New simulation tools developed for the S2C2

Wiel Kleeven on behalf of the IBA accelerator physicist group

Introduction

- Up to recently, all IBA cyclotrons were AVF-isochronous
- Existing simulation tools therefore applied to these types of cyclotrons
- The fast development of the S2C2 (a synchro-cyclotron) was only possible through a close collaboration with AIMA development, based in Nice, France.
- They were a key driver in the accelerator design especially regarding the beam physics calculations
- Since the start of this project, IBA is also developing and improving its beam as well as magnet computation/simulation tools for calculation of the synchro-cyclotron
- This presentation gives an overview
- We would like to thank Jerome and Pierre Mandrillon and Matthieu Conjat for the many helpful discussions on these subjects

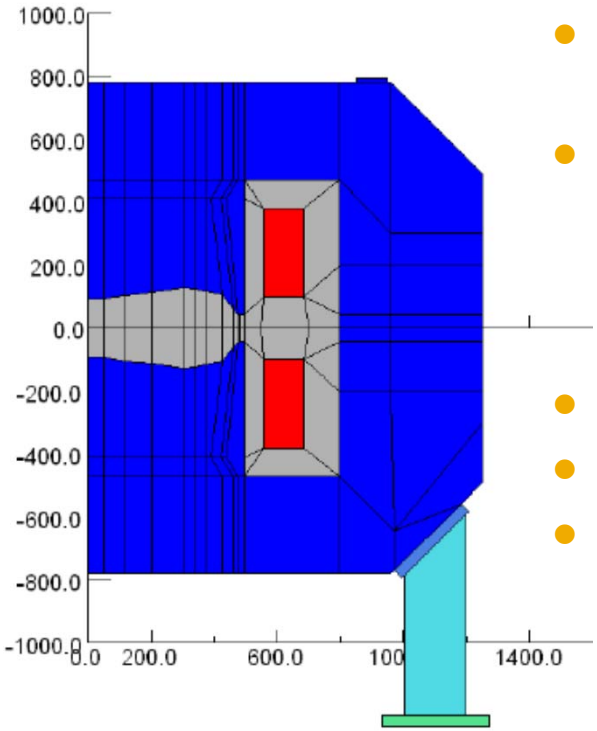
Content

i. Tools for magnetic field finite element modeling with OPERA
ii. Tools related to the synchro-cyclotron beam-dynamics
   a) Update of the orbit tracking code AOC for the synchro-cyclotron case
   b) A tool to dertermine the (properties of) synchronous particles
   c) A tool to study the longitudinal phase space motion
   d) A tool to study the effect of harmonic field errors in the horizontal orbit-center phase-space
iii. A tool for fast computation of iron shims in a high field environment
iv. Tools for smoothing of magnetic field maps

Tools for magnetic modeling in OPERA

- OPERA2D
- OPERA3D => modeler interface
  - Easy to use
  - Easy to include fine geometrical details
  - 3D FE-mesh automatically generated;
    - Tetrahedal mesh => less regular => magnetic fields may be more noisy
- OPERA3D => pre-processor interface
  - More difficult to use and to include geometrical details
  - 3D FE-mesh full created by the user and more regular
    - Hexahedral mesh => less noisy magnetic fields => more precise prediction of magnetic forces

