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Use of Complementary Simulation Codes in Complex Beam Optics

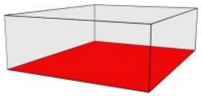
Content

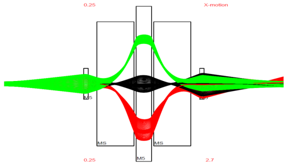
- Superconductivity in gantries
- Design proposed by PSI
- Beam optics code comparison
- Magnet design in OPERA
- Optics design including fringe fields

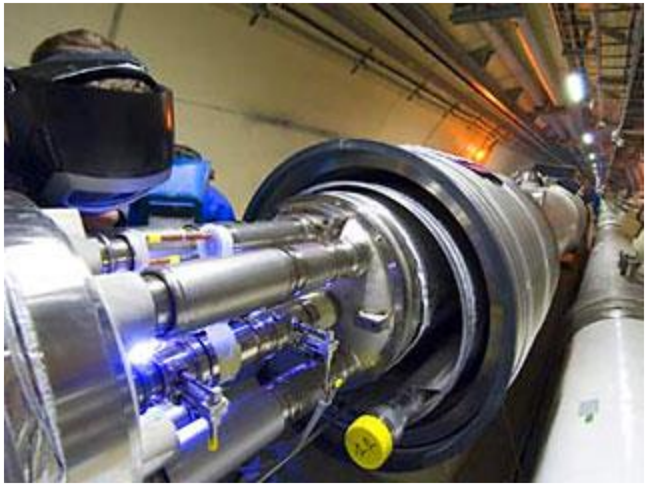
Superconductivity in particle gantries

Advantages

- Lower:
  - Weight
  - Size
  - Power consumption
  - Overall facility cost

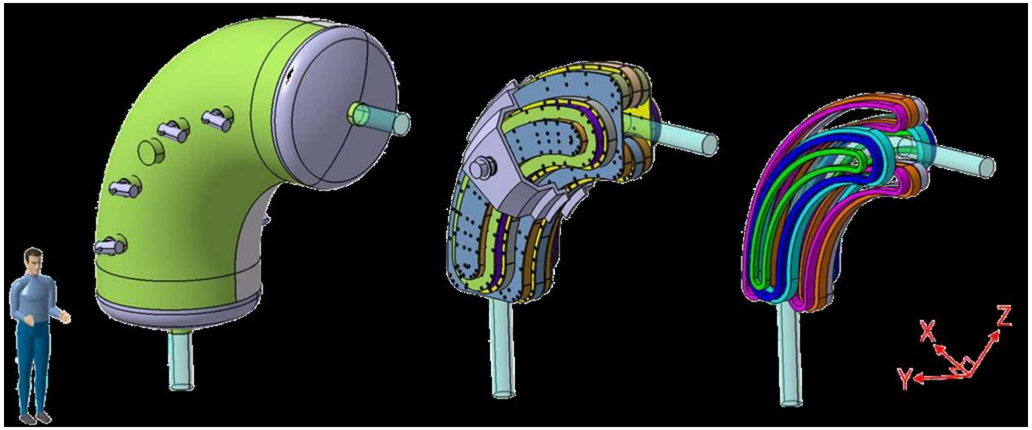






- Strong fields

=> new treatment techniques

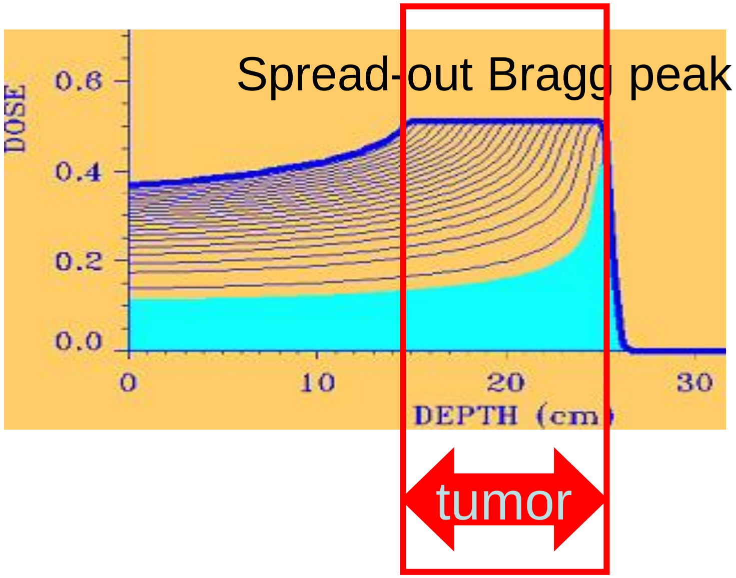


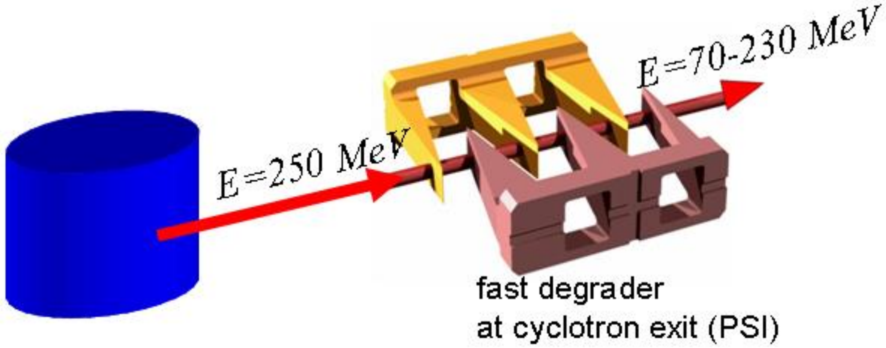
Disadvantages

- Cost from cooling
- Risks of quenching
- Large stray fields
- Fast ramping required

Figure courtesy: F. Kircher

Energy modulation - ramping





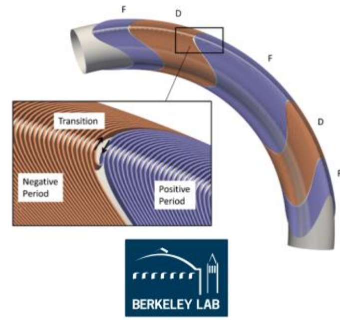
- Scanning is performed in layers
- The momentum step between two layers is ~1%
- Energy change between two layers should be performed fast, e.g. in ~100 ms

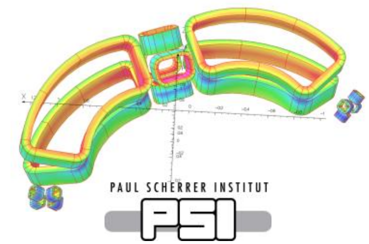
  => Two options:

  - Magnet ramping speed of ~1% dB/B in 100 ms
  - Gantry momentum acceptance very large (Δp/p > 10-20%)

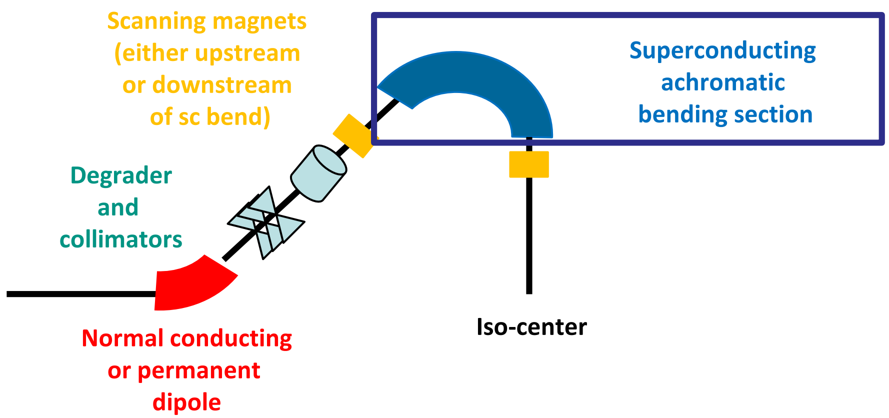
SC gantry design – PSI & LBNL

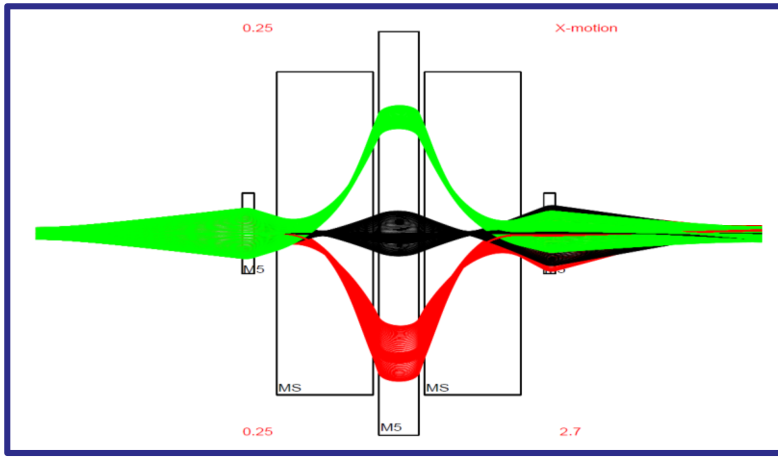
- Combined function magnets, e.g.
  - CCT magnets with alternating gradient
  - 3-5 racetrack magnets





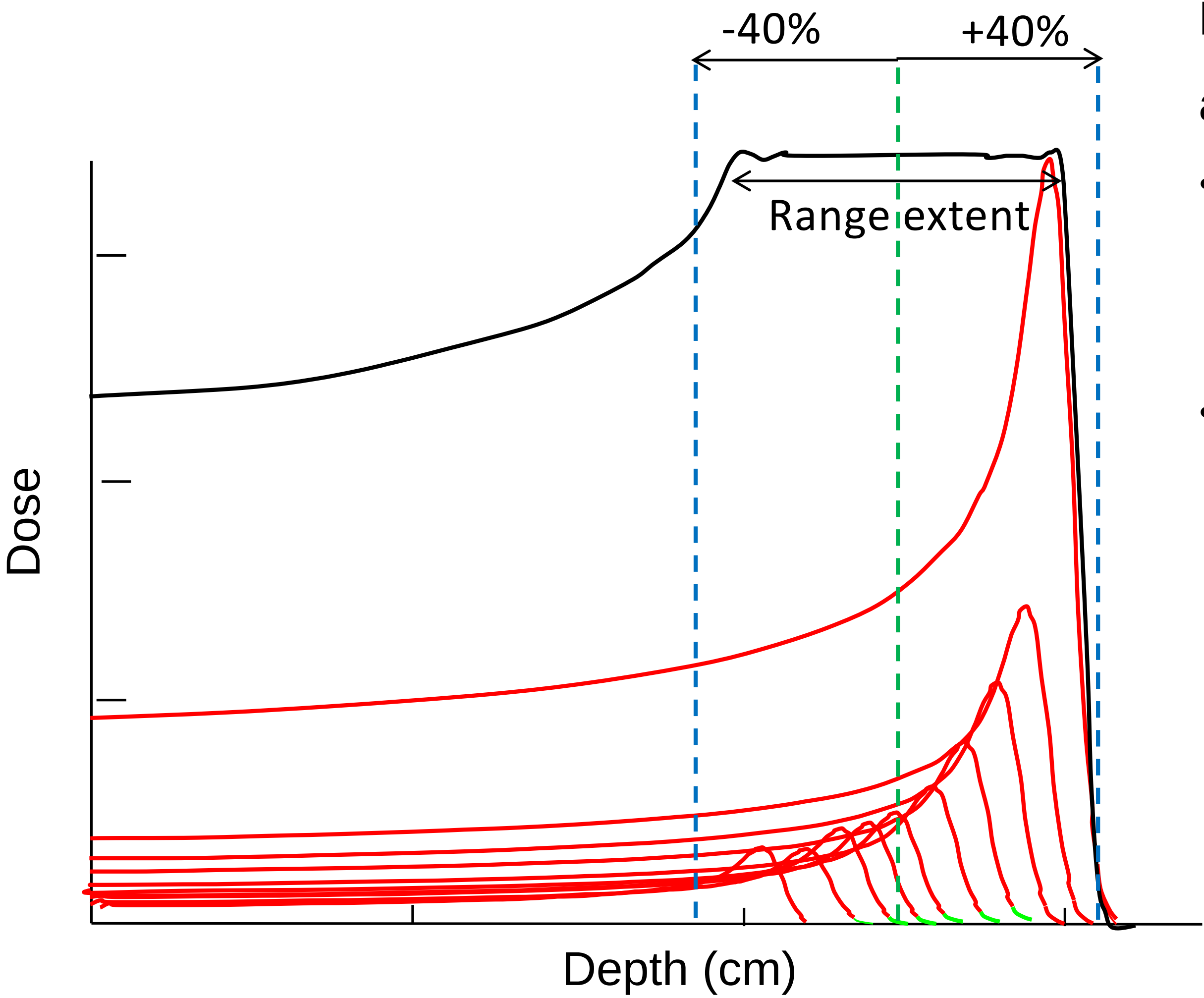
- Momentum acceptance of over ±10%
  - No energy selection needed
  - Degrader can be mounted on the gantry





