T_R_A_C_K : an accurate ray-tracing tool for magnet development at PSI

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Beam Dynamics meets Magnets – II
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Motivation I

The ultimate magnet quality inspection tool is a particle beam.

Motivation II

- particle ray-tracing is integral part of magnet design and magnetic measurements analysis
- true particle ray-tracing (integration in space with the real non-parametrised fields)
- available option (VF Opera-3d) was restricted, inflexible and slow for ray-tracing
- own code allowing for future modifications and extensions at will and at no extra costs

History

- predecessor was a 2D programme (“gokart”)
- development started in 1987
- written in FORTRAN 77
- graphics are X11 based (PSI-GRAPHX package)
- original platform DEC VAX / VMS
- ported to Tru64 UNIX, Mac OS X and Linux

General description I

- based on the analytical solution of the EOM, not implementation of Runge-Kutta or any other numerical method
- integration accuracy depends only on the field accuracy
- originally designed for analysis of beam line magnets and parts of beam lines (Cartesian coordinate system)
- fully 3D, horizontal as well as vertical beam bending planes
- tracks single particles and full phase-space beam with outputs at any point along the beam

General description II

- magnetic fields are input – either calculated or measured fields on grid points
- electric fields added, allowing for analysis of magnetic separators or particle spin rotators
- implemented relativistic effect on particle mass
- time-harmonic varying field option added for analysis of cyclotrons
- built-in scripting language

Methodology I

$$\vec{F} = q \cdot \left(\vec{E} + \vec{v} \times \vec{B}\right)$$

equation of motion

$$\vec{F} = \tfrac{d}{dt}\vec{p} = \tfrac{d}{dt}\left(m \cdot \vec{v}\right) \approx m \tfrac{d}{dt}\vec{v}$$

assumption:
the particle mass does not change

$$\dot{v}_x = \tfrac{q}{m} \cdot \left(E_x + v_y \cdot B_z - v_z \cdot B_y\right)$$
$$\dot{v}_y = \tfrac{q}{m} \cdot \left(E_y + v_z \cdot B_x - v_x \cdot B_z\right)$$
$$\dot{v}_z = \tfrac{q}{m} \cdot \left(E_z + v_x \cdot B_y - v_y \cdot B_x\right)$$

set of partial differential equations

$$\vec{v}(t) = \vec{\psi}_1 + \vec{\psi}_2 \cdot t + \vec{\psi}_3 \cdot \cos(\omega \cdot t) + \vec{\psi}_4 \cdot \sin(\omega \cdot t)$$
$$\vec{\psi}_i = f\left(\tfrac{q}{m}, \vec{E}, \vec{v}(0), \vec{B}\right)$$
$$\omega = f\left(\tfrac{q}{m}, B\right)$$

assuming that the fields are constant
this can be solved analytically

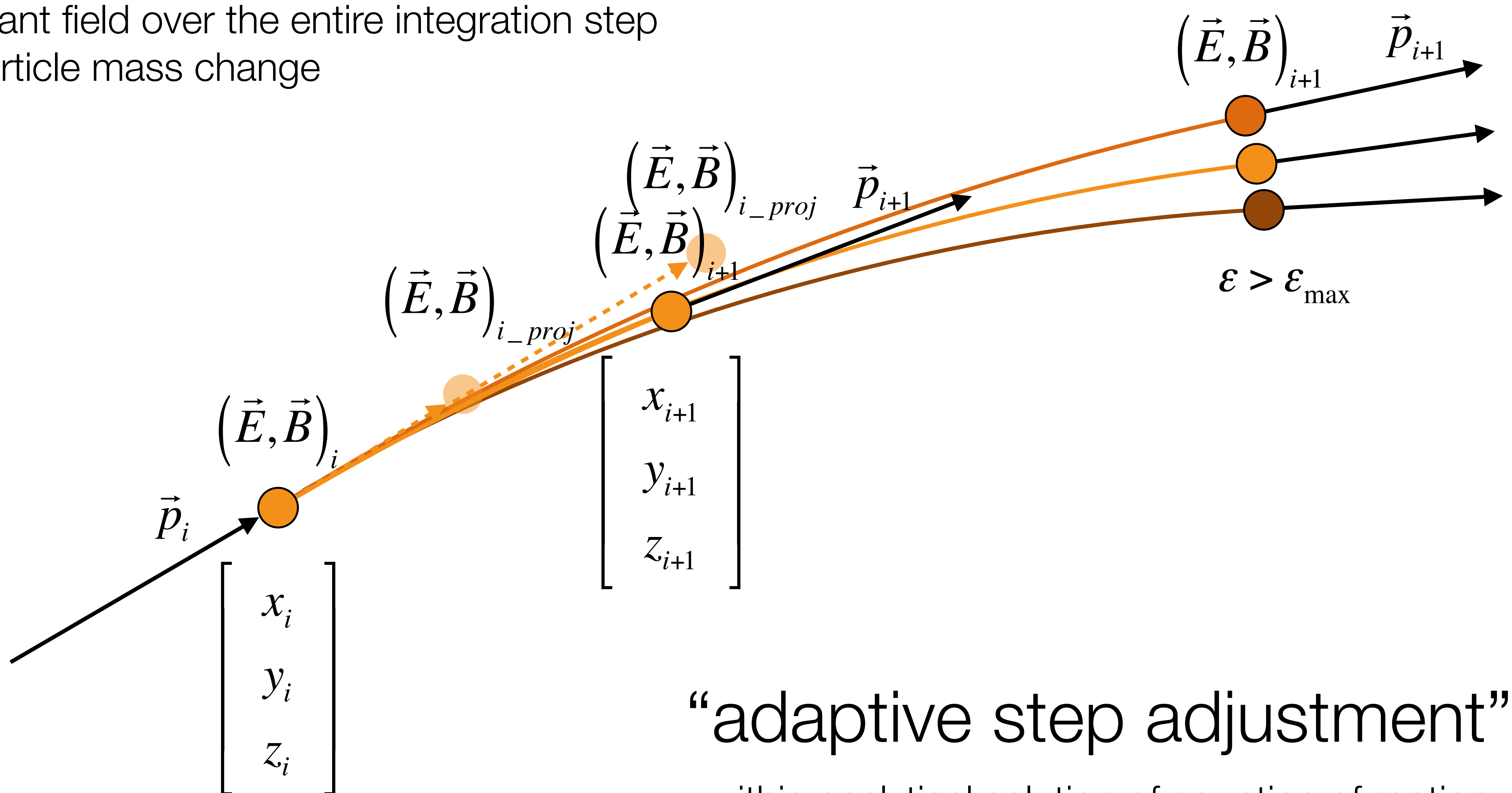
$$\vec{s}(t) = \int \vec{v}(t)dt$$

position in space is then exact

Methodology II

<u>assumptions</u>:

