Simulation of High Current Linacs

R. Tiede

April 28’th, 2009

430. WE-HERAEUS-SEMINAR
“Accelerators and Detectors at the Technology Frontier”

Outline

- The LORASR beam dynamics code
  - ● A new space charge routine based on a PIC 3D FFT algorithm
  - ● Tools for loss profile and machine error study calculations
- Description of the 'Combined Zero-Degree Structure' ('Kombinierte Null Grad Struktur – KONUS') concept
- KONUS design examples
- Summary and outlook

LORASR Code Features - Overview

Longitudinale und **ra**diale **S**trahldynamikrechnungen mit **R**aumladung

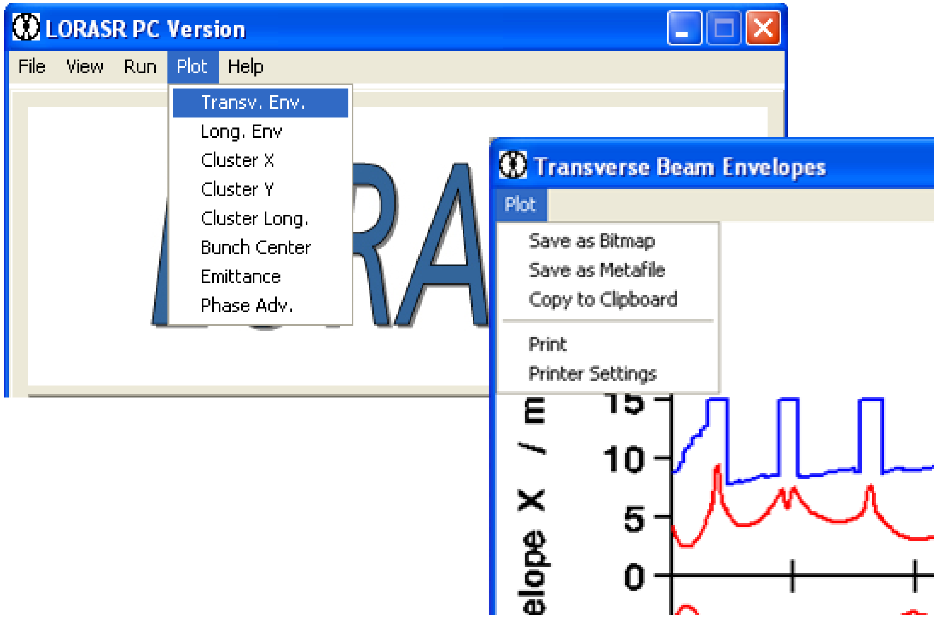
Longitudinal And Radial Beam Dynamics Calculations including Space Charge

- General :
  - **Multi particle tracking along drift tube sections, quadrupole lenses, short RFQ sections including fringe fields and dipole magnets.**
  - **Running on PC-Windows platforms (Lahey-Fujitsu Fortran 95).**

- Available Elements :

magnetic quadrupole lens
solenoid lens
dipole bending magnet
accelerating gap
RFQ section (constant rf phase, 'Superlens')
3D FFT space charge routine
error study routines

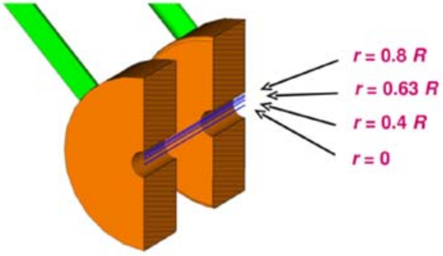
- GUI :



Accel. Gap Calculation Routine : Single Particle Tracking - 30 Steps Per Gap

E-field shape distributions for 10 gap geometries with different *g/Ø* ratios are stored as input parameter list.

“Thick” Alvarez-type



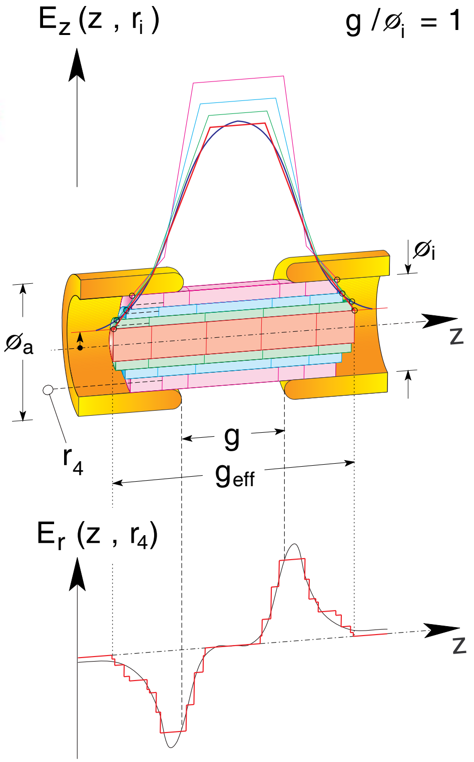
$$\vec{\nabla}\cdot\vec{E} = 0$$

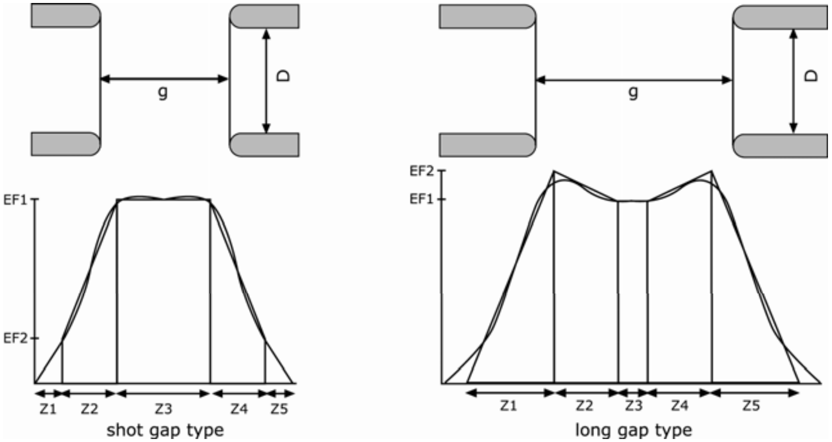
$$\frac{\partial E_r}{\partial r}+\frac{1}{r}E_r+\frac{\partial E_z}{\partial z}=0$$