  - Use of new treatment techniques

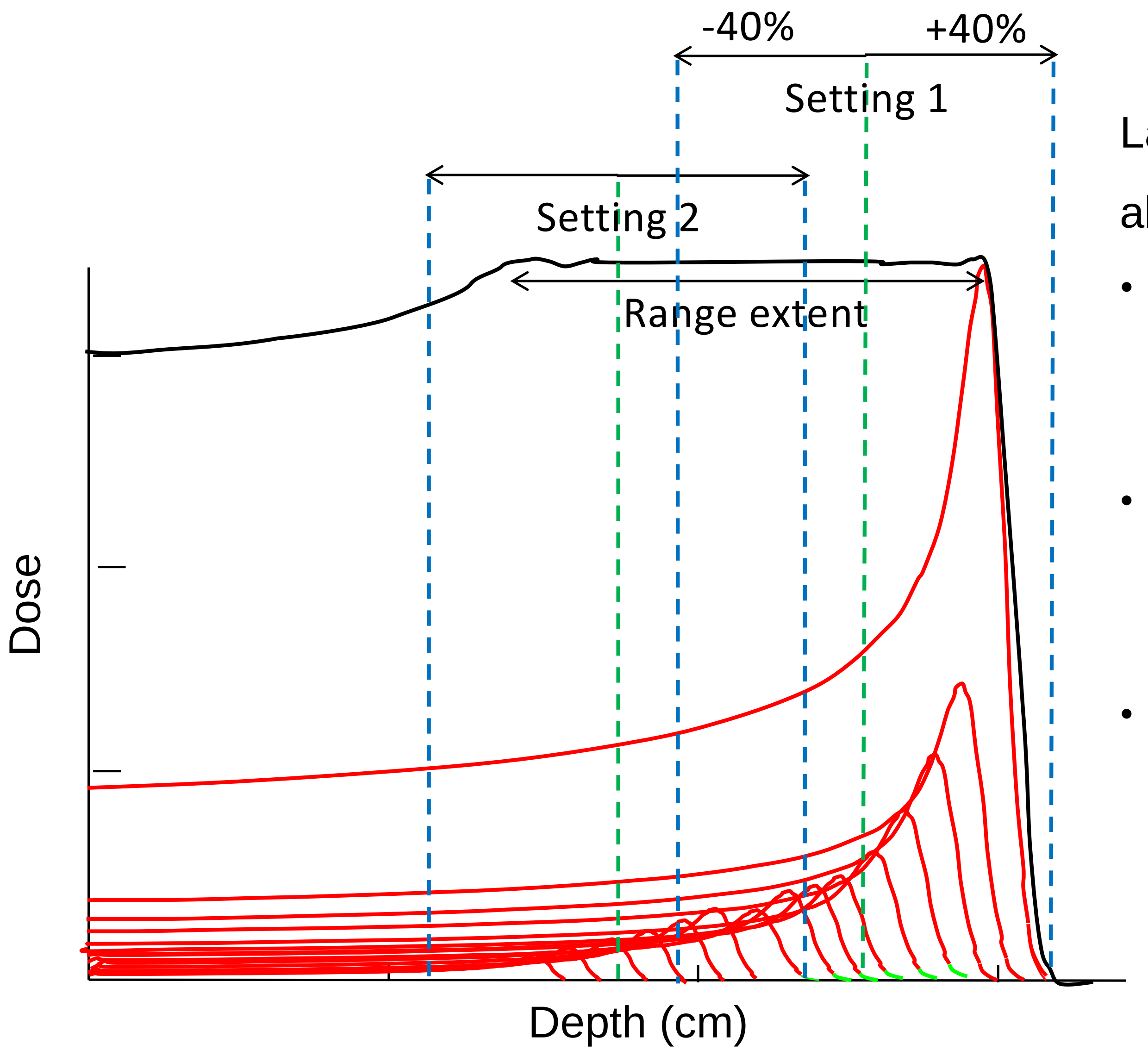
Treatment with large momentum acceptance



Large momentum acceptance allows:

- Treatment of the small tumors without change of the SC magnet field
- Can be used i.e. for volumetric rescanning on a very fast time scale

Treatment with large momentum acceptance



Large momentum acceptance allows:

- Treatment of the small tumors without change of the SC magnet field
- Can be used i.e. for volumetric rescanning on a very fast time scale
- Treatment of large tumors with only one or two of such changes (Magnet field change in 30-60 s)

Generation of SCOFF field maps

Sharp Cut Off Fringe Field (SCOFF) optics solution developed:

- 1st order in Transport and
- Higher orders in COSY

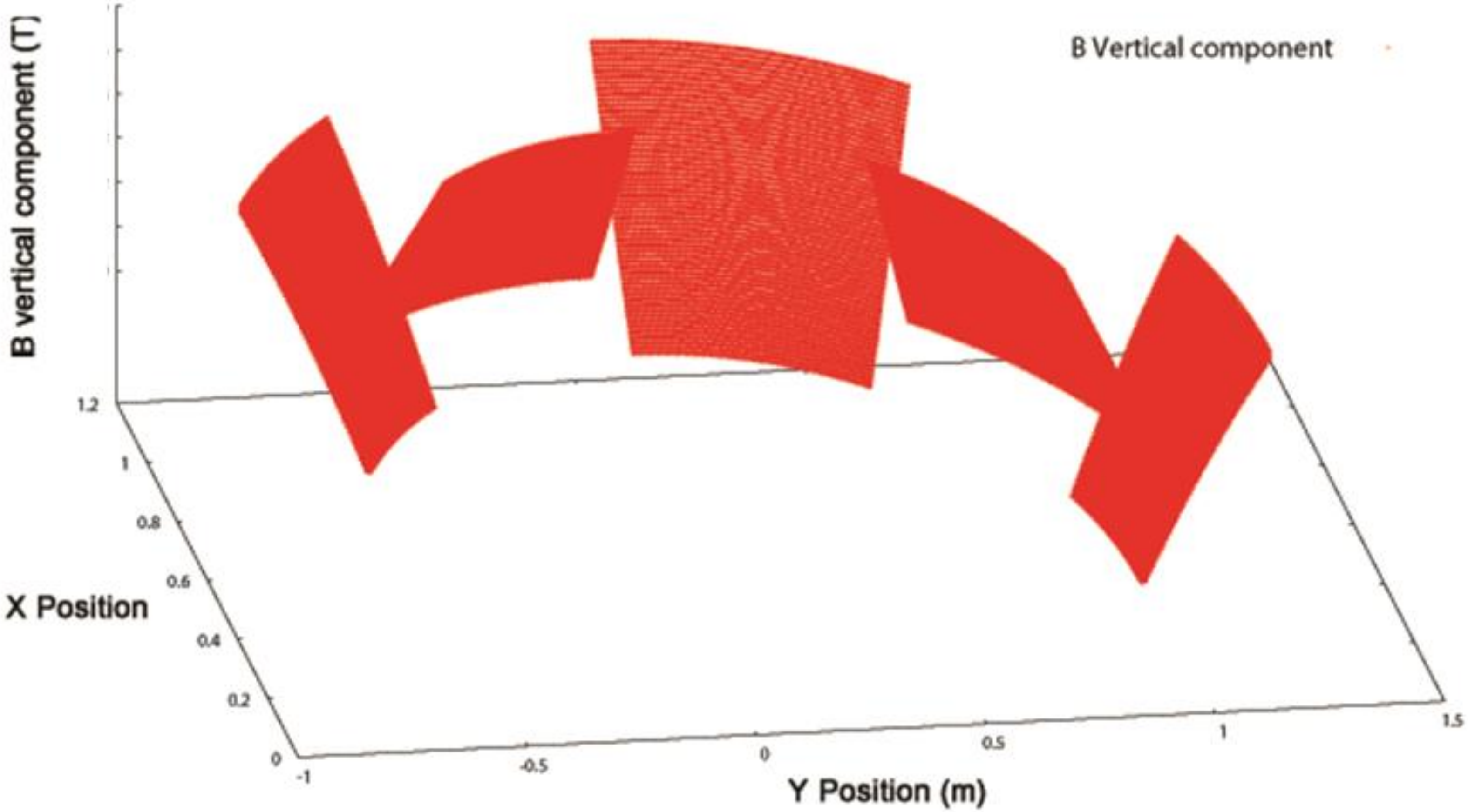
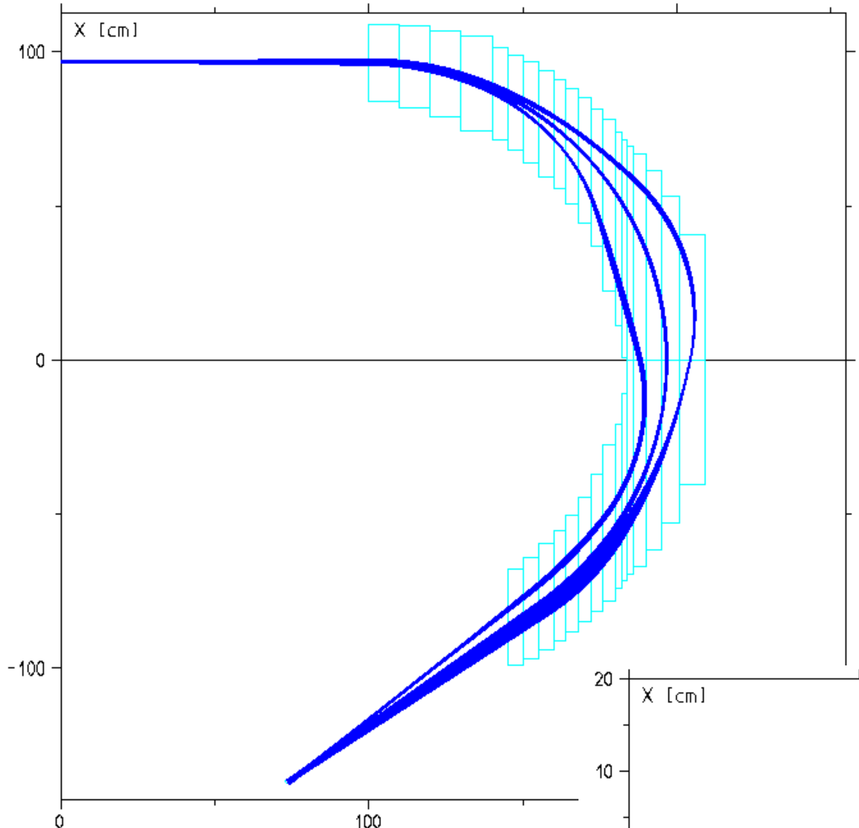


Figure courtesy: J. Bokor

Verification of the results by Track software

Tracking through the 3D field map in Track



- Use 35 field maps

  (because of field map size limit)
- Initial beam parameters:
  - 3 mm x 10 mrad at 2σ
  - The Δp/p is
    - from -11.5 % (lower curve)
    - to +13.5 % (upper curve)

