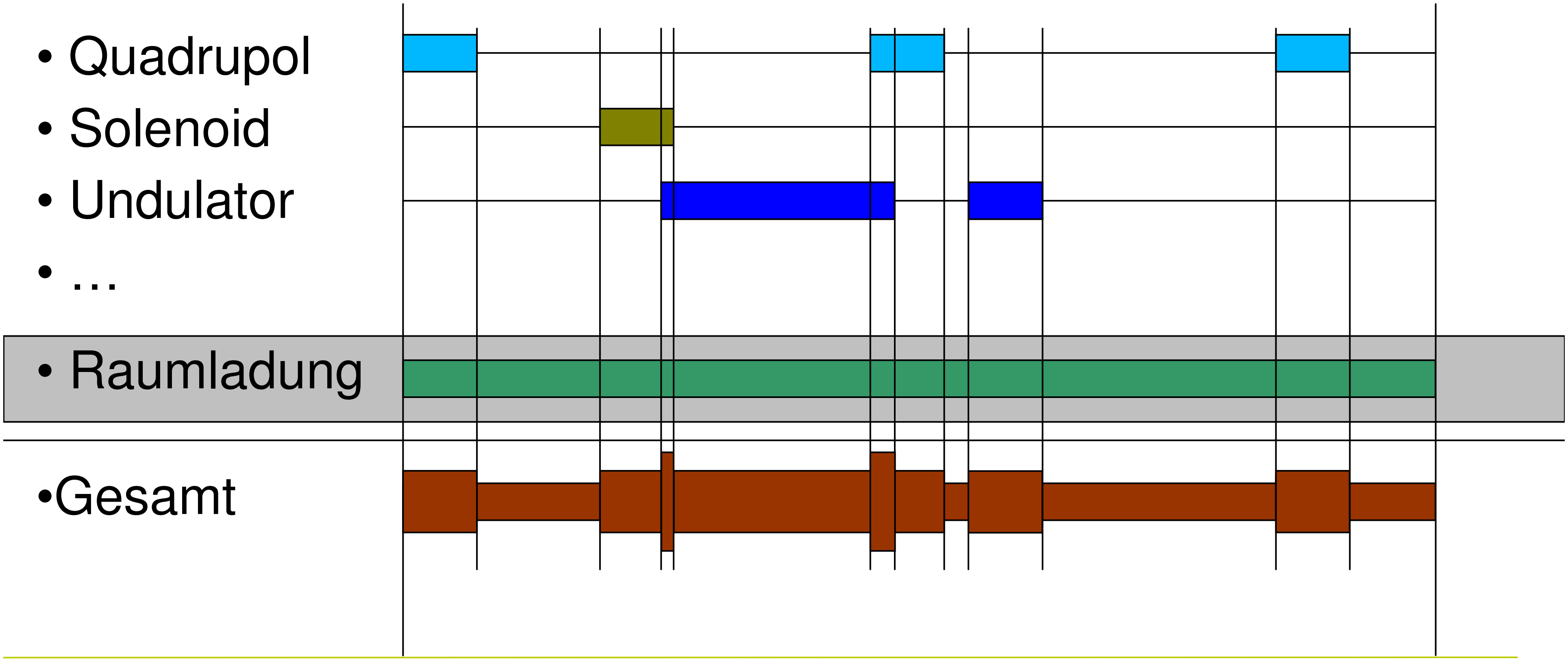


- Quadrupol
- Solenoid
- Undulator
- …

•Gesamt

Genesis 1.3 – Optikberechnung

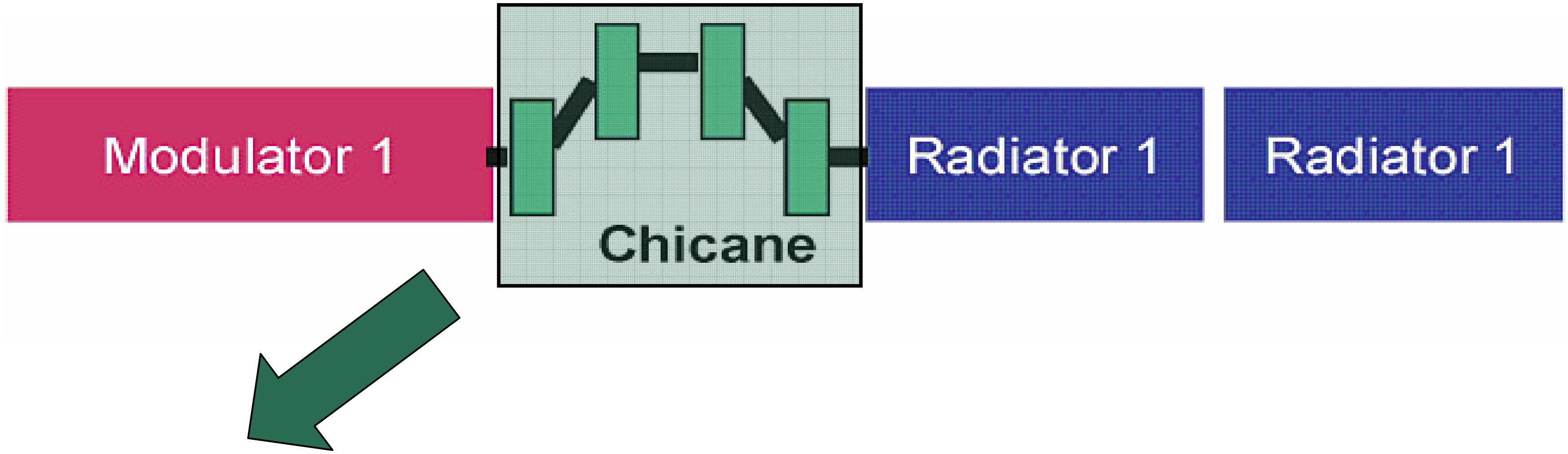
`track.f`



- Quadrupol
- Solenoid
- Undulator
- ...
- Raumladung

•Gesamt

Grenzen der Optik Genesis1.3



Wichtig für SEED-/HGHG-FEL Simulationen.