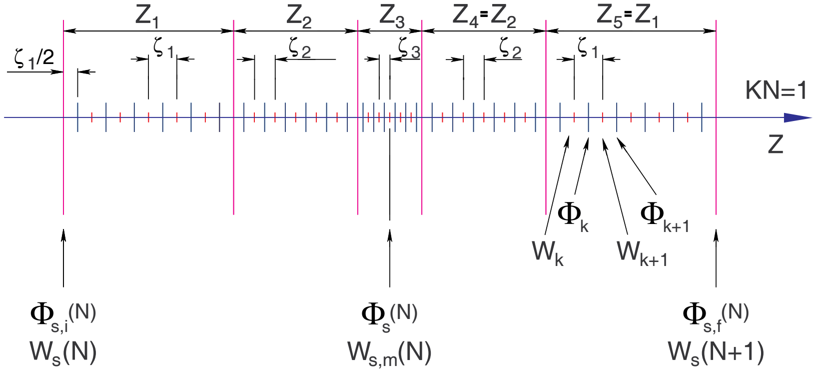
$$\Downarrow$$

$$\int_0^R \frac{d}{dr}\left(r\cdot E_r\right)dr = \int_0^R -r\,\frac{dE_z}{dz}\,dr$$

“Slim” H-mode type



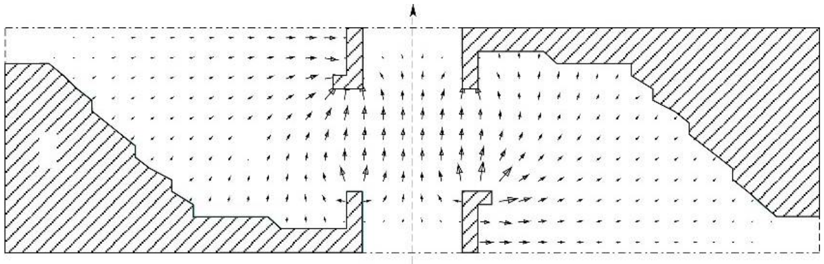


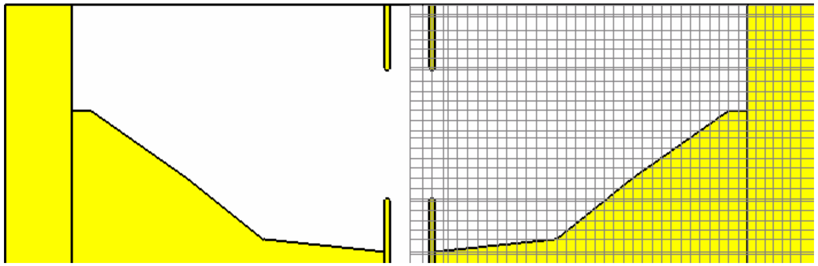


The evolution of the single particle coordinates x, x’, y, y’, ΔW, ΔΦ, is performed in a 30 step per gap procedure for 4 different radial zones. The field components at the particles positions are linearly interpolated from the stored fields at the adjacent radial zones.

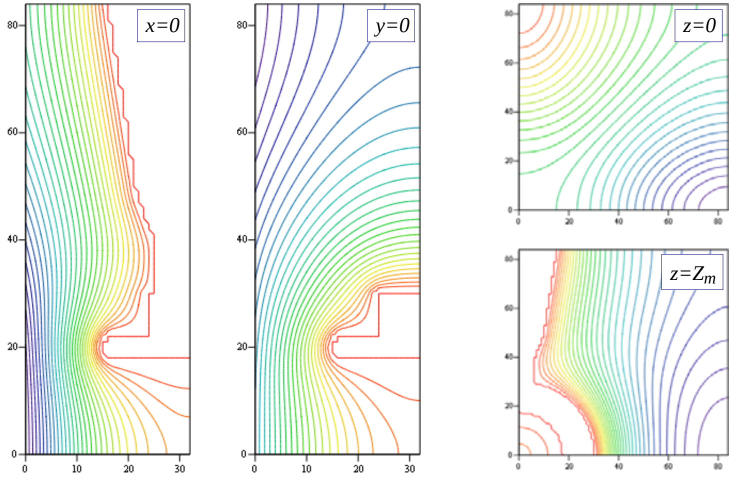
GAP Field Modelling : Upgrade Options

- **Read in the RF field of each cell, as generated by MICROWAVE STUDIO™, from an external file.**
  - **Accuracy (mesh resolution)?**





- **Consideration of dipole and quadrupole content of IH- and CH-gaps).**



Magnetic Quadrupole Lens

Hard edge approximation :

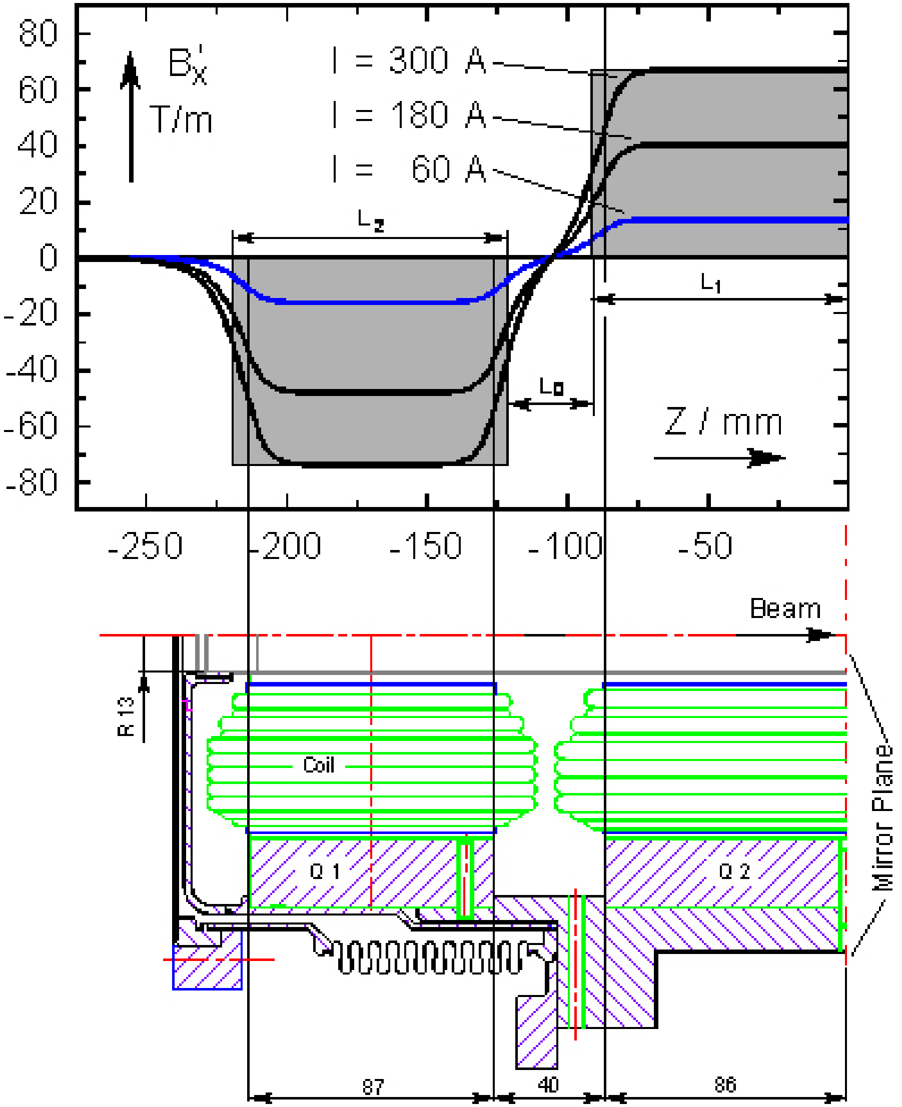
Focusing lens :