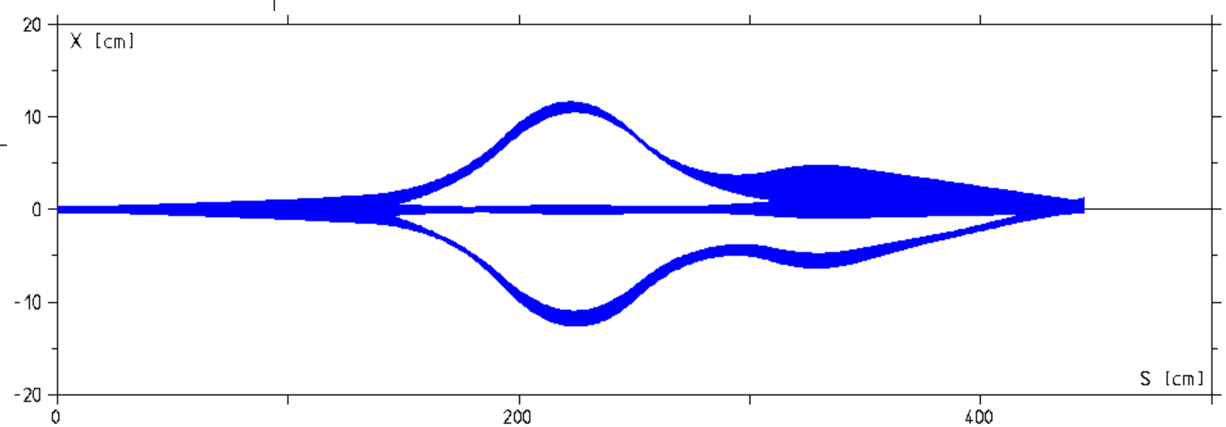
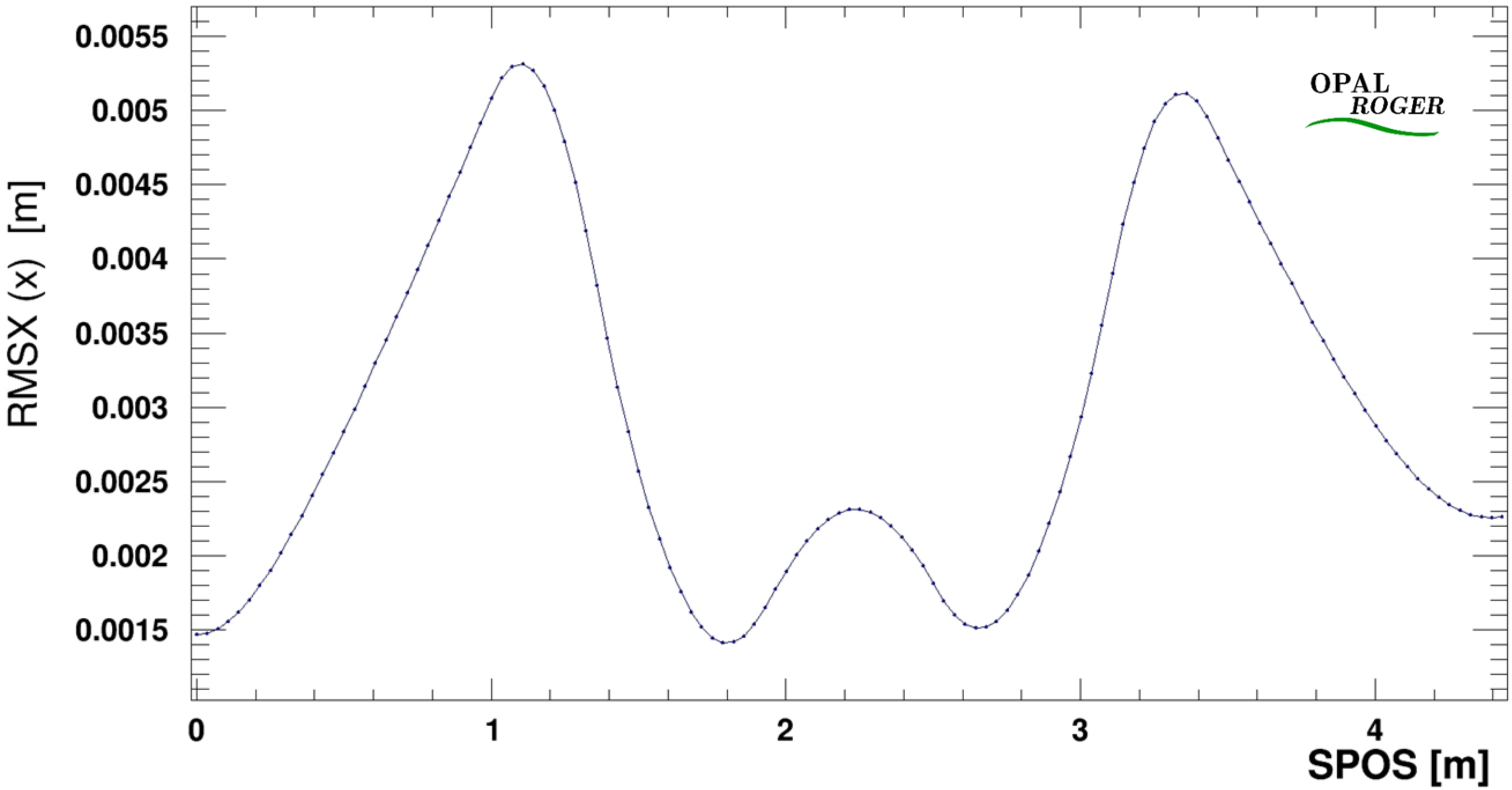


Figure courtesy: H. Zhang

Verification of the results by OPAL software

Horizontal beam size (1σ)



https://amas.psi.ch/OPAL

Converting from COSY to OPAL

OPAL and Track use MAD(X) convention

2.1 Magnetic Field and Vector Potential (Transverse Field, Curved Reference)

For all mid-plane symmetric elements MAD defines the magnetic field on the mid-plane of a sector dipole by its Taylor expansion:

$$B_x(x,0,s)=0, \qquad B_y(x,0,s)=B_0+B_1\frac{x}{1!}+B_2\frac{x^2}{2!}+B_3\frac{x^3}{3!}+\ldots \qquad B_s(x,0,s)=0. \tag{2.1}$$

For positive x a positive field coefficient gives a contribution to the field in positive y-direction. The vector potential has a longitudinal component A_s depending on x, y only. Expanded to order four it takes the form

$$\begin{aligned}
A_x(x,y,s) &= 0,\\
A_y(x,y,s) &= 0,\\
A_s(x,y,s) &= -B_0\left(x-\frac{hx^2}{2(1+hx)}\right)-B_1\left(\frac{1}{2}(x^2-y^2)-\frac{h}{6}x^3+\frac{h^2}{24}(4x^4-y^4)+\ldots\right)\\
&\quad -B_2\left(\frac{1}{6}(x^3-3xy^2)-\frac{h}{24}(x^4-y^4)+\ldots\right)-B_3\left(\frac{1}{24}(x^4-6x^2y^2+y^4)+\ldots\right)+\ldots
\end{aligned} \tag{2.2}$$

where h is the curvature of the reference orbit. Taking the curl of A_s in curvilinear coordinates the field components are to order three

$$\begin{aligned}
B_x(x,y,s) &= +B_1\left(y+\frac{h^2}{6}y^3+\ldots\right)+B_2\left(xy-\frac{h^2}{6}y^3+\ldots\right)\\
&\quad +B_3\left(\frac{1}{6}(3x^2y-y^3)+\ldots\right)+\ldots\\
B_y(x,y,s) &= +B_0+B_1\left(x-\frac{h}{2}y^2+\frac{h^2}{2}xy^2+\ldots\right)+B_2\left(\frac{1}{2}(x^2-y^2)-\frac{h}{2}xy^2+\ldots\right)\\
&\quad +B_3\left(\frac{1}{6}(x^3-3xy^2)+\ldots\right)+\ldots\\
B_s(x,y,s) &= 0.
\end{aligned} \tag{2.3}$$