constant field over the entire integration step
no particle mass change

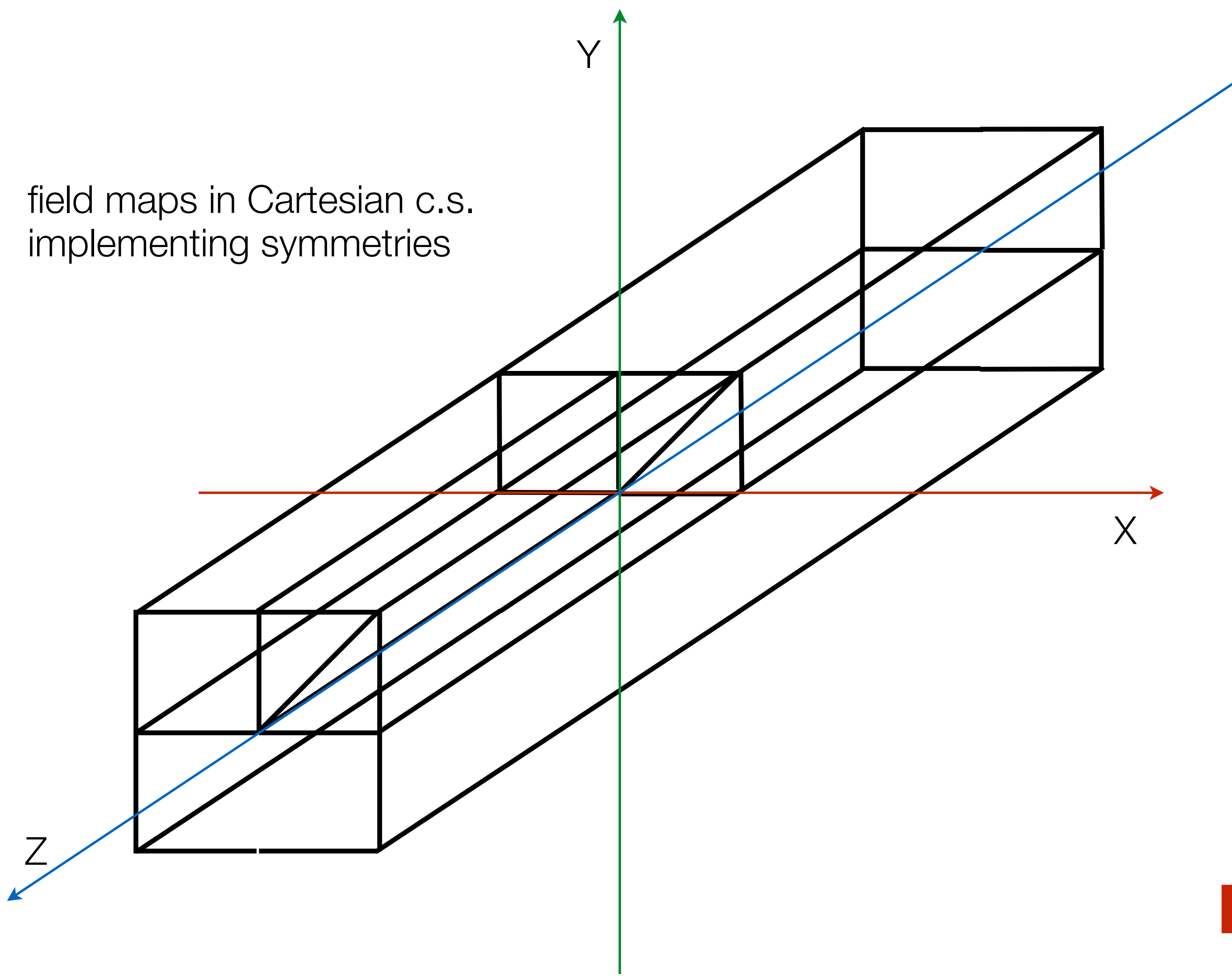


“adaptive step adjustment”

within analytical solution of equation of motion

Usage

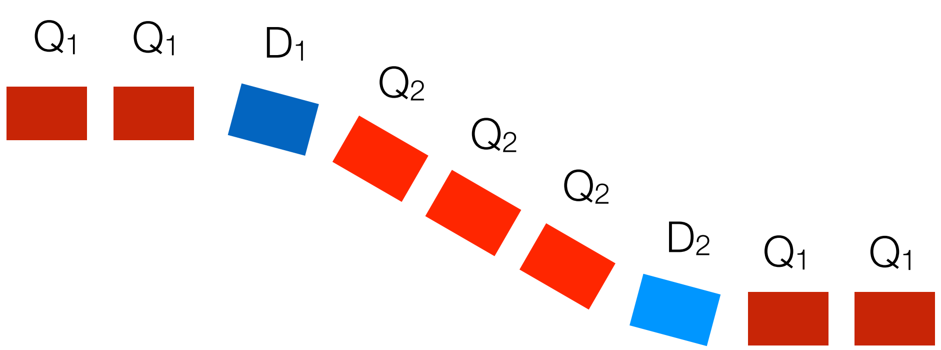
field maps in Cartesian c.s.
implementing symmetries