$$\begin{pmatrix} X_2 \\ X_2' \end{pmatrix} = \begin{pmatrix} \cos kL & \frac{1}{k}\sin kL \\ -k\sin kL & \cos kL \end{pmatrix} \begin{pmatrix} X_1 \\ X_1' \end{pmatrix} \;;$$

Defocusing lens :

$$\begin{pmatrix} X_2 \\ X_2' \end{pmatrix} = \begin{pmatrix} \cosh kL & \frac{1}{k}\sinh kL \\ k\cdot\sinh kL & \cosh kL \end{pmatrix} \begin{pmatrix} X_1 \\ X_1' \end{pmatrix};$$

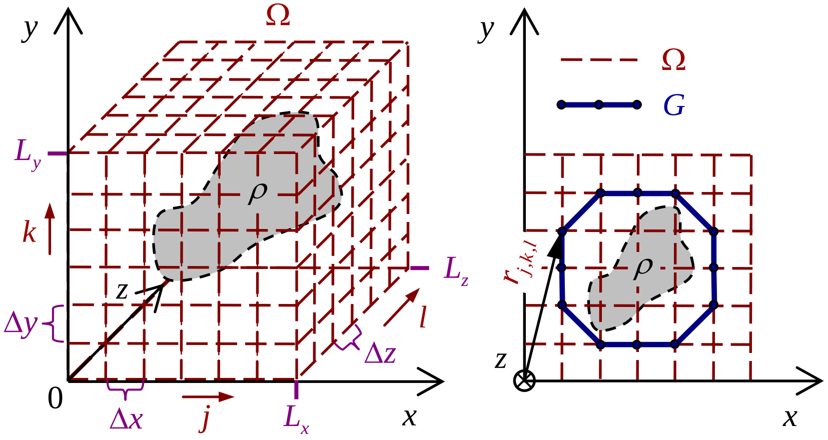
$$\mathrm{k} = \left(\frac{q \cdot B' \cdot c}{\beta \cdot \gamma \cdot m_o} \right)^{1/2}$$



Space Charge Calculation by the "Particle-In-Cell" (PIC) Method

The Poisson equation is solved on the nodes of a Cartesian grid:

$$\Delta\varphi = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\varphi = -\frac{\rho}{\varepsilon_0} \quad on\ G \subseteq \Omega$$



$$r_{j,k,l} \equiv (x_j\ ;\ y_k\ ;\ z_l)$$

$$\rho_{j,k,l} \equiv \rho(r_{j,k,l})$$

$$\varphi_{j,k,l} \equiv \varphi(r_{j,k,l})$$

Boundary condition options:

$a) \quad \varphi = 0 \quad on\ \partial\Omega$

$b) \quad \varphi = 0 \quad on\ \partial G$

$c) \quad \varphi = 0 \quad at\ R \to \infty$

Main Steps of a Particle-In-Cell (PIC) Algorithm

- **Charge discretization on a 3D Cartesian grid and calculation of the charge density distribution** $\rho_{j,k,l}$

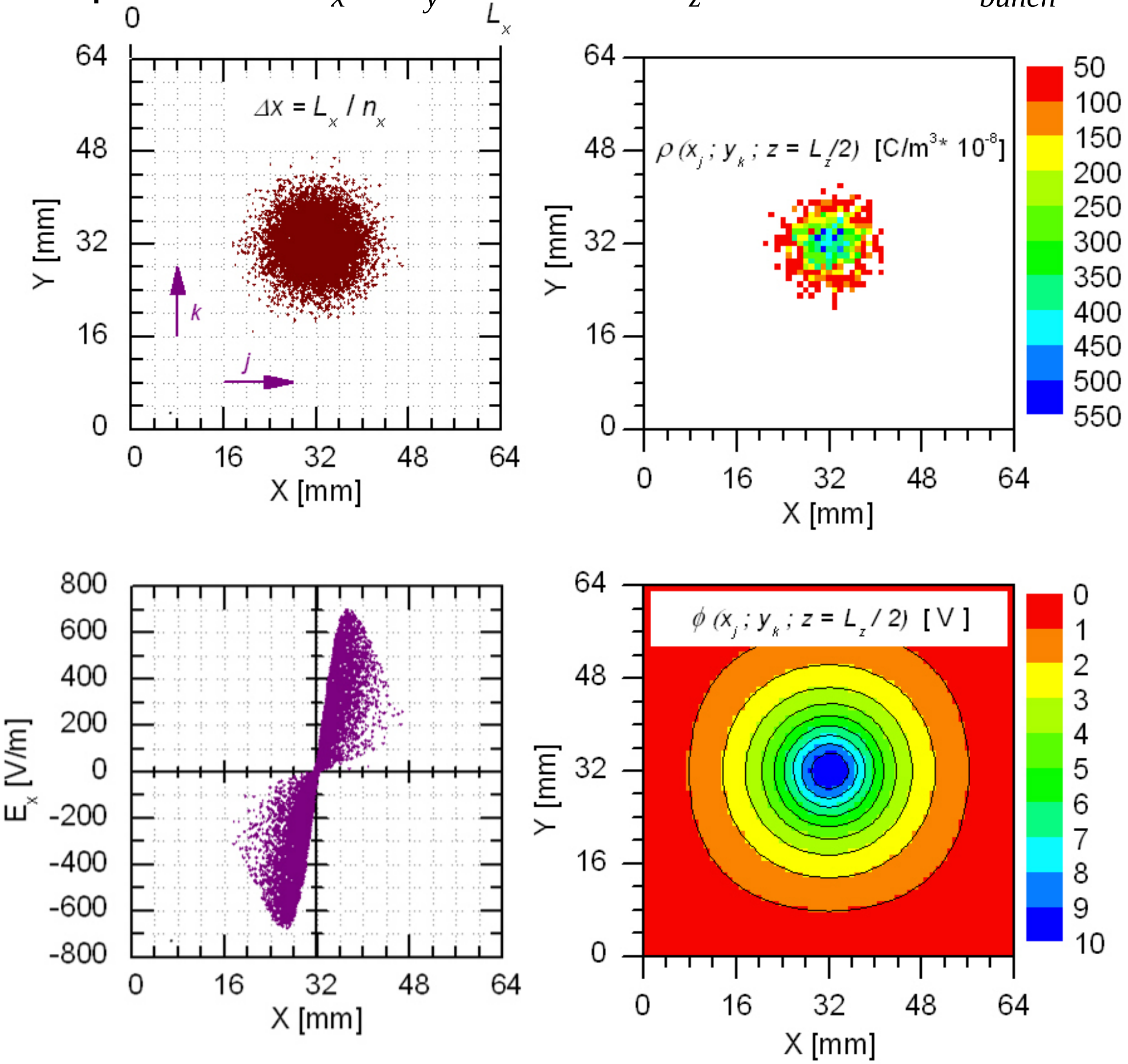
- **Solving the Poisson equation** $\Delta\varphi = -\rho / \varepsilon_0$ **on the grid**