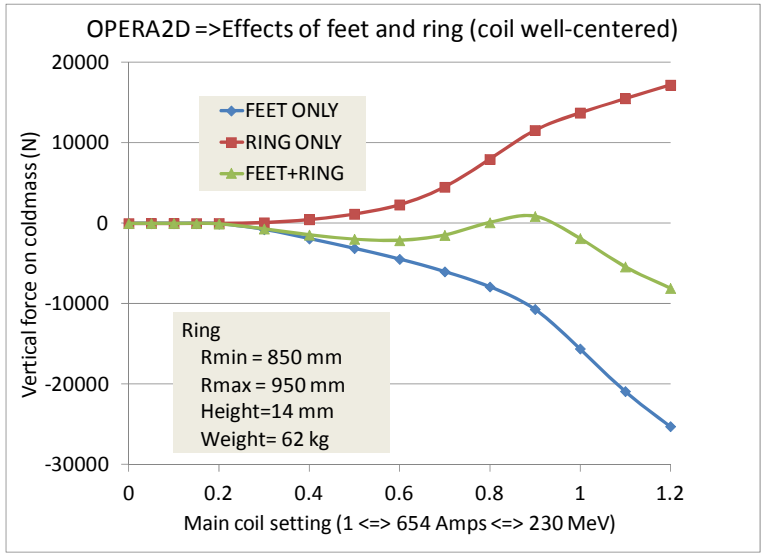
OPERA2D



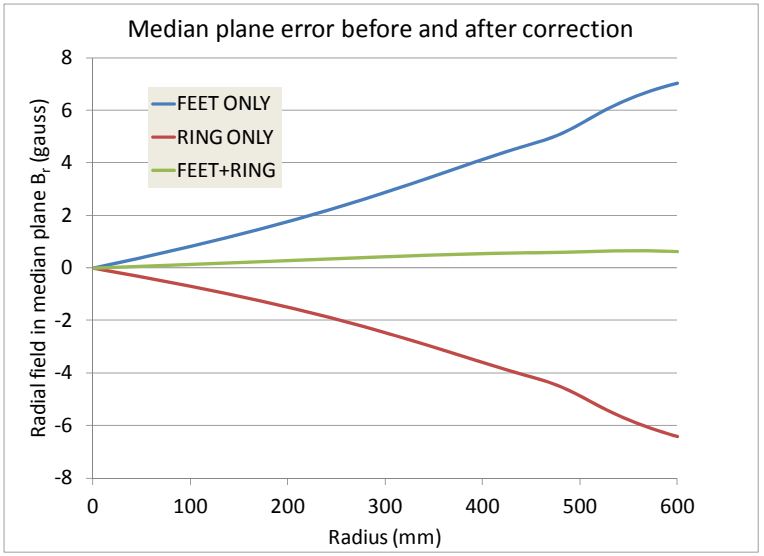
- Initial design of a synchro-cyclotron can very well be done in OPERA2D => rotational symmetry
- Fast optimization of dimensions
  - Pole profile => magnetic field maps => tune functions
  - Yoke dimensions => stray-fields
  - Coil dimensions => Maximum field on the coils
- Yoke-penetrations + feet =>include by stacking factors
- Extraction-elements => assume fully saturated iron
- Study of special features
  - Vertical asymmetry
    - Median plane errors
    - Forces on the cold-mass
  - Compensation of vertical asymmetry

Compensation of median plane error due to cyclotron feet calculated with OPERA2D

Force on cold mass compensated by iron ring on top of yoke

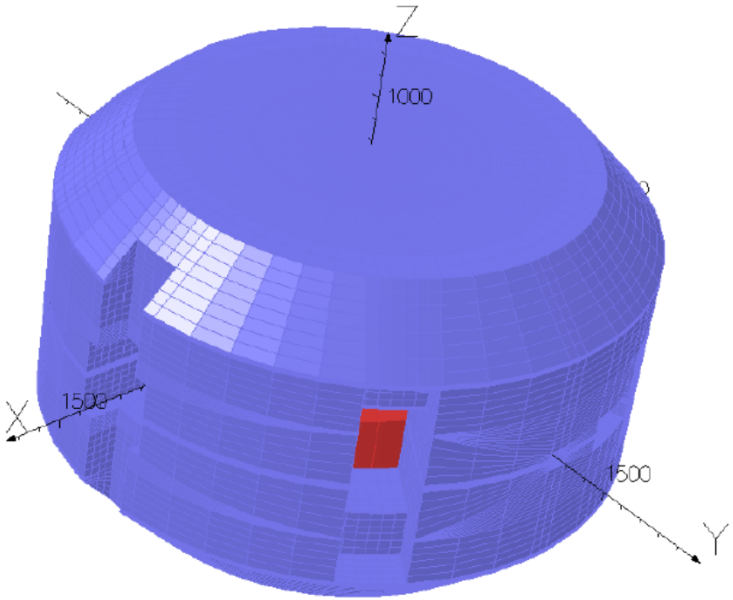


Median plane magnetic field error also compensated



Coil forces in the S2C2 calculated with the pre-processor

A pre-processor model with the typical hexahedral mesh



Differential forces on the cold-mass due to translations or rotation can be calculated with better precision in the pre-processor

FORCES AND TORQUES ACTING ON THE MAIN COIL SYSTEM DUE TO COIL DISPLACEMENTS AND ROTATIONS							
		FORCES			TORQUES		
		dFx ton/mm	dFy ton/mm	dFz ton/mm	dTx Nm/mm	dTy Nm/mm	dTz Nm/mm
coil shift	x-direction	1.99	-0.05	0.00	0	-9	8
	y-direction	-0.05	2.00	0.00	10	2	41
	z-direction	0.00	0.00	0.56	-80	-201	0
coil rotation		dFx ton/deg	dFy ton/deg	dFz ton/deg	dTx Nm/deg	dTy Nm/deg	dTz Nm/deg
	around x-axis	-0.02	0.00	-0.12	91559	-4609	-80
	around y-axis	-0.05	-0.01	-0.30	-4484	91305	79