<u>building beam lines:</u>

- translation, rotation in 3D
- field strength adjustment

e.g. field maps: Q_1 , Q_2 , D_1 , D_2

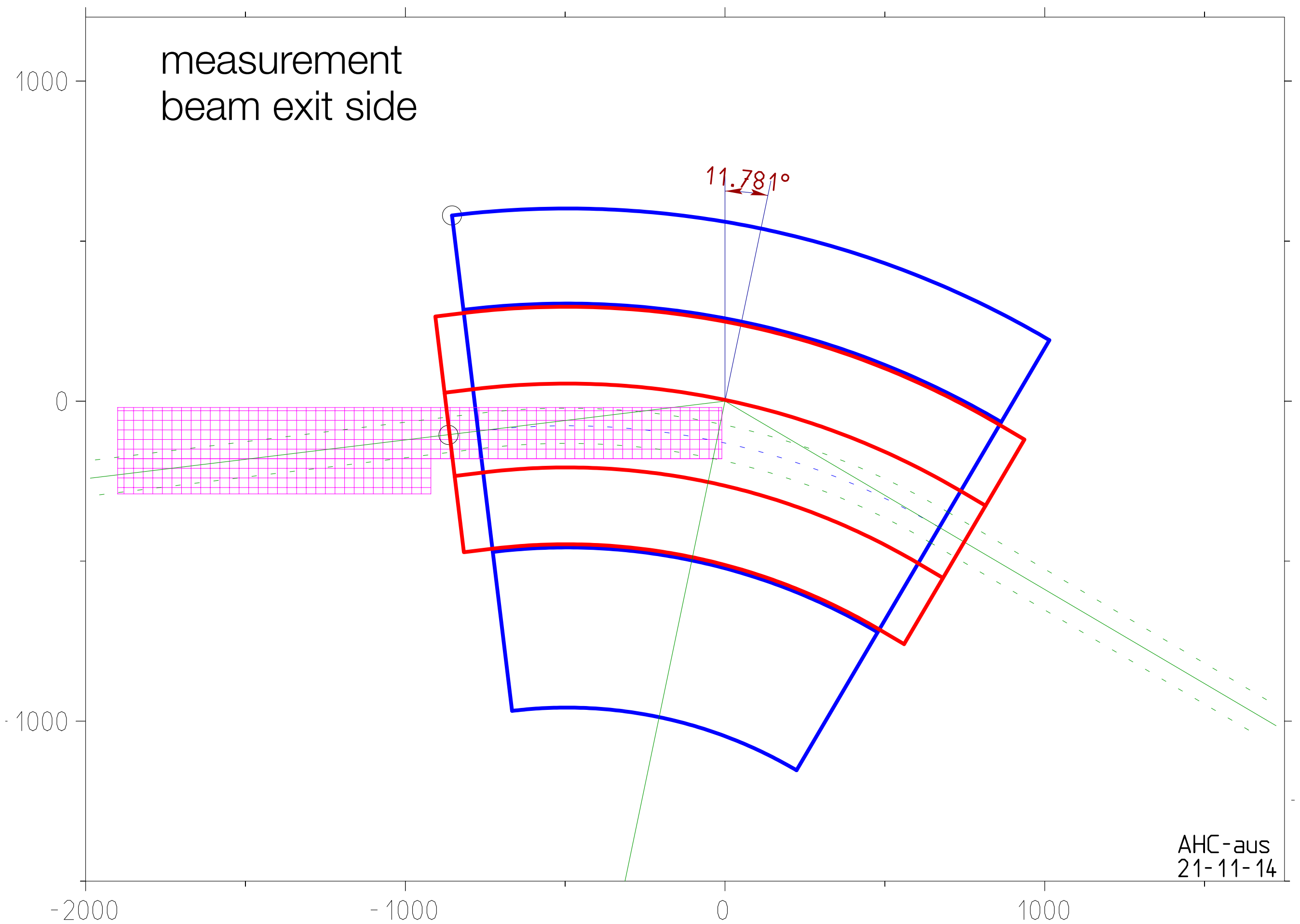


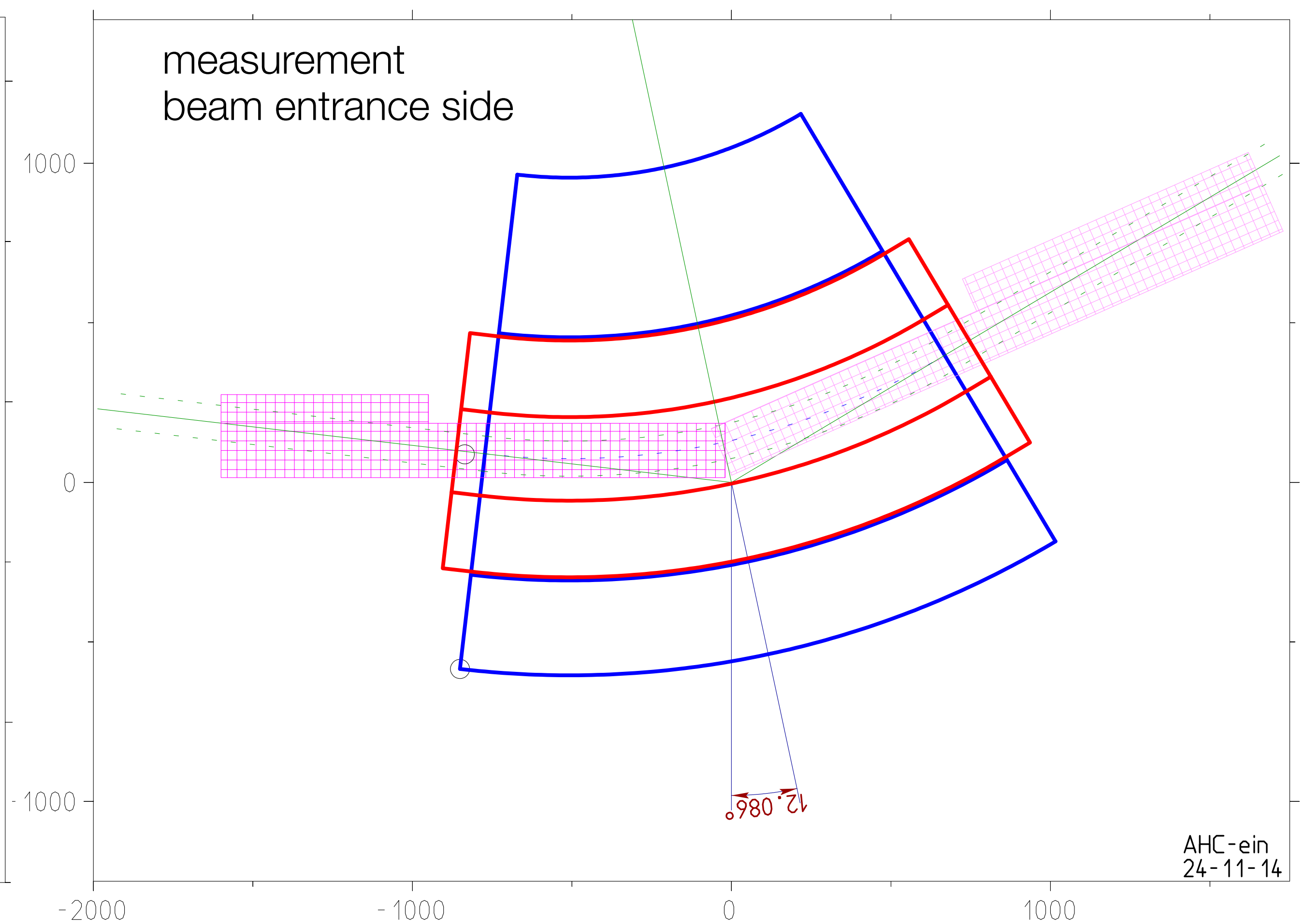
Interface to TRANSPORT

- input/output file format for set of particles (with full beam phase-space)
- transfer matrix, 1st and 2nd order
- K1 fringe field parameter
- beam envelope calculation

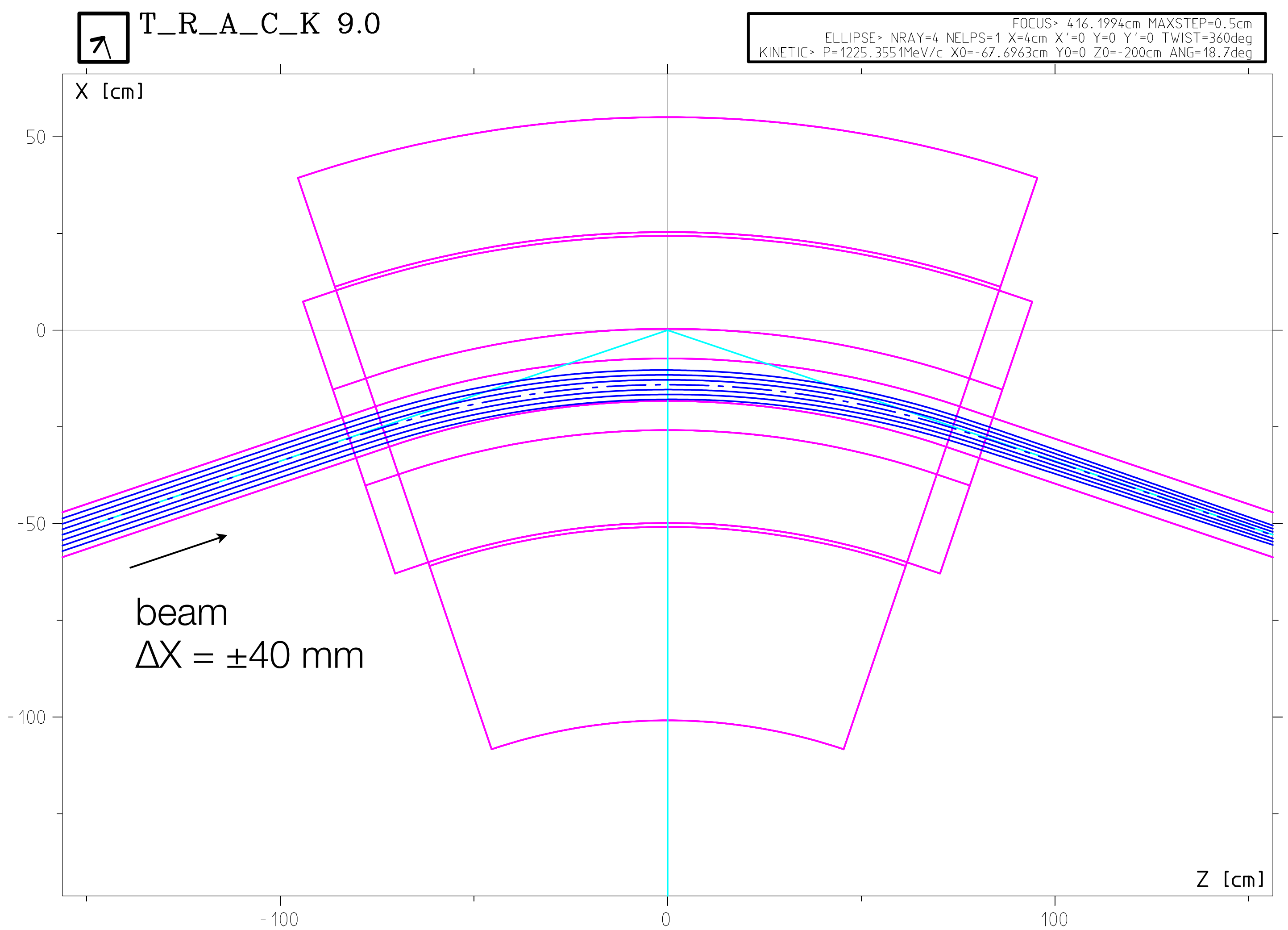
Examples:
single dipole magnet (HIPA, PSI) I