- **Calculation of the electric field components on the grid from** $\vec{E} = -grad\ \varphi$

- **Interpolation of the grid field values to the exact position of each macro particle.**

Main Steps of a Particle-In-Cell (PIC) Algorithm, Example

Gauß distr., 10^4 particles , $L_x = L_y = 64$ mm, $L_z = 184$ mm , $I_{bunch} = 1$ mA $^{238}\mathrm{U}^{28+}$



Computation Complexity of a PIC FFT-based Algorithm

1.) **Grid charge discretization** ($O(N_P) + O(N_G)$)

2.) **Solving the Poisson equation** ($O(N_G \cdot \log_2 N_G)$)

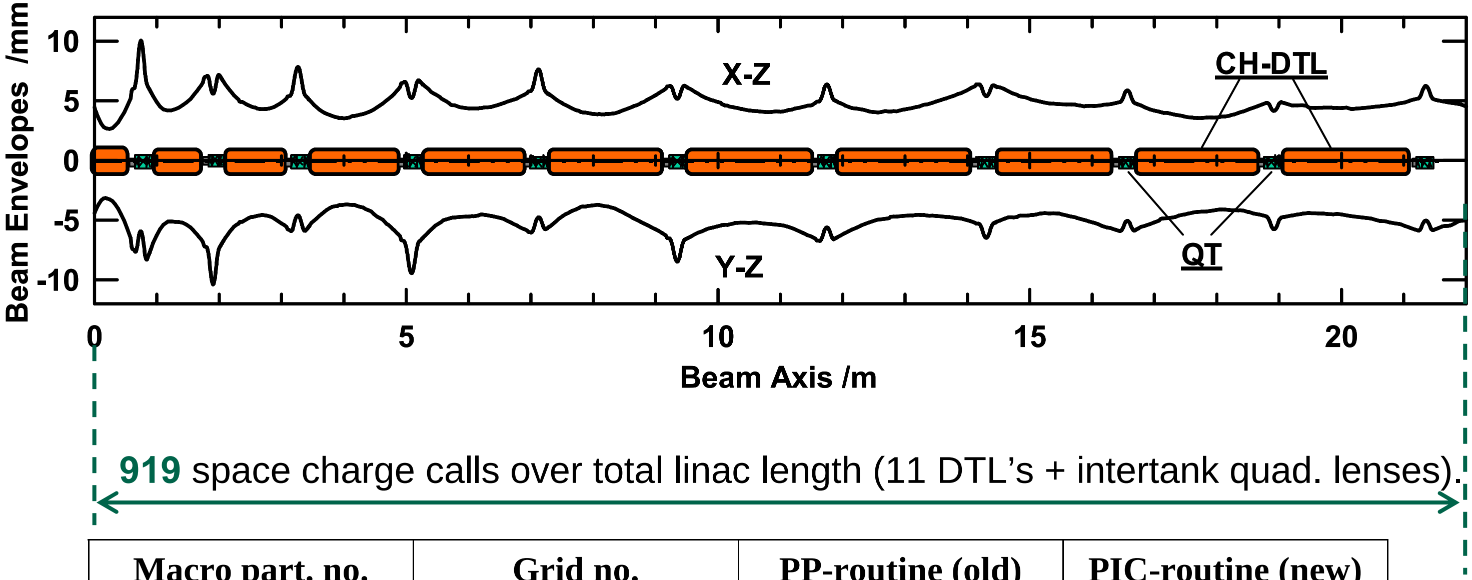
3.) **Calculation of the grid $\vec{E}$-field components** ($O(N_G)$)

4.) **Interpolation of the $\vec{E}$-field to the particle positions** ($O(N_P)$)

Number of operations : ~ ($N_{\text{particles}} + N_{\text{meshpoints}} \times \log_2 N_{\text{meshpoints}}$)

Benchmarking of the New FFT Algorithm

Example: GSI Proton Linac preliminary design, LORASR Run on a 733 MHz, Intel PIII PC



919 space charge calls over total linac length (11 DTL's + intertank quad. lenses).

Macro part. no. N_P	Grid no. N_G	PP-routine (old) CPU time / call	PIC-routine (new) CPU time / call
2 000	32 768 (32×32×32)	1.307 s	0.103 s
10 000	32 768 (32×32×32)	34 s	0.294 s
100 000	262 144 (64×64×64)	3 500 s (58 min 20 s)	3.1 s
1 000 000	2 097 152 (128×128×128)	350 000 s (4 d 1 h 13 min)	28.8 s

Error Study Tools for LORASR: Classification of Error Types

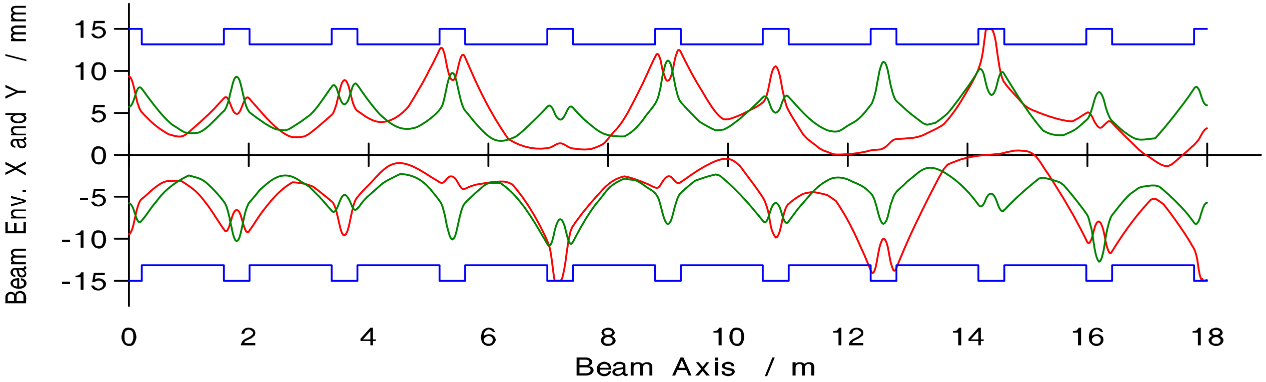
Static errors:

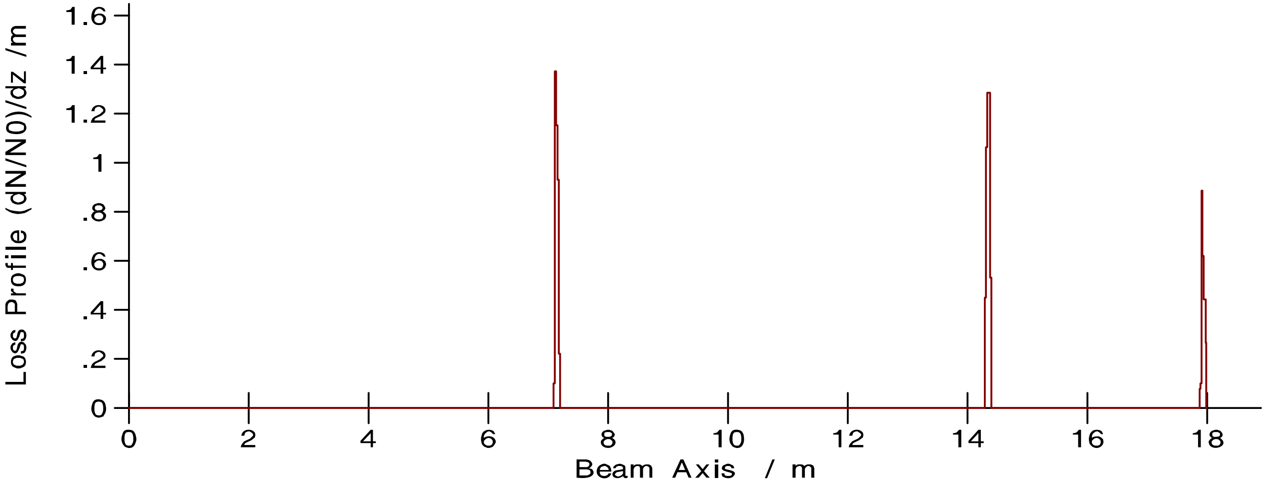
- Appear during design and running in phase. Can be detected and cured.
- Examples: quadrupole, cavity, drift tube misalignment,
  manufacturing errors (geom. lengths),
  field-flatness, quadrupole gradient errors.

Dynamic errors:

- Appear during operation. Are time-dependent. Remain often uncorrected.
- Examples: rf source instabilities (amplitude, phase),
  mechanical vibrations,
  transient beam loading.

LORASR Error Studies Analysis Tools
Loss Profile for Single Runs

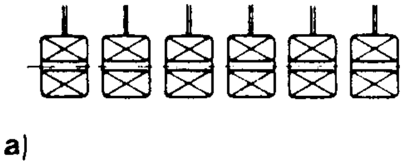




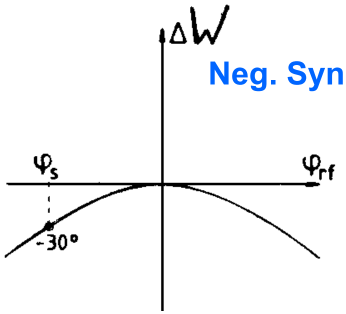
KONUS Concept

- “Standard” linac design (up to ≈ 100 MeV) : **Alvarez** DTL + **FODO** beam dynamics.

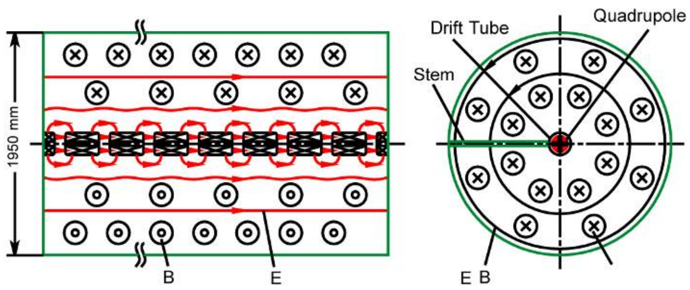
FODO



Neg. Synchr. Phase



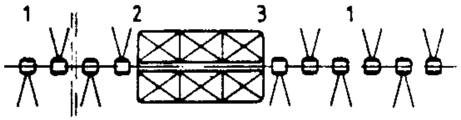
ALVAREZ - Cavity , E_{010}, 108 MHz



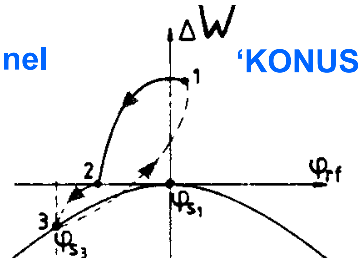
Alternative :

- H-Type DTL (**IH** or **CH**) and **KONUS** beam dynamics,
  each lattice period divided into 3 regions with separated tasks:
  - **Main acceleration** at Φ_s = 0°, by a multi-gap structure **(1).**
  - **Transverse focusing** by a **quadrupole triplet or solenoid (2).**
  - **Rebunching:** **2 - 7** drift tubes at Φ_s = **- 35°** , typically **(3).**