“The MAD Program (Version 8.13) - Physical Methods Manual“

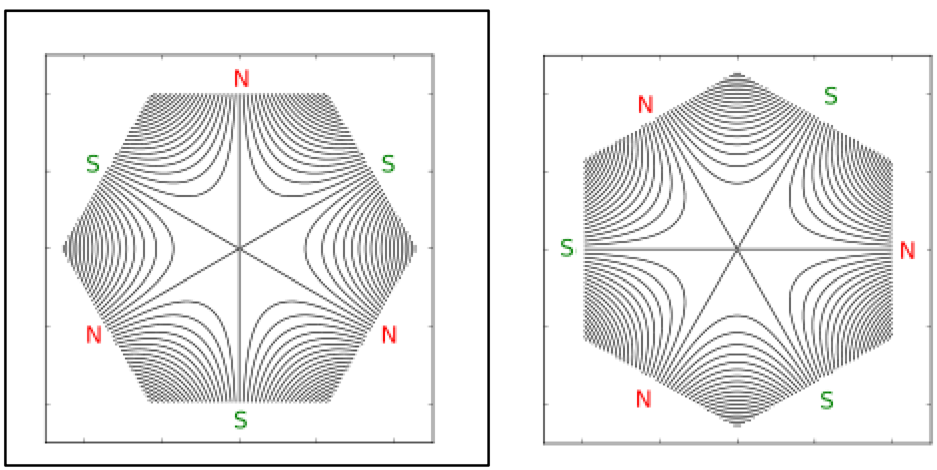
Converting between the codes

COSY → Transport: Change signs of quadrupoles and sextupoles

COSY → (Win)AGILE: Multiply sextupole field strength by factor 2

Transport → MAD(X), OPAL, Track: Multiply sextupole field strength by factor 2

(Win)AGILE → MAD(X), OPAL, Track: Change signs of quadrupoles and sextupoles



Rotation by 90º is not needed

Code options

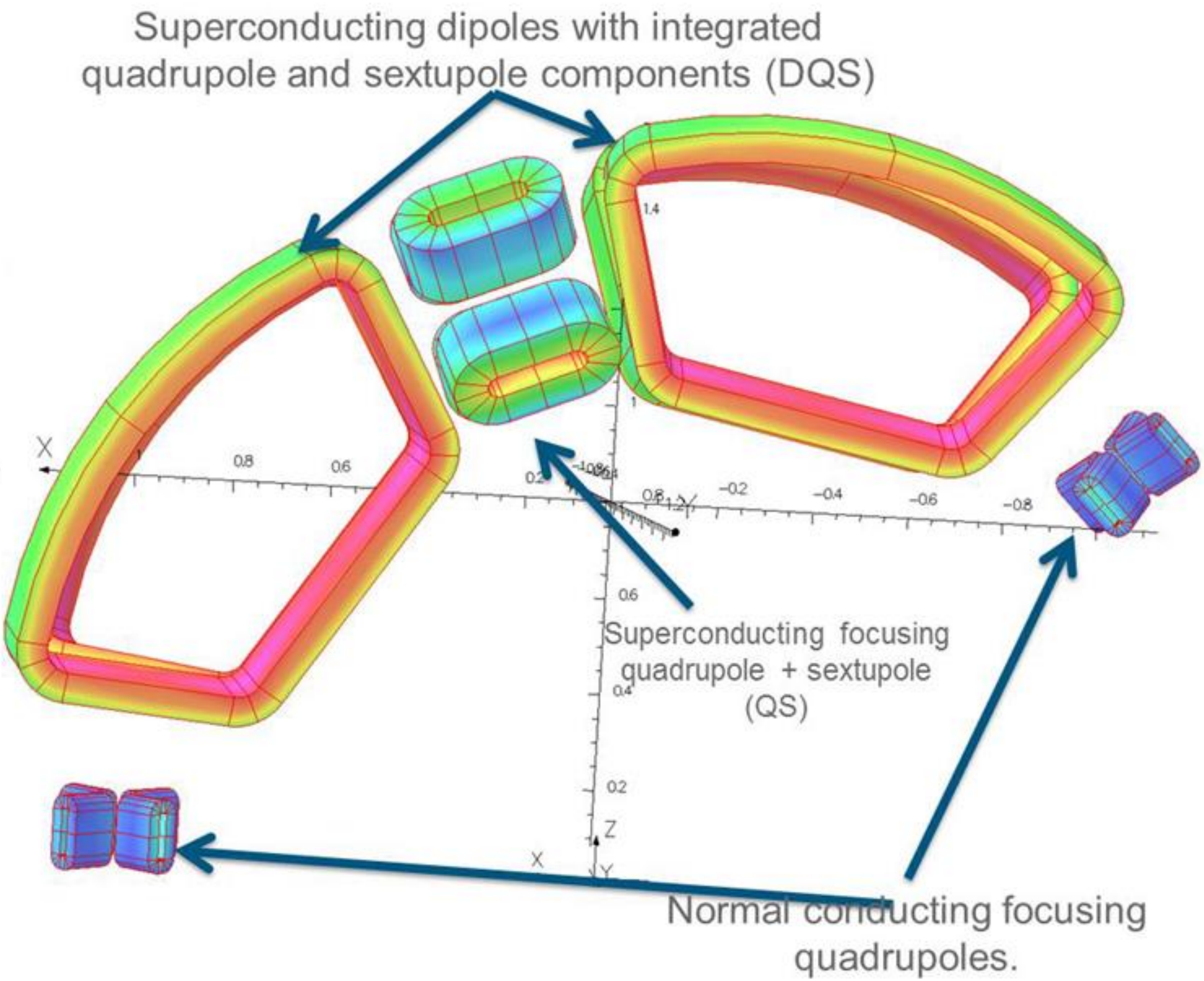
Conversion rules developed for COSY, OPAL, Track, Transport and AGILE. However, not all codes are suitable for our purpose:

- Transport
    - Capable of calculating 2nd order effects
    - Optimization of sextupole fields does not function well
- WinAGILE
    - No 2nd order matrix calculation
- COSY
    - Capable of optimization with higher order effects and constraints
    - No matching of external 3D maps
- OPAL
    - OPAL-t
        - Can perform optimization (genetic algorithm optPilot)
        - 3D field maps only in straight geometries
    - OPAL-cycl
        - Tracking in a 3-D map
        - Can scale, but not modify the 3D field maps
- Track
    - Tracking in a 3-D map
    - Map size is limited
    - No optimization algorithms