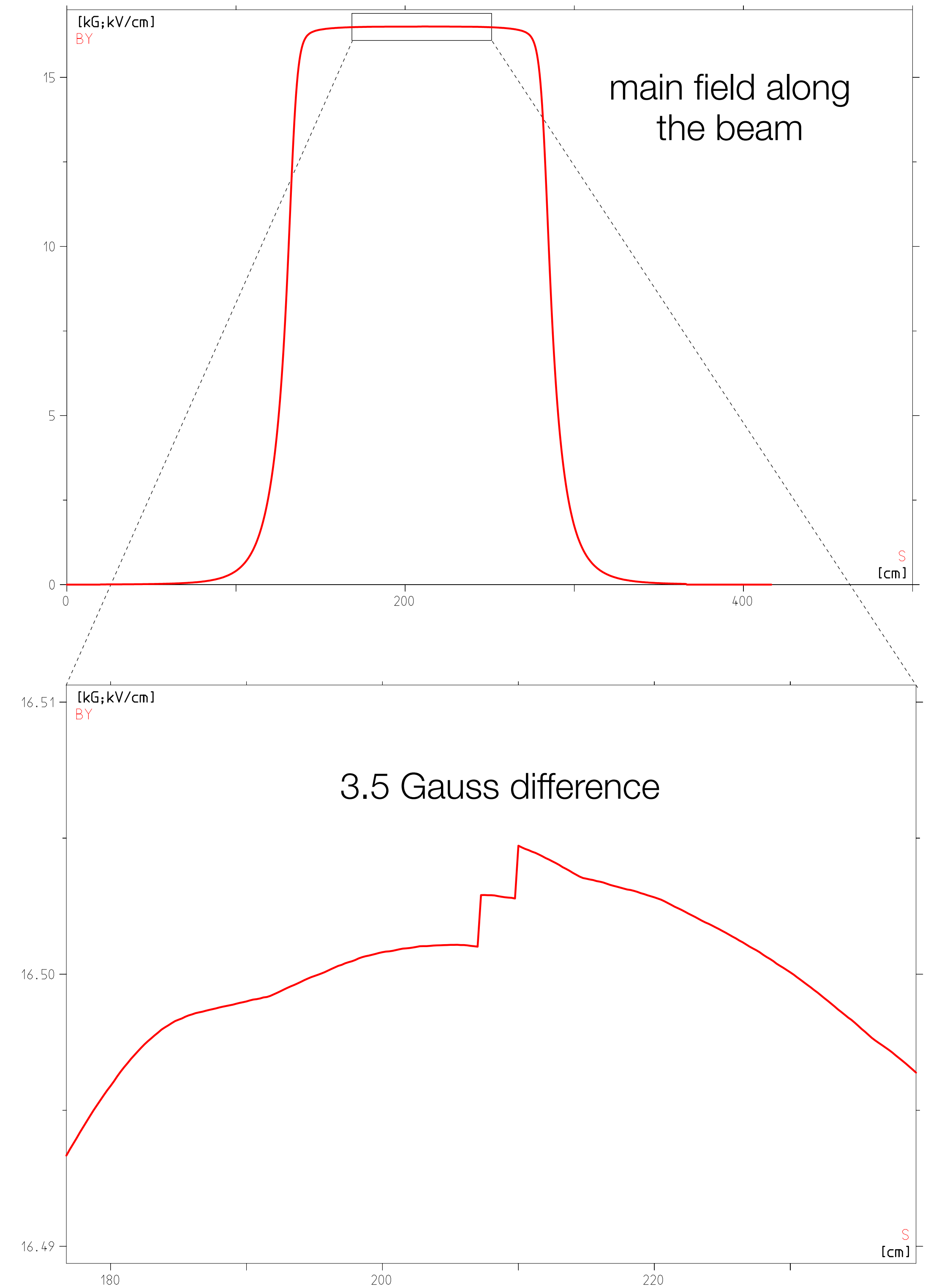
sector magnet
gap = 100 mm
B_0 = 1.64 T
bending angle = 37.4°
bending radius = 2.5 m
p^+ 590 MeV