Quadrupole Triplet Channel

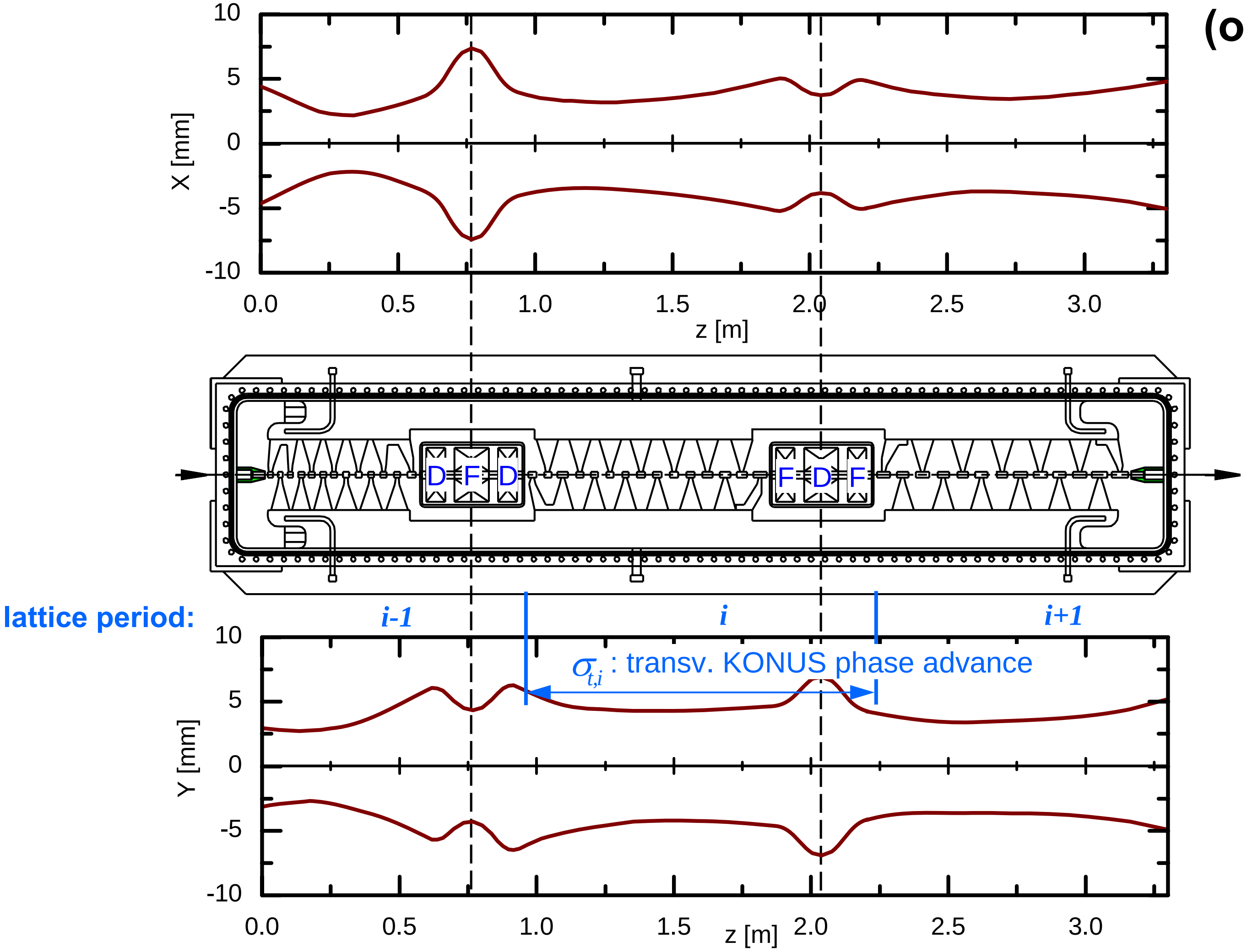


‘KONUS‘ – Combined 0° Structure



Transverse KONUS Beam Dynamics: Quadrupole Triplet Channel

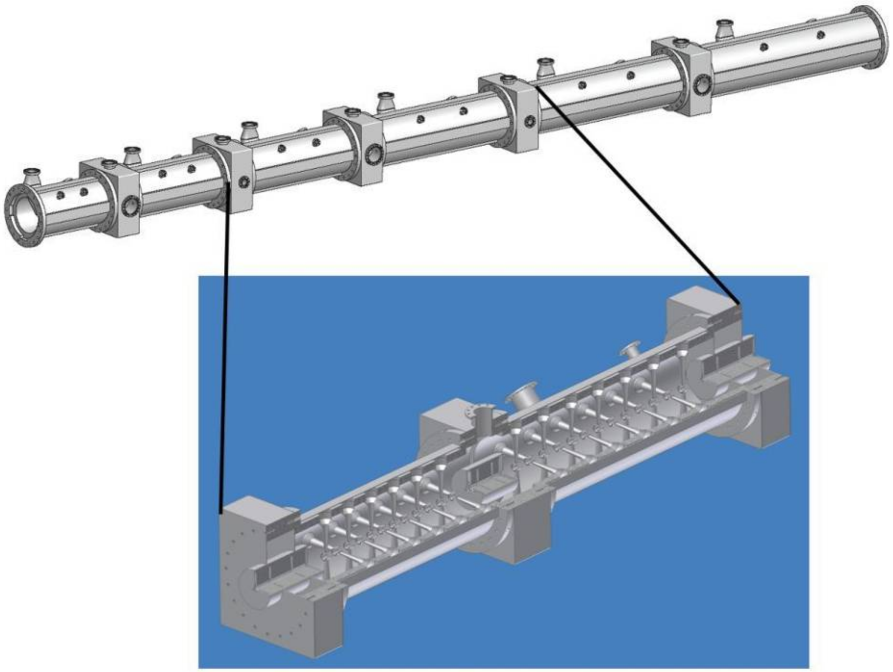
IH cavity of GSI HLI injector: first built cavity containing several KONUS periods (op. since 1991)