Erzeugung der Dichtemodulation durch R_{56}

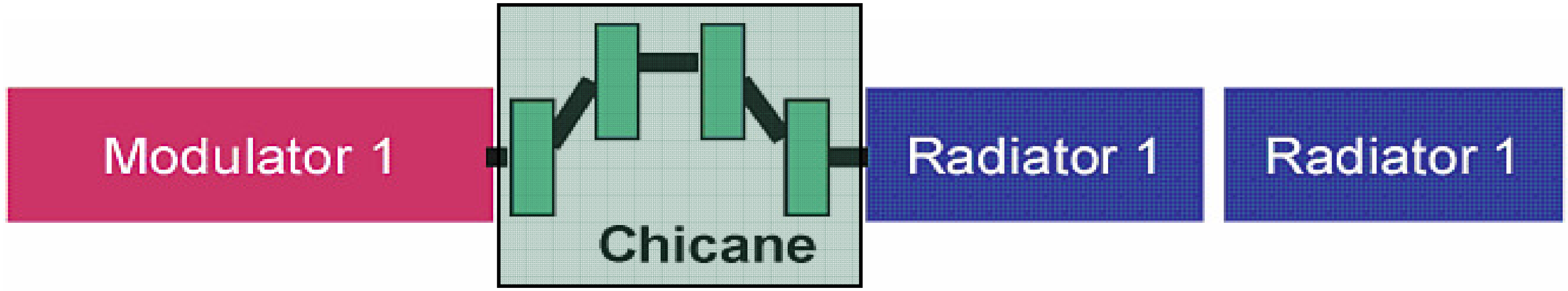
$$R_{56} = \delta l\ (\Delta p/p)$$

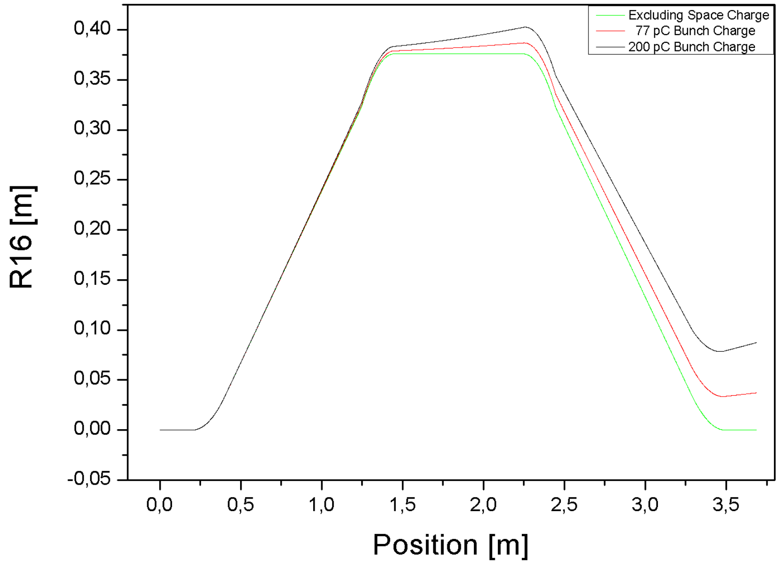
Bisher: Chicane = C-Chicane*

Implementierung über Transfermatrix

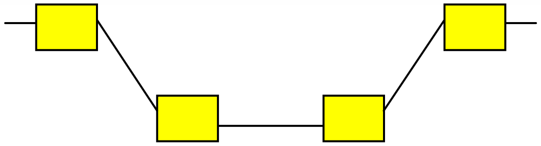
* feste Konfiguration

Grenzen der Optik Genesis1.3

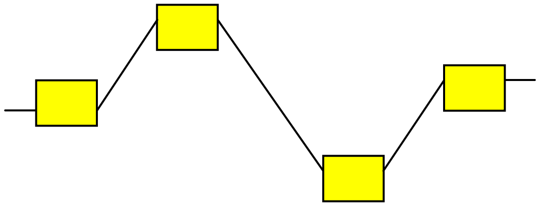




C-Chicane



S-Chicane

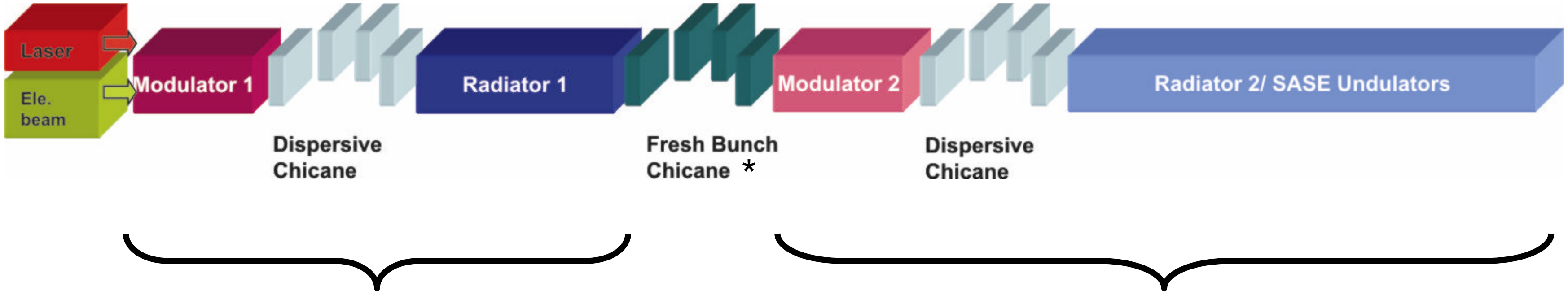


...