Examples:
single dipole magnet (HIPA, PSI) II





I_{meas} = 900 A

tune for 37.4°
p^+ 605.24 MeV

beam vertex off by:
ΔZ = 3.6 mm
ΔX = 1.2 mm

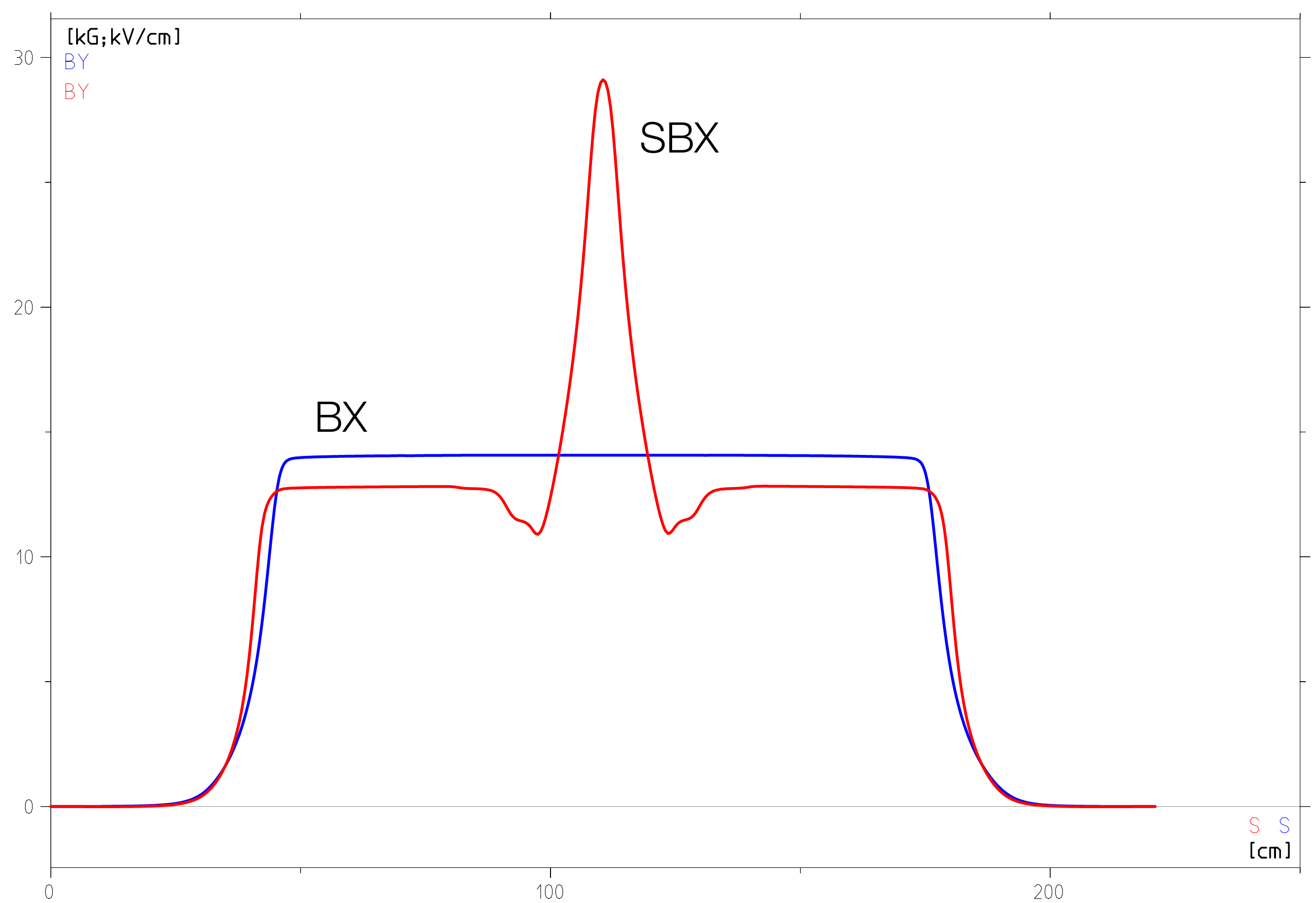
correction:
move magnet in Z by +1.5 mm

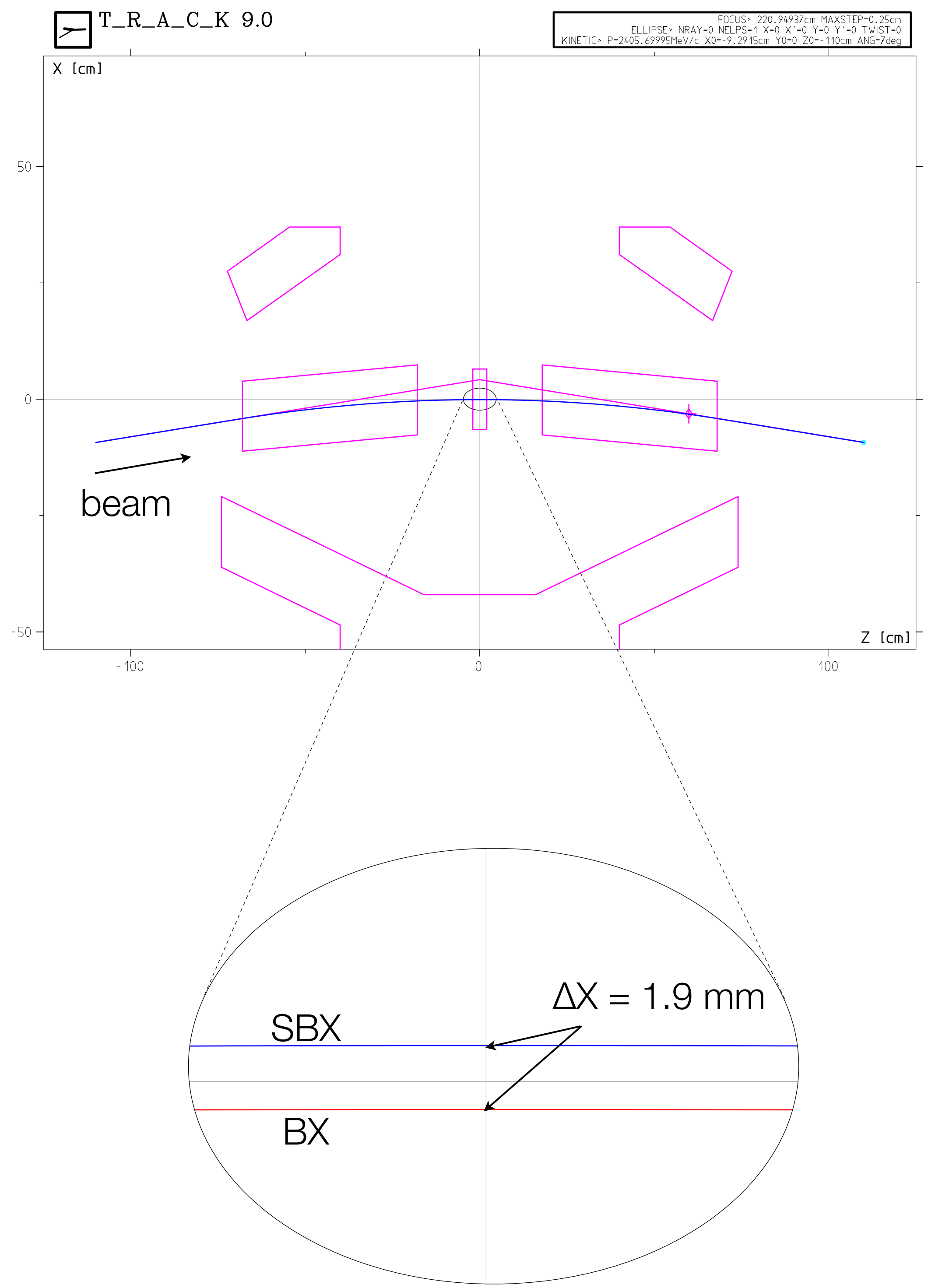
Examples: single dipole magnet (SLS, PSI)