Analytic

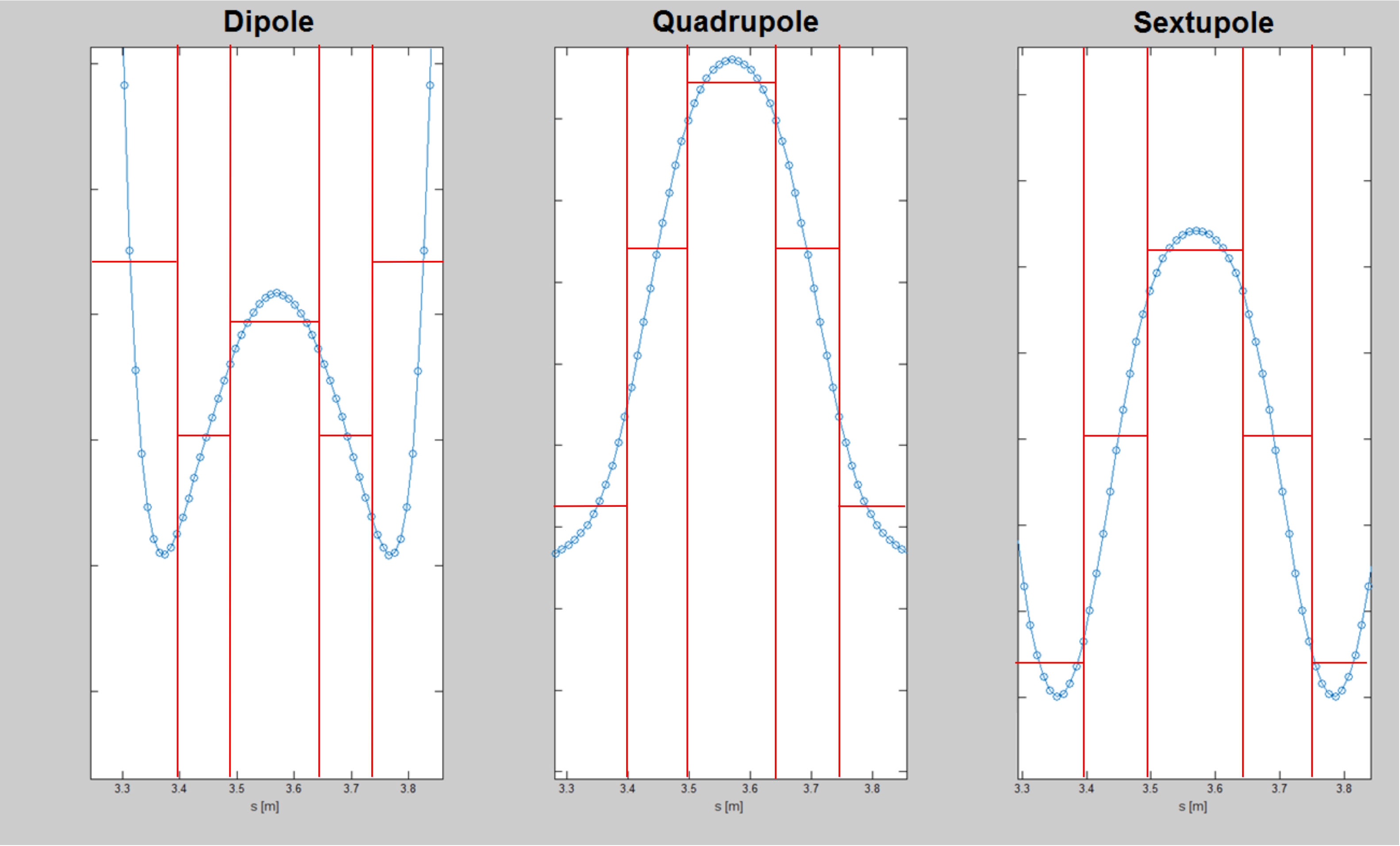
Tracking

Magnet in OPERA



Steps for fringe field simulation

- Segmet along the beam path
- Calculate averages for different segments

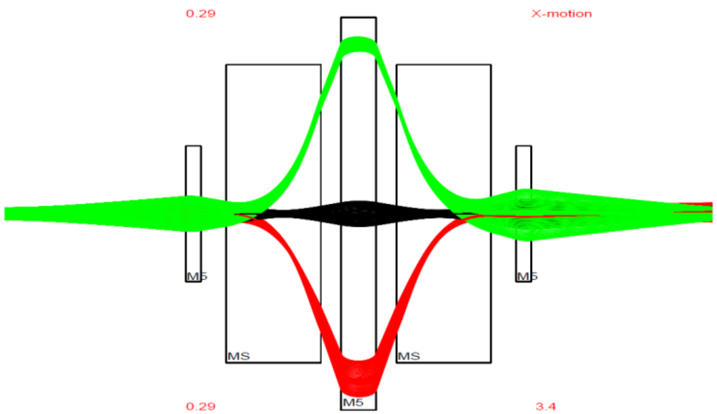


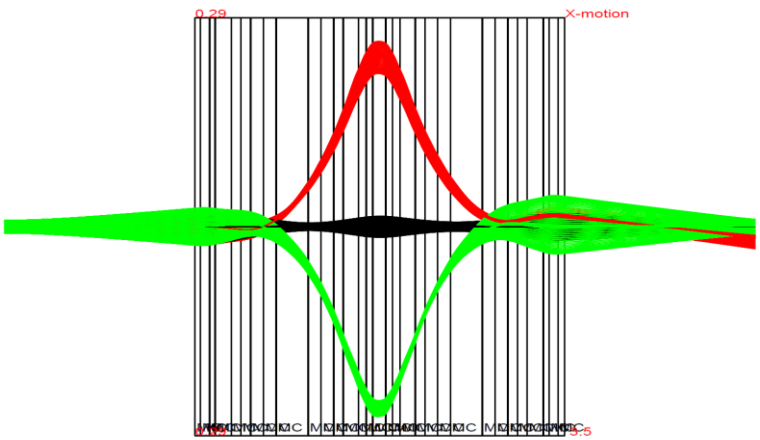
Fringe field simulation with step function