→ **P12**

FEL – Simulation

FLASH II / STARS:



STAGE 1

STAGE 2

200nm SEED → 40nm Abstrahlung 40nm SEED → 8nm **FLASH II** (1200MeV)

800nm SEED → 200nm Abstrahlung 200nm SEED → 40nm **STARS** (325MeV)

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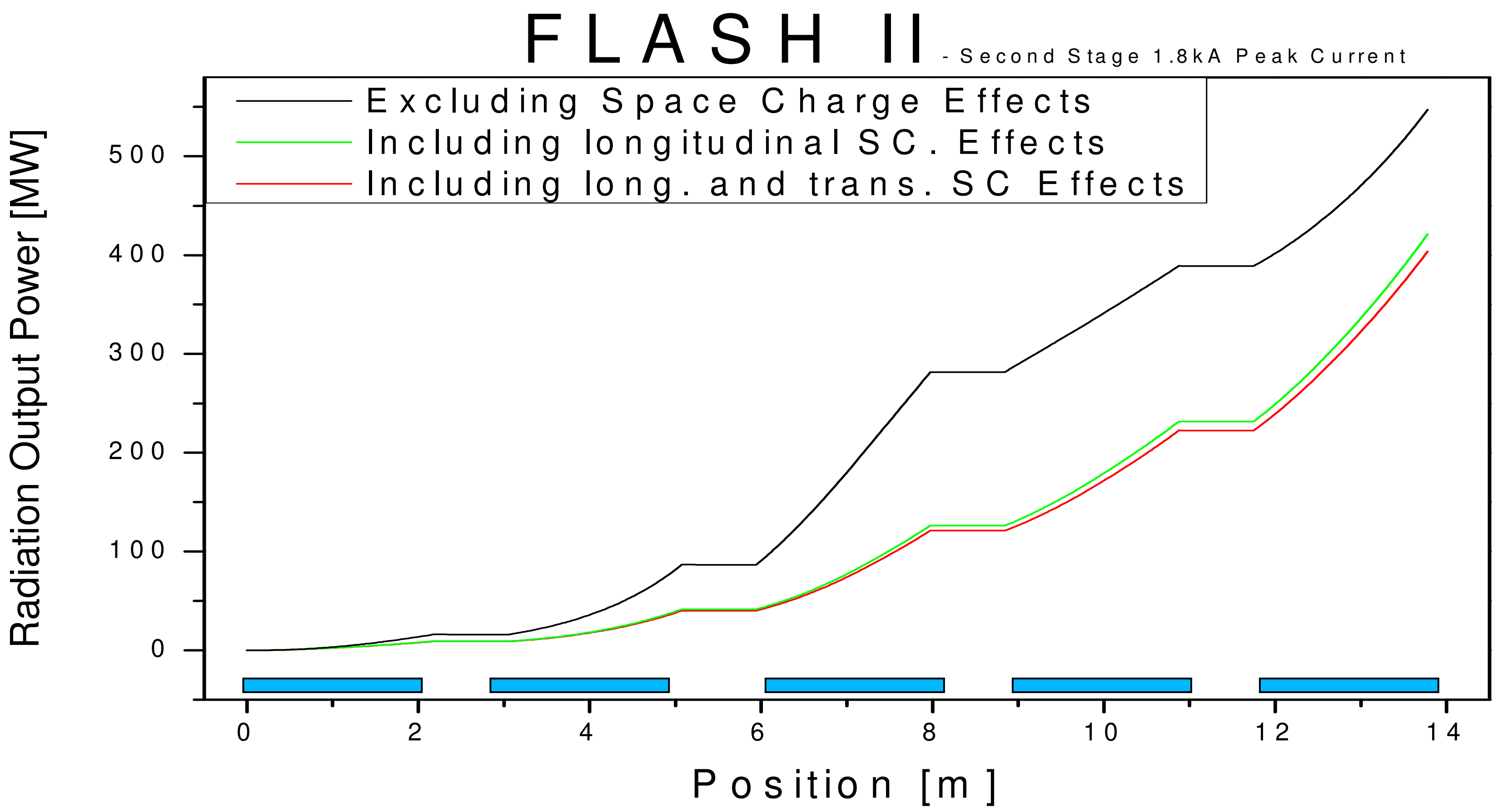
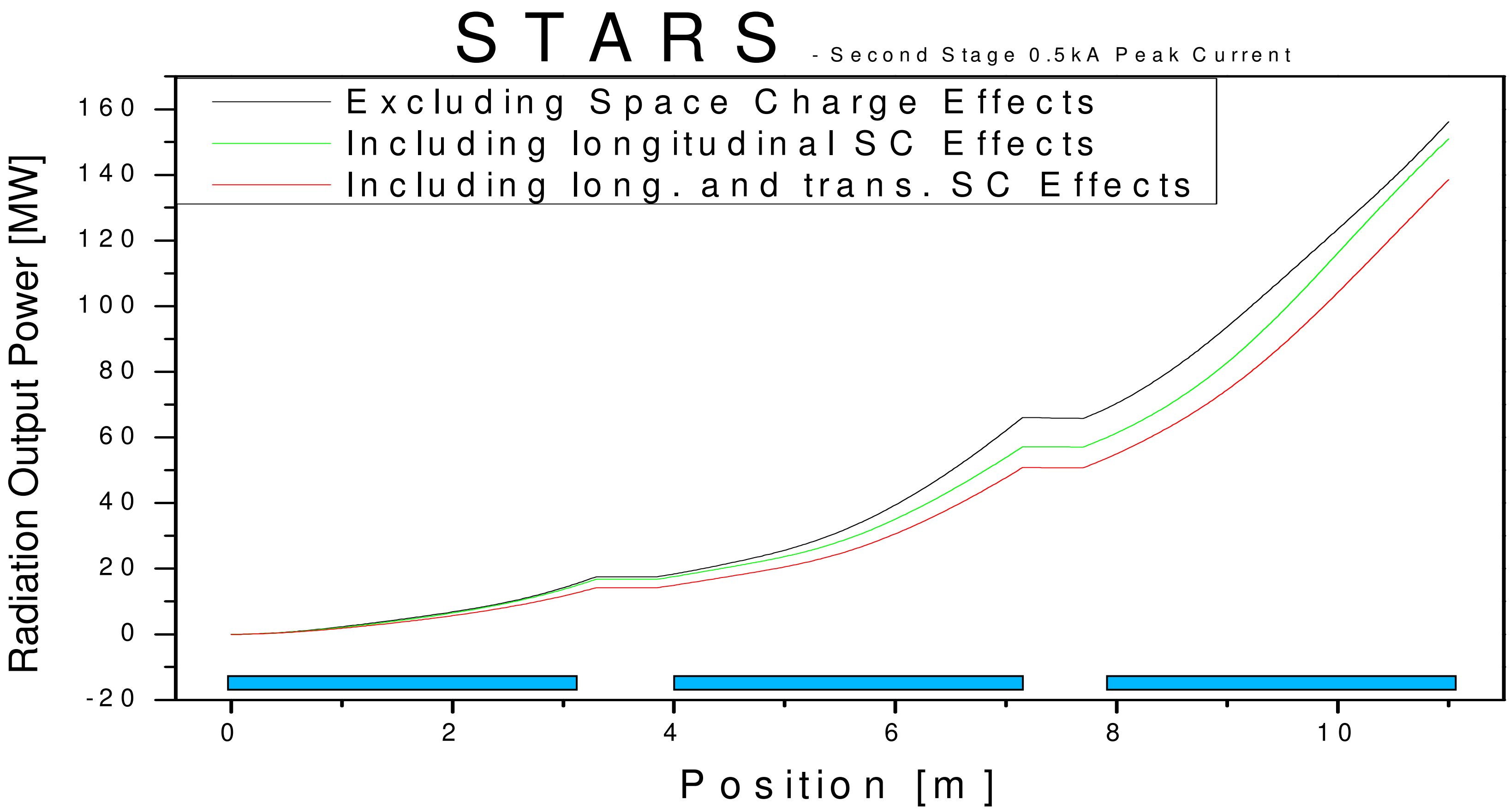
*„High-gain harmonic generation of soft X-rays with the ‚fresh bunch' technique", Li-Hua Yu, NIM A393(1997)