BX : H-magnet
B_0 = 1.4 T

SBX : H-magnet with 3 poles
B_0 = 3 T

gap = 42 mm
bending angle = 14°

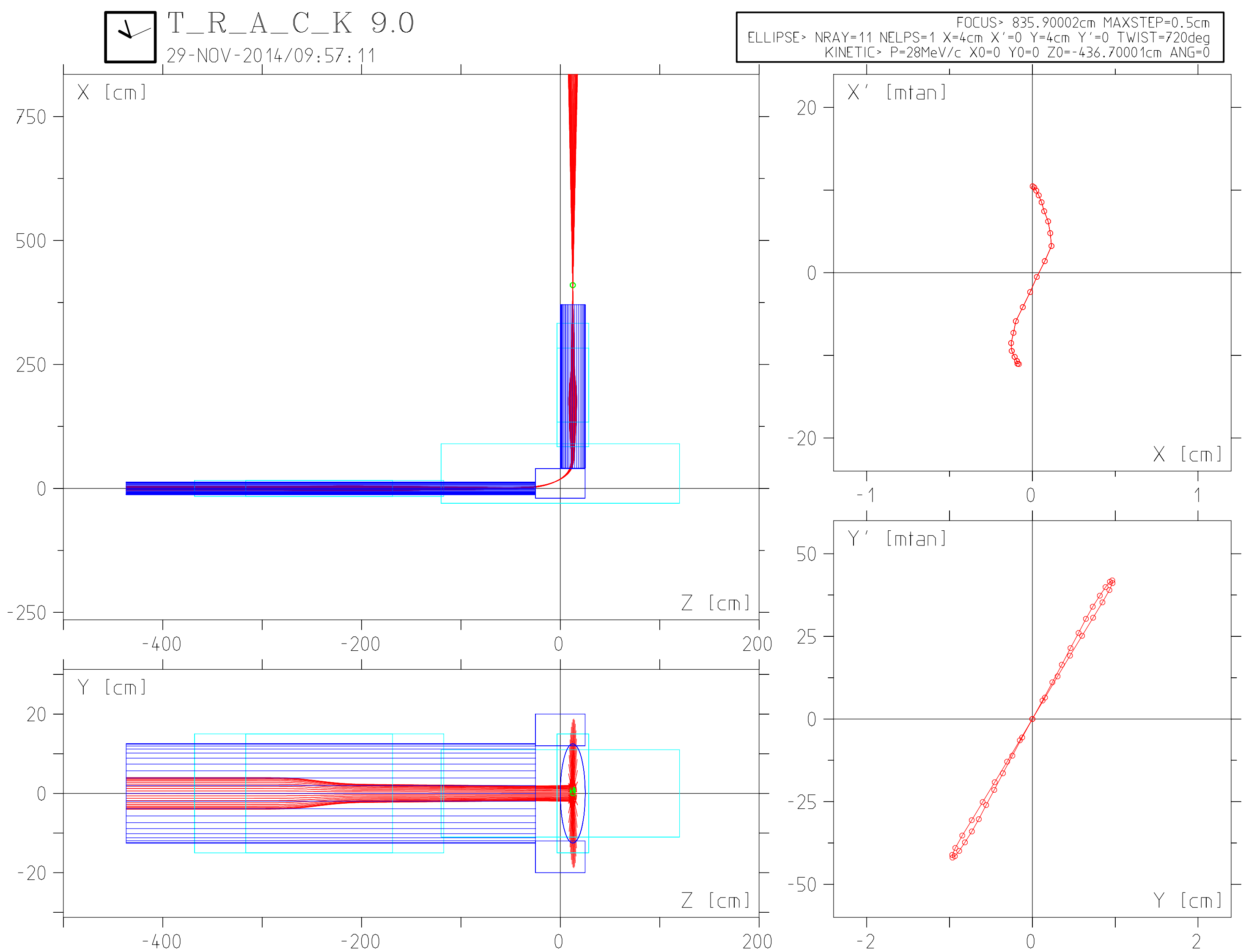


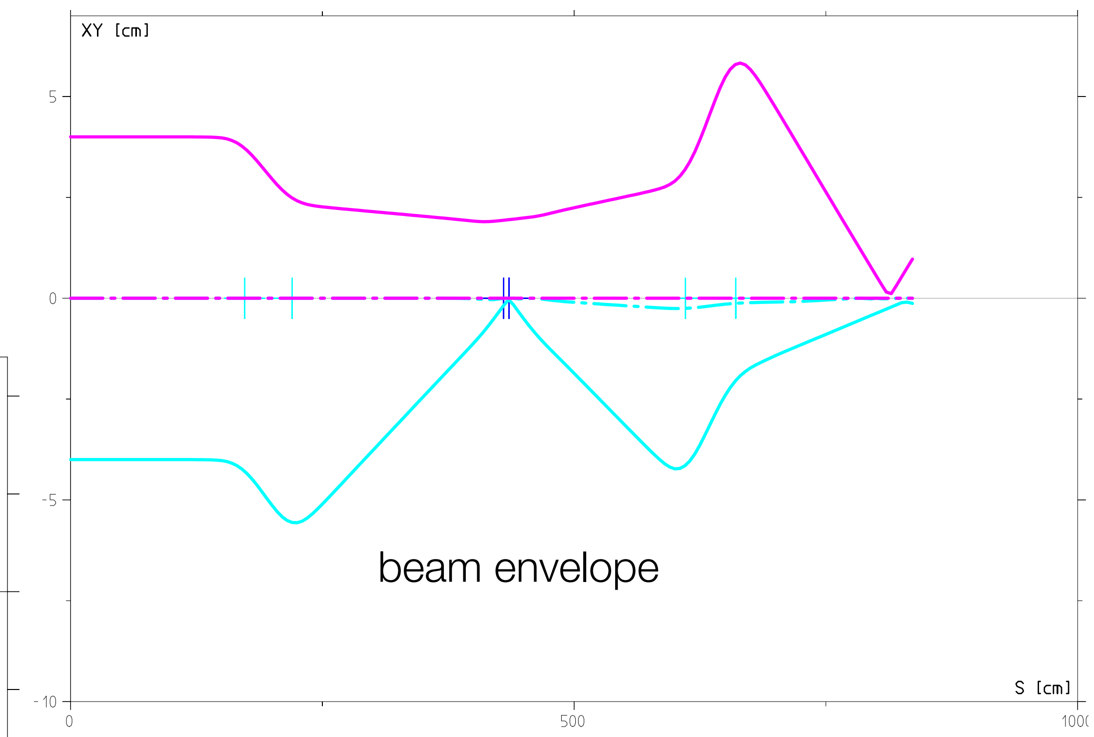


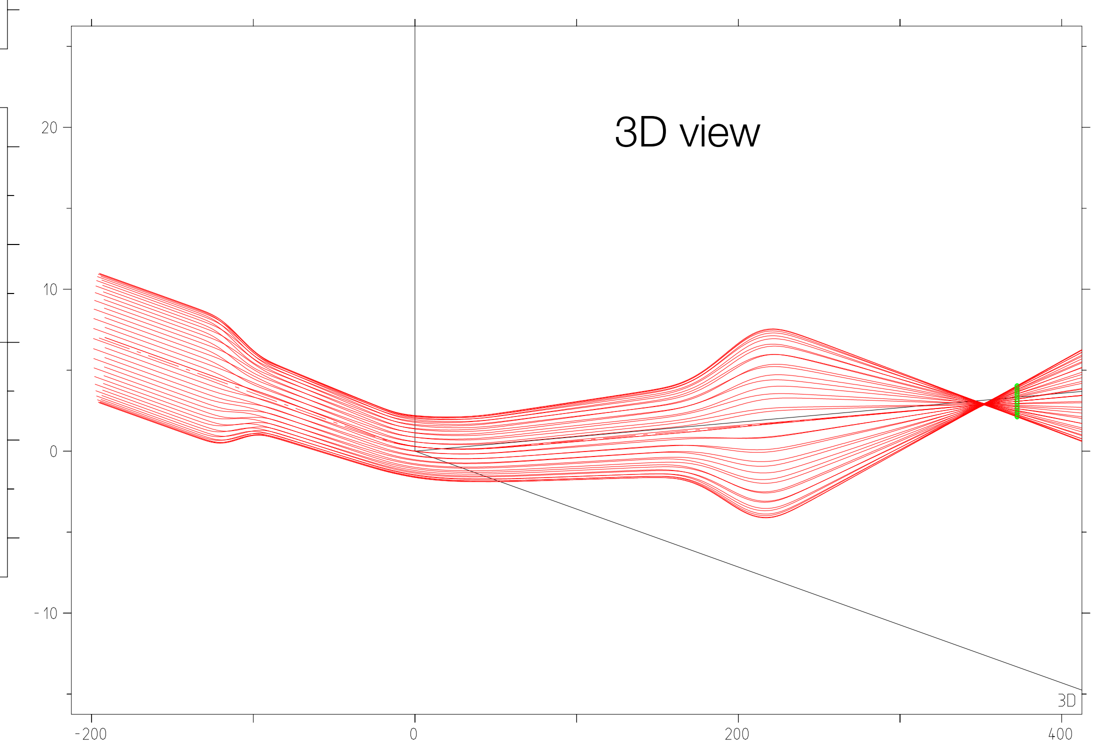
Examples:
part of a beam line (πE1, PSI)