SCOFF simulation

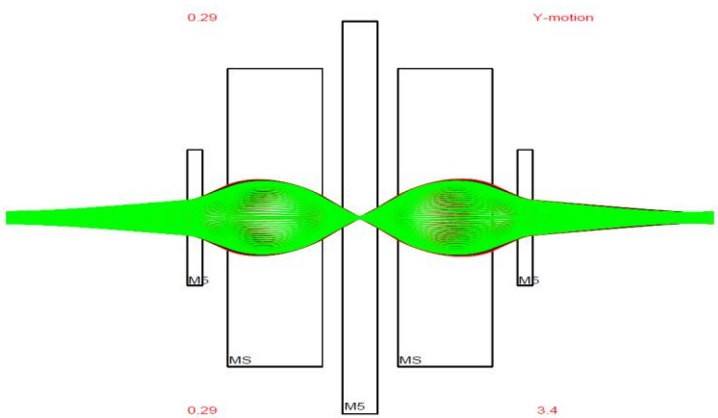
Step function simulation

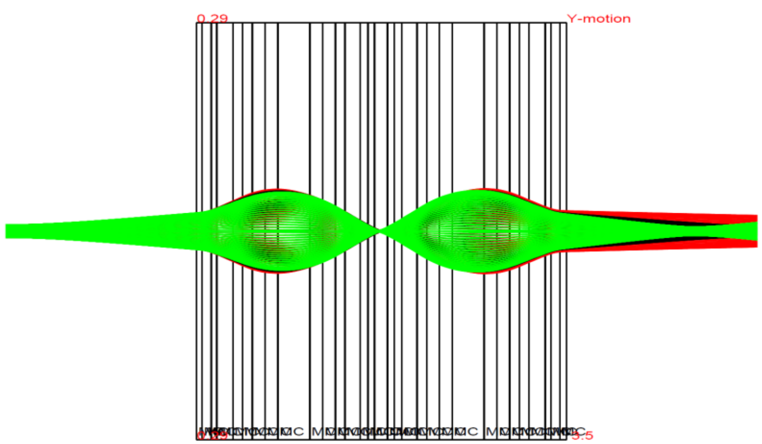
X-plane



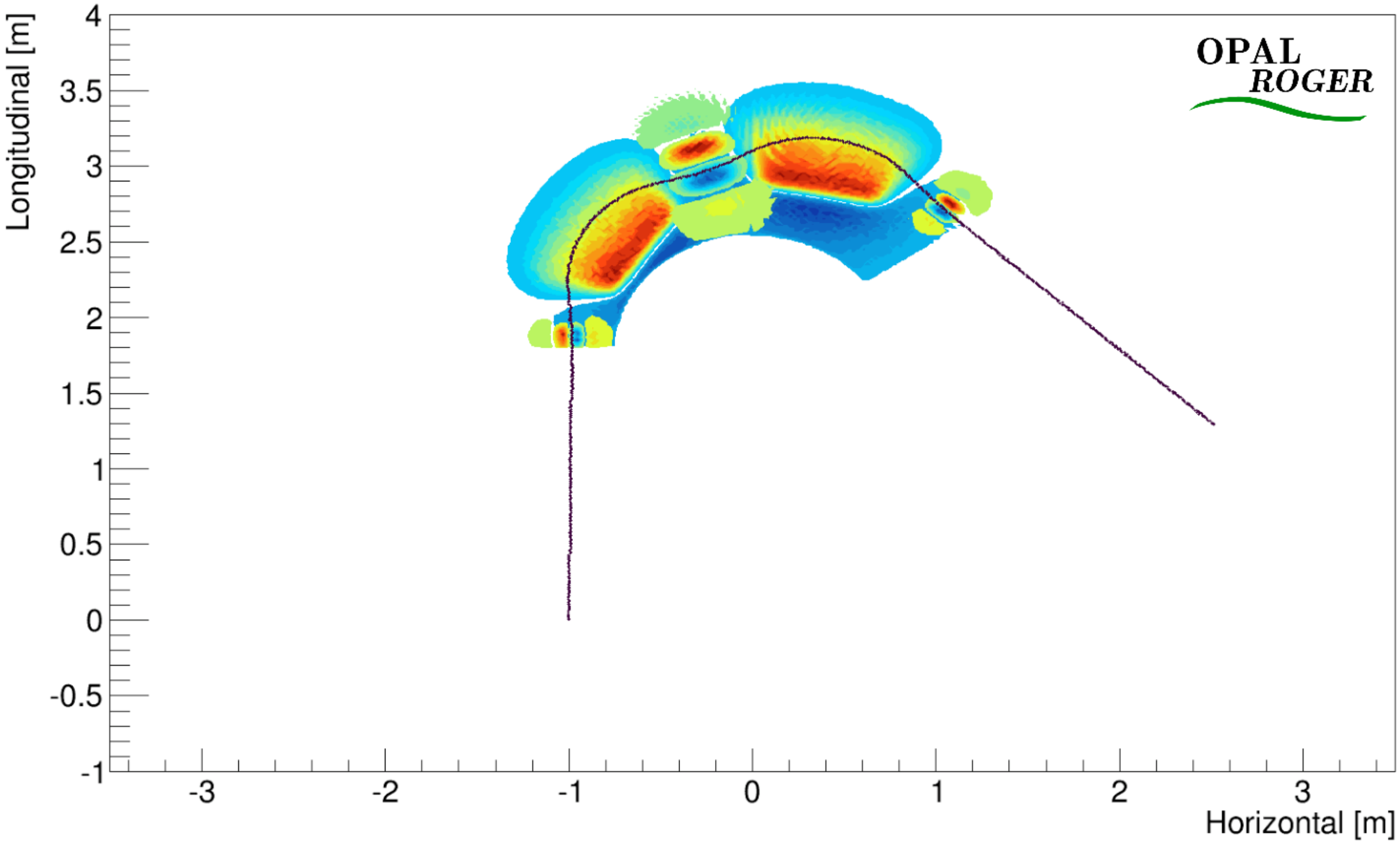


Y-plane

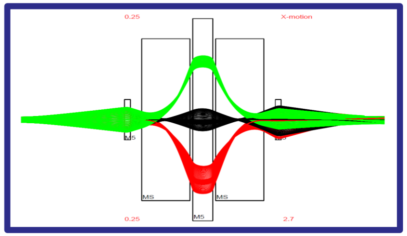


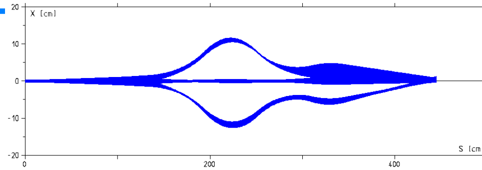


Realistic 3D field maps in OPAL

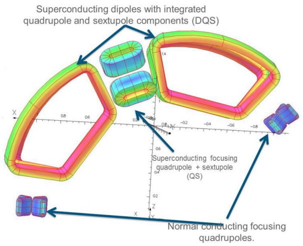


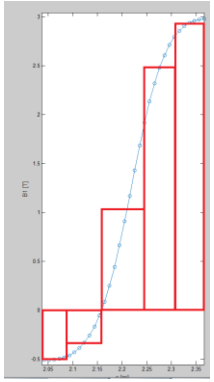
Summary: Workflow from SCOFF to 3D maps



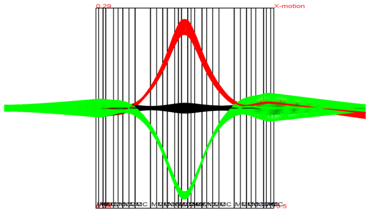


- Calculate SCOFF fields in COSY
- Verify SCOFF model with a tracking code

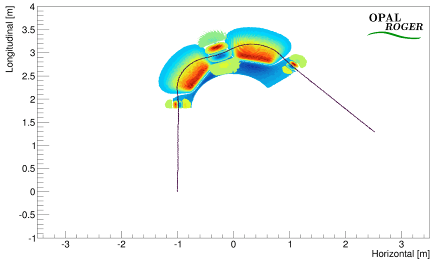


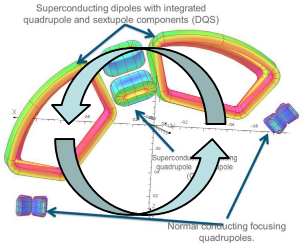


- Develop magnets in OPERA
- Approximate fringe fields with step functions



- More precise calculation of the required fields in COSY
- Modify magnets in OPERA
- Confirm with OPAL tracking through 3D field map





Thank you very much for your attention!