FEL – Simulation I



Bunch charge	1nC	1nC
Peak current	1.8kA	0.5kA
λ_{res}	8 nm	40nm
Energy	1.175GeV (2300γ)	325MeV (636γ)

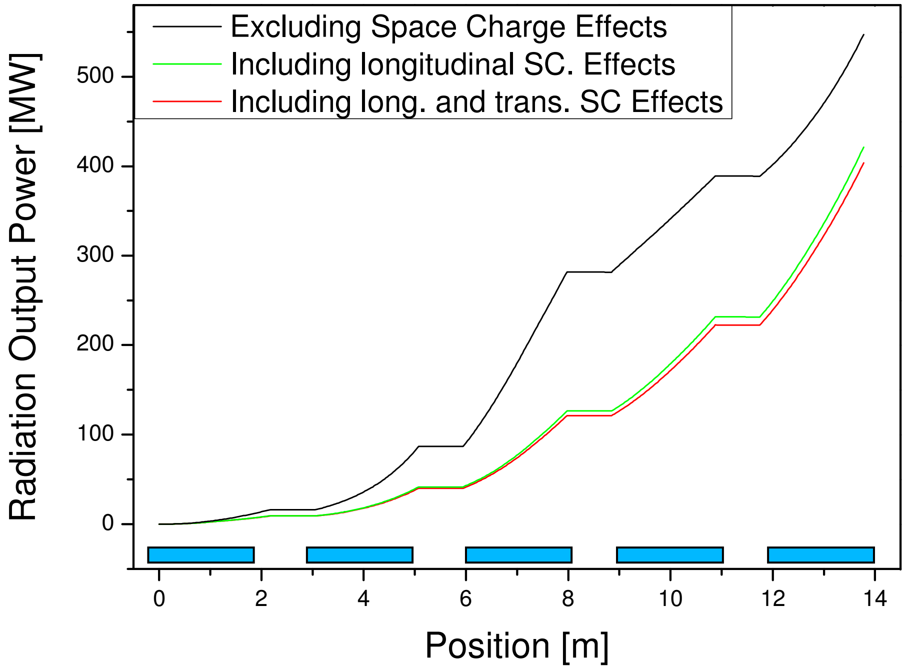
FEL – Simulation II



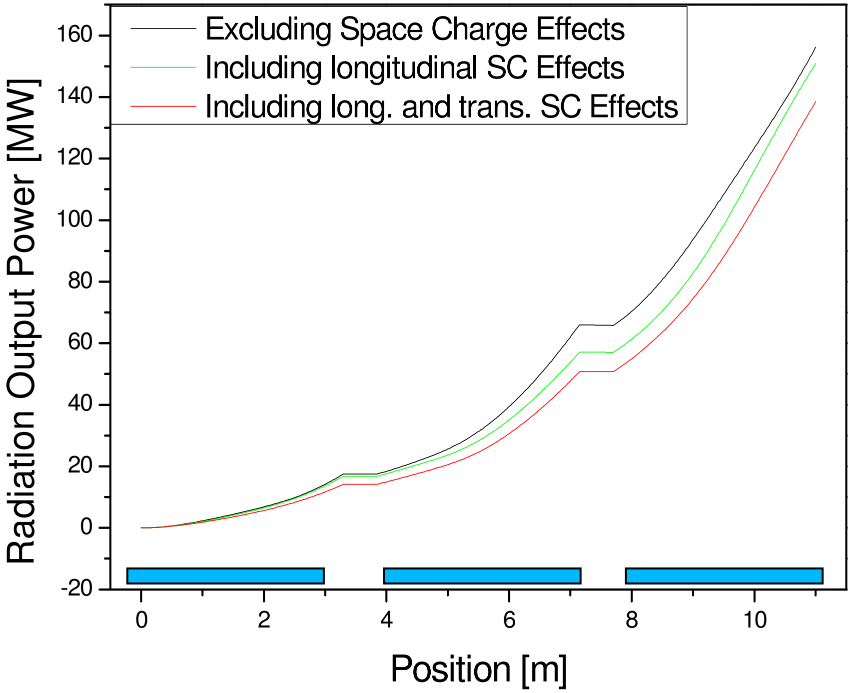
Bunch charge	1nC	1nC
Peak current	1.8kA	0.5kA
λ_{res}	8 nm	40nm
Energy	1.175GeV (2300γ)	325MeV (636γ)