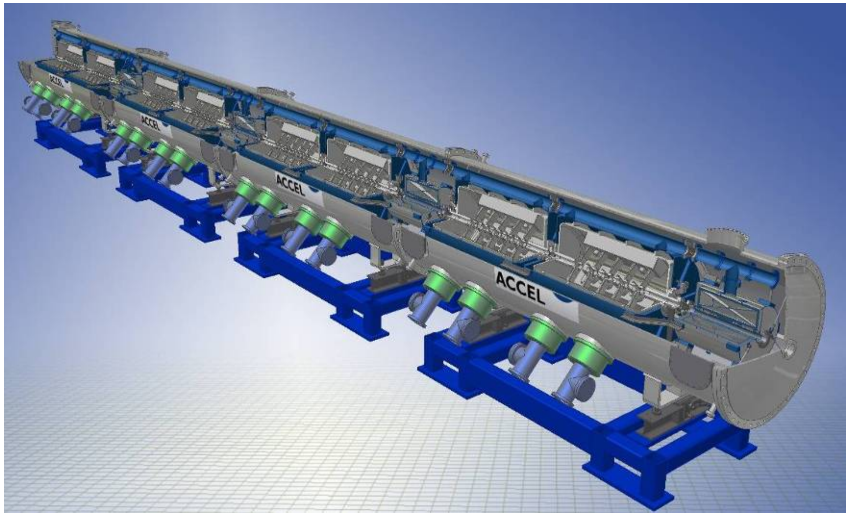


Applications

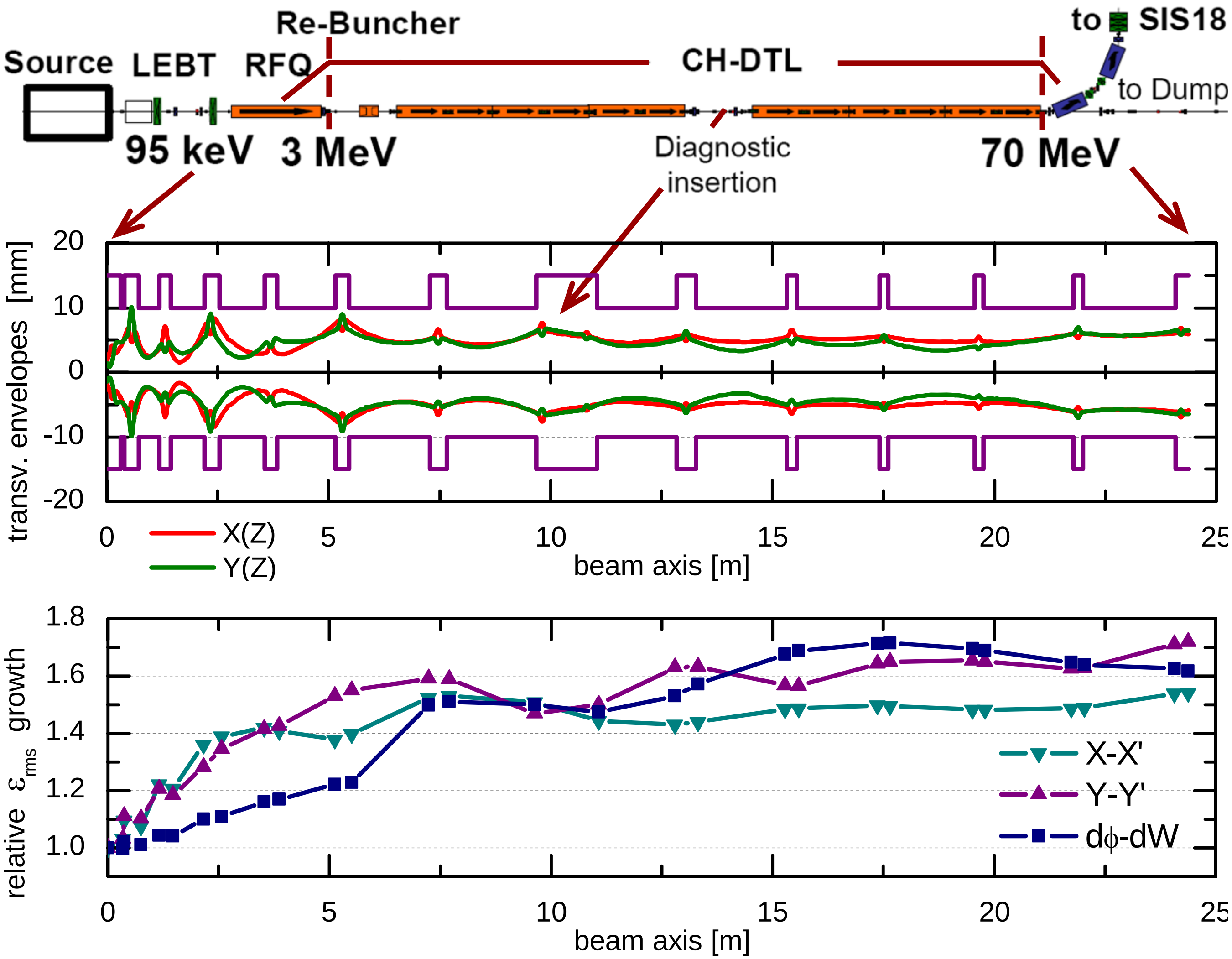
- **Proton Injector for the GSI FAIR Facility**
  325 MHz, 70 mA protons, 3-70 MeV, 0.1% duty cycle.

- **Superconducting CH-DTL section for IFMIF (IAP proposal)**
  175 MHz, 125 mA deuterons, 2.5 – 20 MeV/u, cw operation.