beam line:
4 quads (1 field map)
90° bending magnet

zero emittance beam







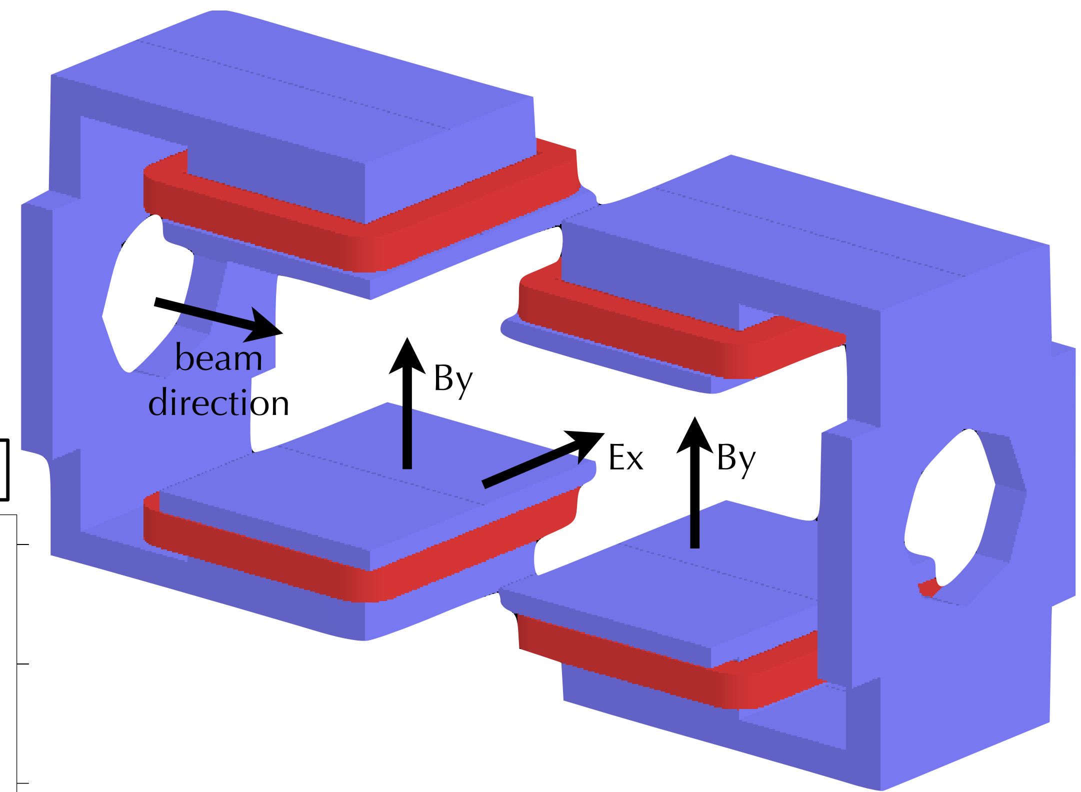
courtesy of: D. Reggiani, PSI

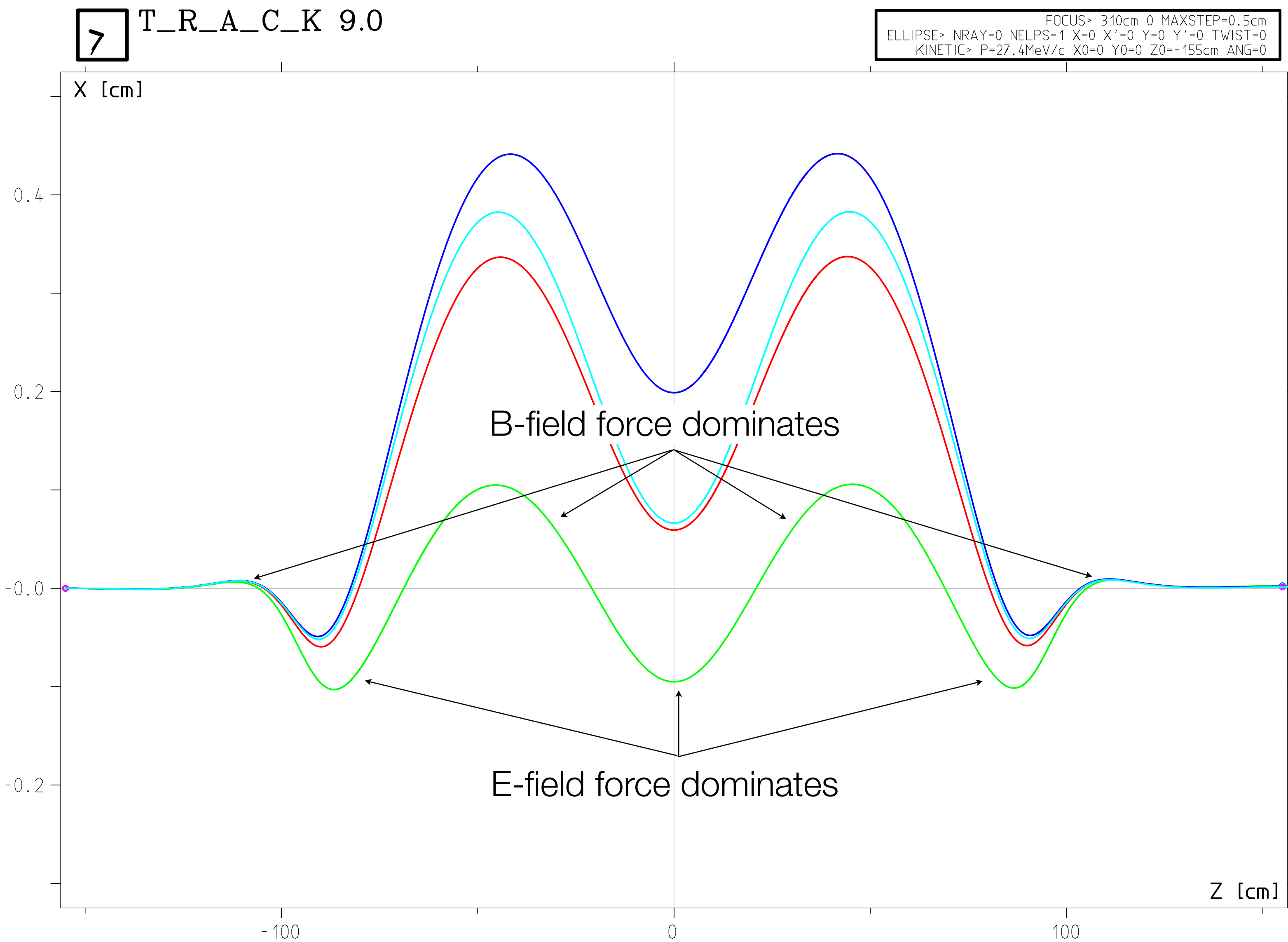
Examples:
ExB device (μSR, PSI) I

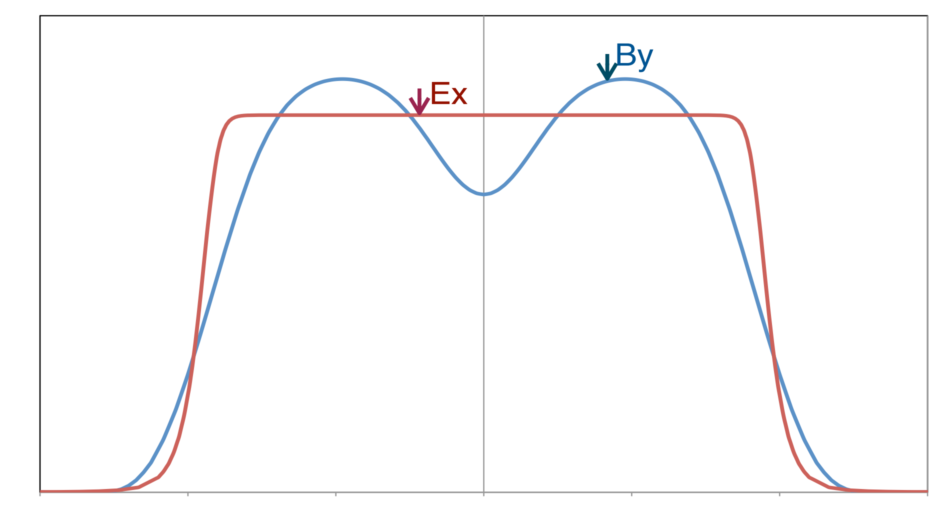
TOSCA calculations
with *T_R_A_C_K* optimisation
for the device geometry

V = ±175 kV
gap = 120 mm
L = 1.8 m

B = 380 Gauss
gap = 610 mm
L = 2.6 m







V. Vrankovic et al., “Design of a Magnet for the Spin-Rotator Device for the High Magnetic Field μSR Instrument at Paul Scherrer Institute”, IEEE Transactions on Applied Superconductivity, 22(3), 2012