FEL – Simulation III

FLASH II - Second Stage 1.8kA Peak Current

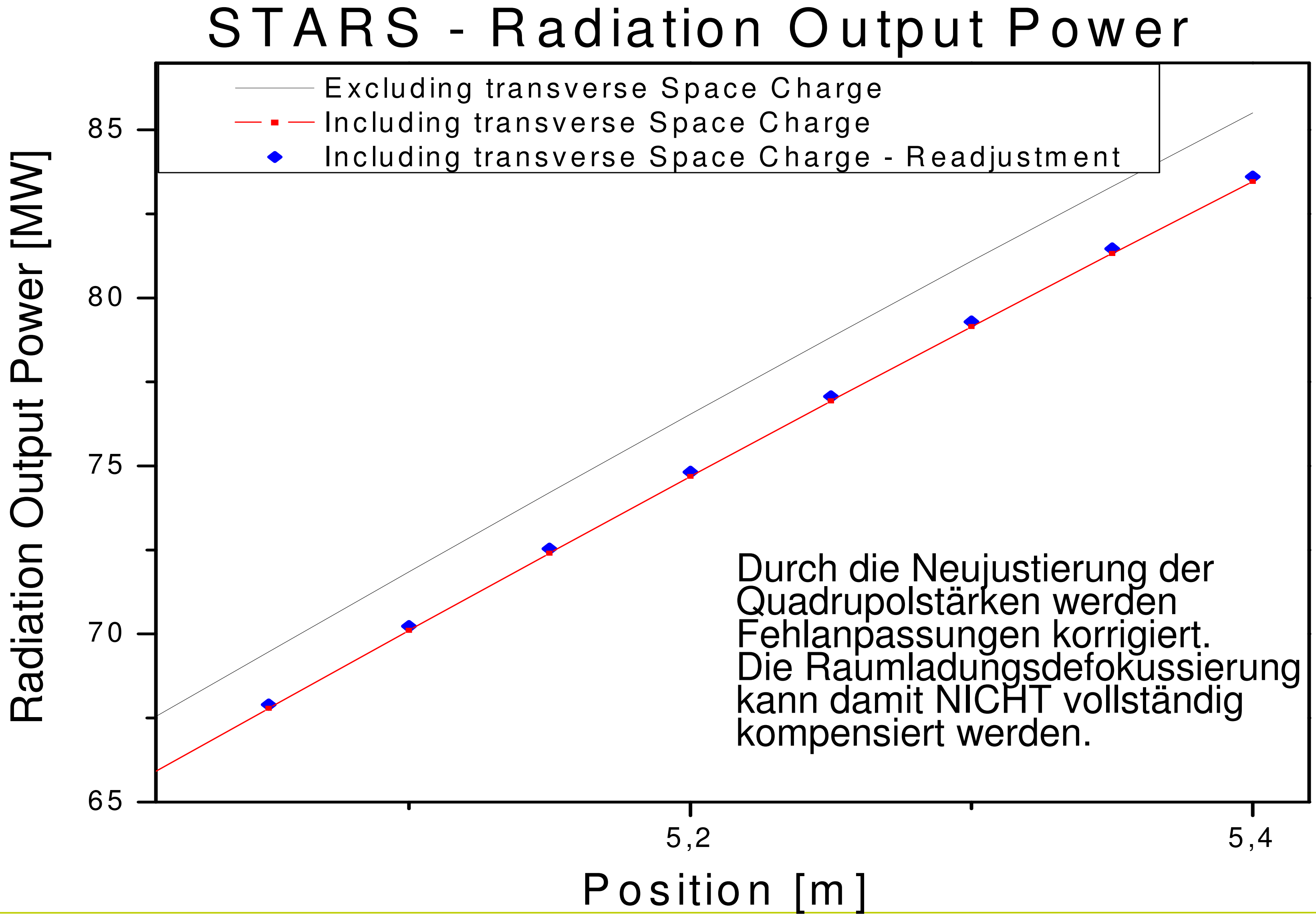


STARS - Second Stage 0.5kA Peak Current



Bunch charge	1nC	1nC
Peak current	1.8kA	0.5kA
λ_{res}	8 nm	40nm
Energy	1.175GeV (2300γ)	325MeV (636γ)

Optimierung der Quadrupolstärke



Durch die Neujustierung der Quadrupolstärken werden Fehlanpassungen korrigiert.
Die Raumladungsdefokussierung kann damit NICHT vollständig kompensiert werden.

First Stage-Radiator

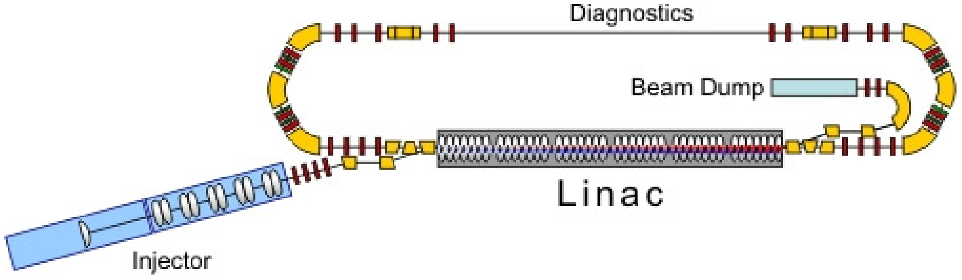
Zusammenfassung

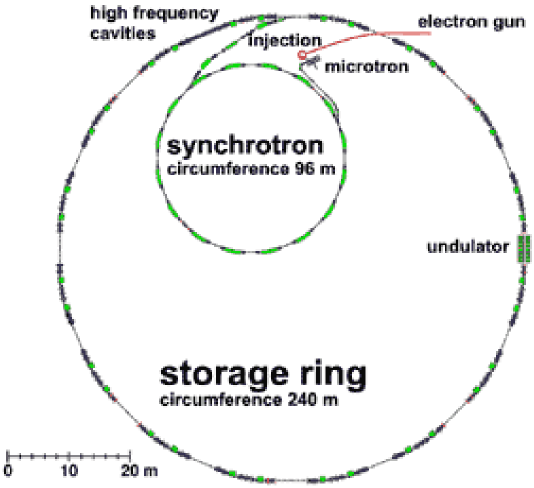
- Bunchparameter sind sehr wichtig für FEL-Prozess
  → Raumladung ändert Buncheigenschaften
- HGHG-FELs besonders sensible auf Raumladung
- Raumladung koppelt Lattice-Eigenschaften mit Bunch-Eigenschaften
- Raumladungsbedingte Fehlanpassungen von Lattices
- Keine vollständige Kompensation der Lichtleistungsverluste durch Readjustment

→Raumladung muss in der Auslegung von Lattices und Abschätzungen von FEL-Performanzes berücksichtigt werden!!

Ausblick

P12-Anwendungsbeispiele:





- Implementierung von longitudinaler Raumladung in P12
- Verbesserung der Undulatormodelle
- Neue magnetoptische Elemente

ENDE