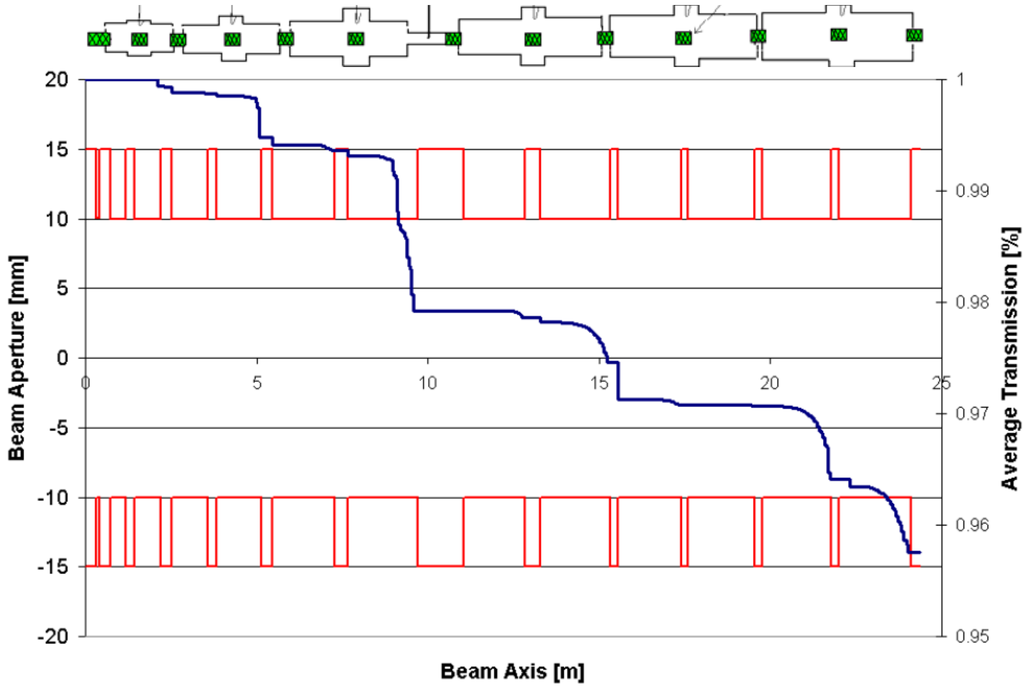


FAIR Proton Linac Design

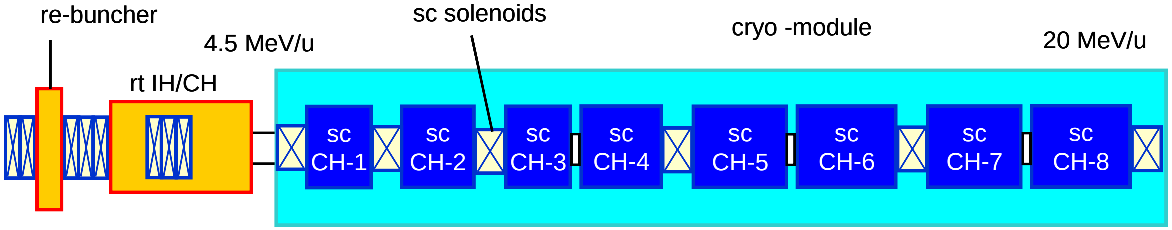


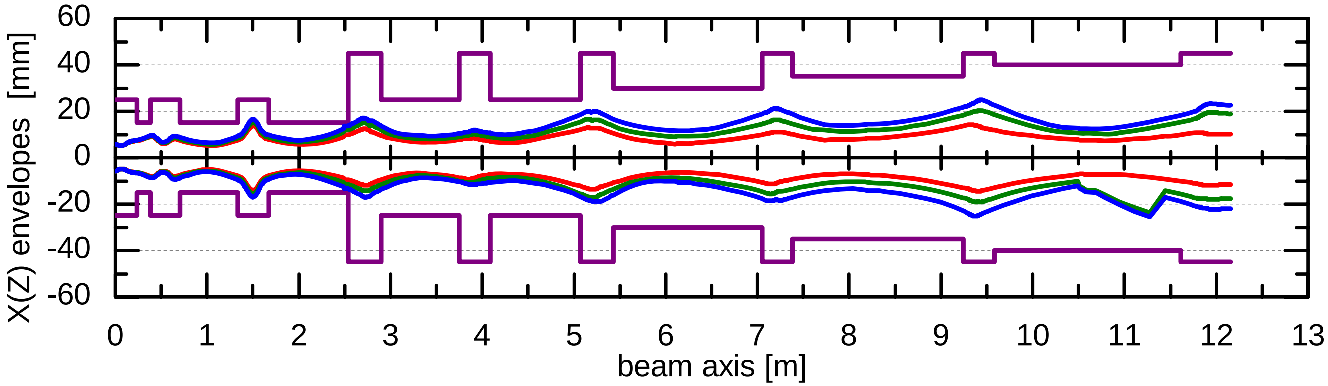
FAIR Proton Linac Design: Machine Error Studies

Error type	range
lens translations ΔX, ΔY [mm]	≤ 0.1
lens rotations $\Delta\phi_x$, $\Delta\phi_y$, $\Delta\phi_z$ [mrad]	$\lvert\Delta\phi_x\rvert \leq 1$ $\lvert\Delta\phi_y\rvert \leq 1$ $\lvert\Delta\phi_z\rvert \leq 5$
gap voltage variation $\Delta U_{i,j}$ [%]	$\lvert\Delta U_{gap}\rvert \leq 1.0$ $\lvert\Delta U_{tank}\rvert \leq 1.0$
tank rf phase oscillations $\Delta\phi_i$ [°]	≤ 1.0



S.C. CH-Linac for IFMIF



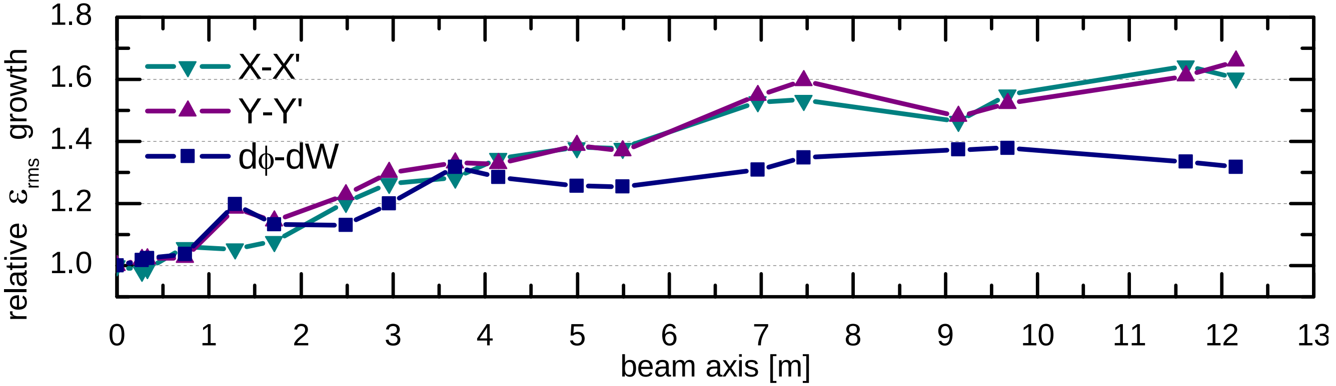


100% common beam envelopes of 100 runs, 10^6 particles each

red: nominal run

green: error settings 1

blue: error settings 2



Setting1	Setting2
$\Delta X_{lens} = \pm 0.1$ $\Delta Y_{lens} = \pm 0.1$	$\Delta X_{lens} = \pm 0.2$ $\Delta Y_{lens} = \pm 0.2$
$\Delta \varphi_x = \pm 1.5$ $\Delta \varphi_y = \pm 1.5$ $\Delta \varphi_z = \pm 2.5$	$\Delta \varphi_x = \pm 3.0$ $\Delta \varphi_y = \pm 3.0$ $\Delta \varphi_z = \pm 5.0$
$\Delta U_{gap} = \pm 5.0$ $\Delta U_{tank} = \pm 1.0$	$\Delta U_{gap} = \pm 5.0$ $\Delta U_{tank} = \pm 1.0$
$\Delta \Phi_{tank} = \pm 1.0$	$\Delta \Phi_{tank} = \pm 1.0$

Summary

- A new LORASR PIC 3D FFT space charge routine was developed and implemented to the LORASR code. It provides the ability to perform simulations with up to 1 million macroparticles routinely and within a reasonable computation time. This will give a strong impact to the design of high intensity linacs (e.g. GSI FAIR Facility Proton Linac, IAP-proposal for IFMIF Accelerator, …).

- Machine error settings routines and data analysis tools were developed and applied for error studies on the FAIR Proton Linac and the IAP IFMIF proposal.