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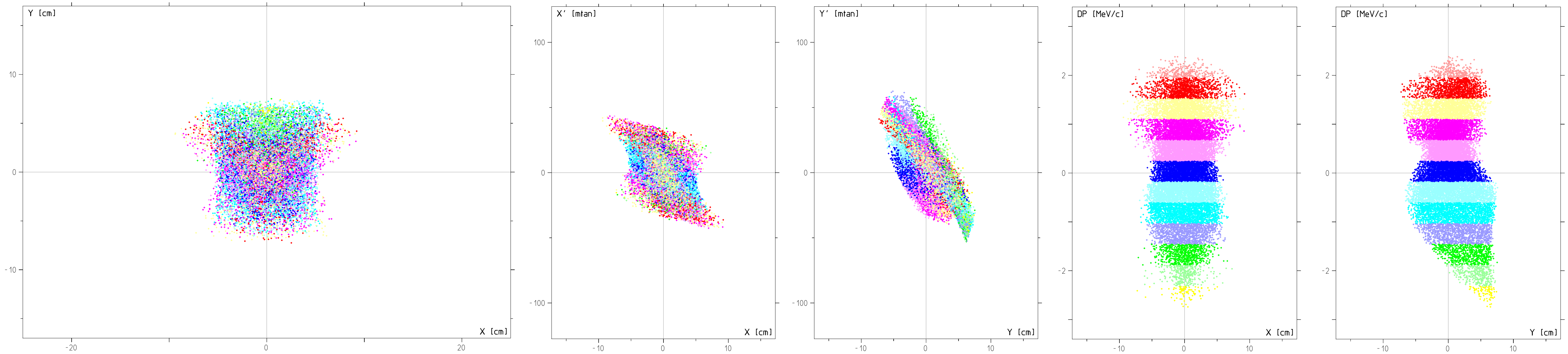
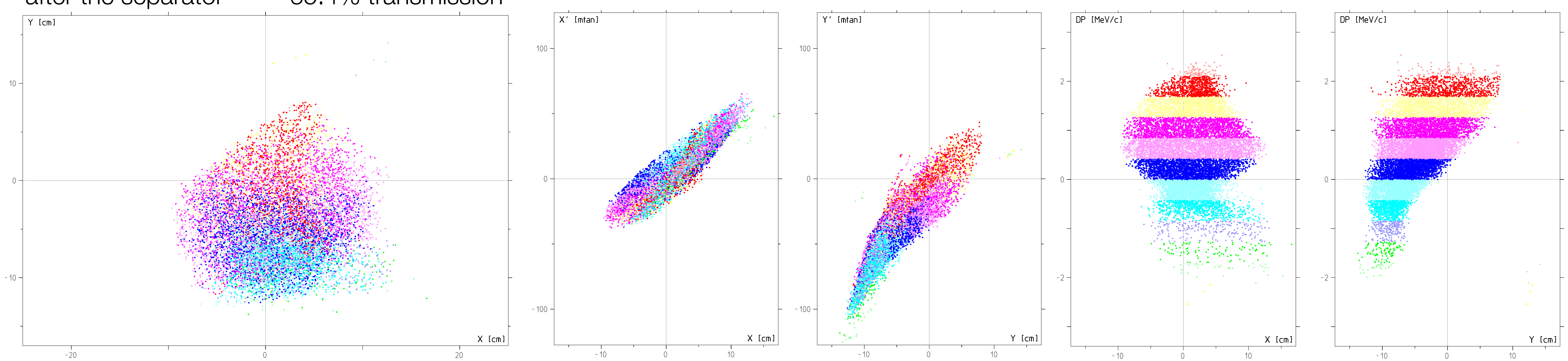
Examples:
ExB device (μSR, PSI) II

before the separator p_0 = 27.4 MeV/c
20’000 rays



after the separator 65.4% transmission

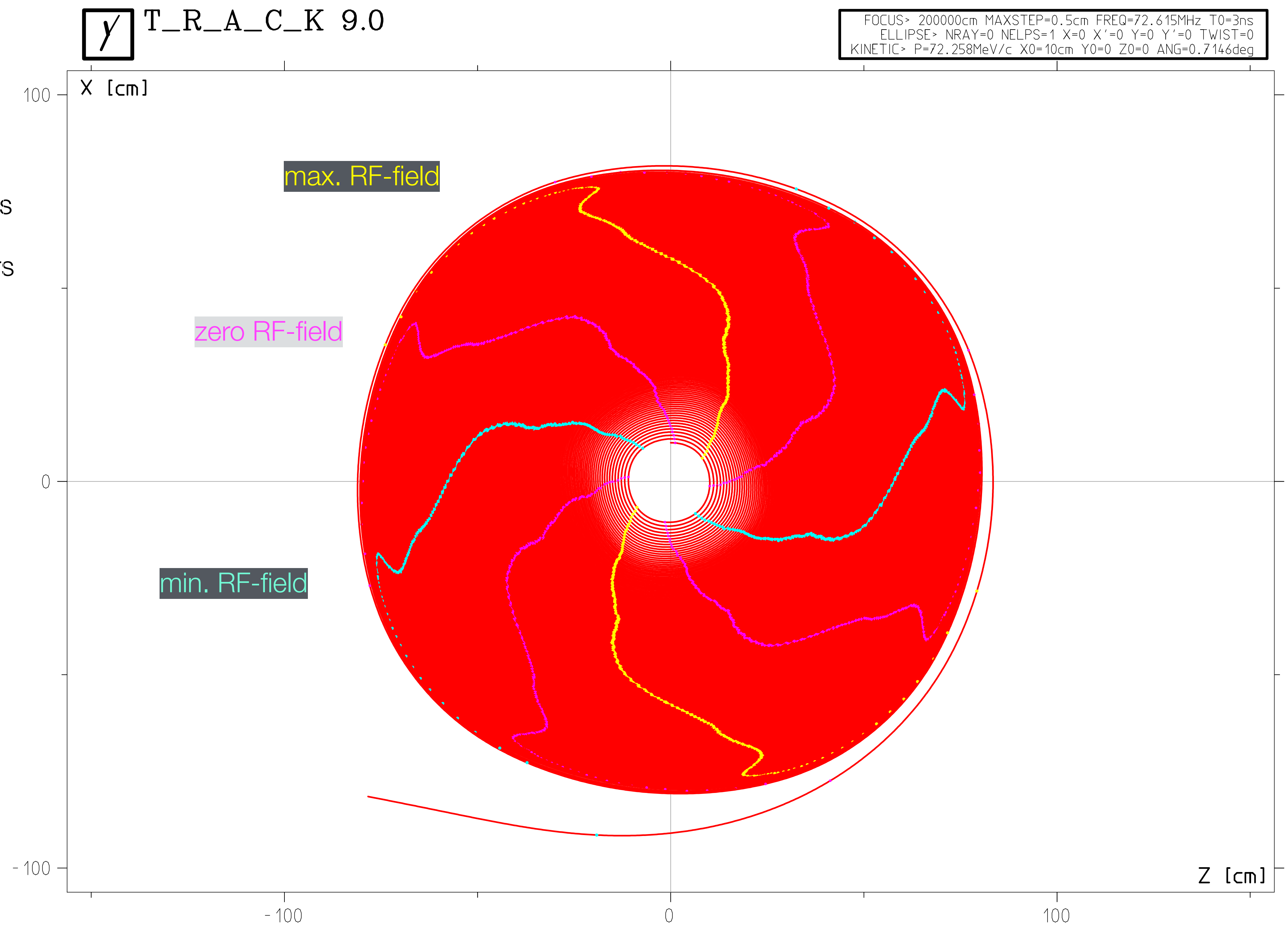


beam courtesy of K. Sedlak, PSI

Examples: cyclotron (PROSCAN, PSI)

<u>various effects investigated:</u>

- effect of coil geometry errors (tilt, shift, asymmetry)
- magnetic field random errors
- dee voltage asymmetry



J.M. Schippers, D.C. George, V. Vrankovic, "Results of 3D Beam Dynamic Studies in Distorted Fields of a 250 MeV Superconducting Cyclotron", 17th International Conference on Cyclotrons and Their Applications, Japan, 2004

Summary

- true ray-tracing with analytical solution of EOM
- without any approximation or parametrisation of fields
- from 1987 till now and still going strong
- usage outside the Magnet Section but also outside of PSI
  available at http://magnet.web.psi.ch/Analysis/track.html
- VMS ☞ UNIX ☞ Linux migrations
- improvement? yes – GUI
- enhancement? maybe and reluctantly – scattering

Contributors

- David George - co-author
- John Crawford - 1st “step” donator
- Stefan Adam - file formats’ adviser
- Phil Mees - VMS QIO events
- Urs Rohrer - TRANSPORT interface tips
- David Taqqu - particle damping
- Marco Schippers - cyclotron parameters
- Christina Wouters - useful user guide