- All forces vary linear with displacement or rotation
- All coil movements are unstable => forces want to increase their cause

OPERA3D model design approach

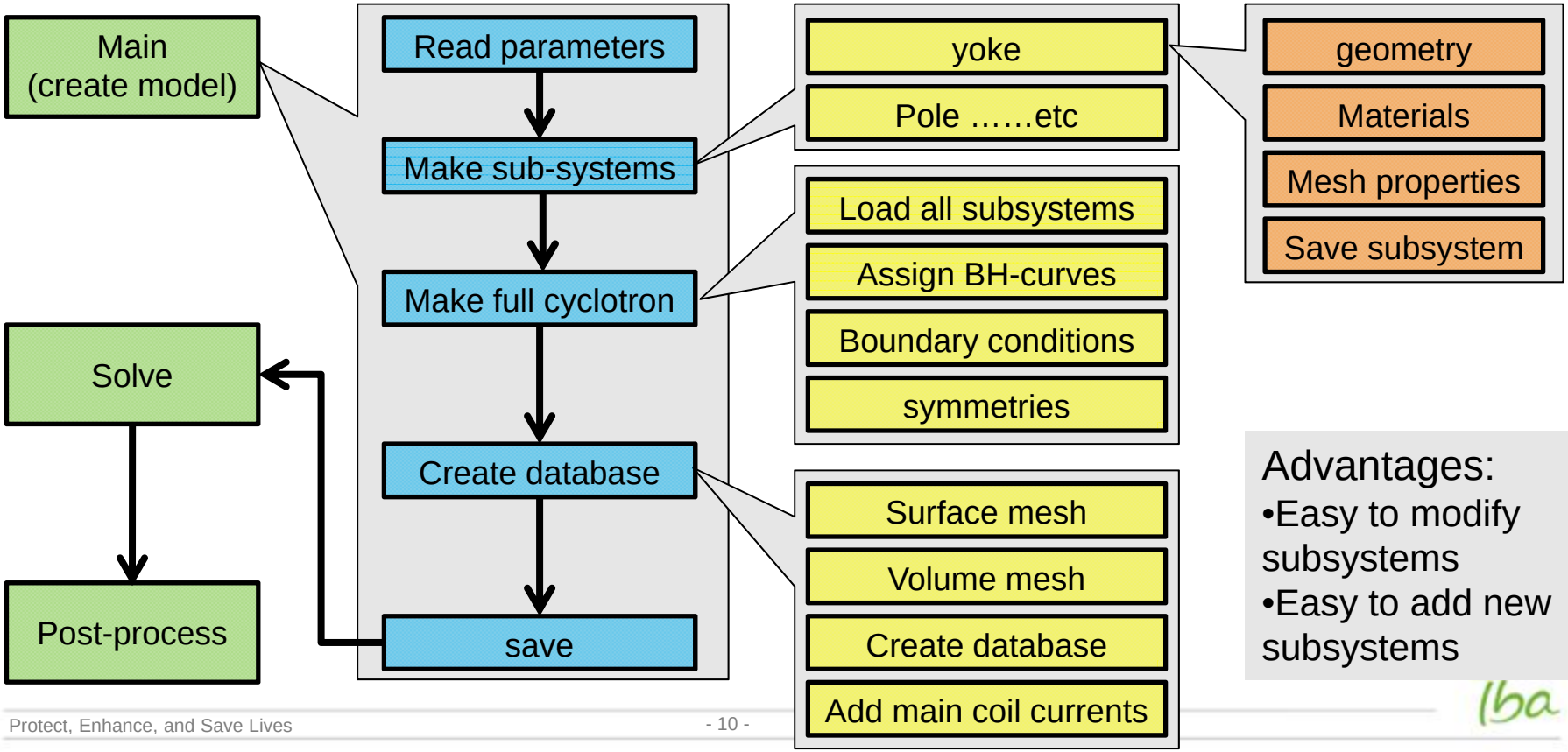
- Full parameterization of 3D models
- Automatic generation of models using macro-structures
- One common macro-structure for all different types of IBA cyclotrons:
  - S2C2, C230, C30-family, C3, …..
- Automatically keep track of and save each different model with a unique model number in a separate directory
  - with all sub-files required to re-generate the model if needed
- Verify iron BH-curves with in-house permeability meter
- Keep track of software modifications by use of the sub-versioning software SVN

OPERA3D

Different types of parameters

- All dimensional parameters and pole profiles
- Main coil settings
- Material properties (different BH-curves for different subsystems)
- Finite element mesh sizes
- Solver tolerances
- Switches for (de-) selection of separate subsystems
- Switches for filling separate subsystems with air or iron
- …….

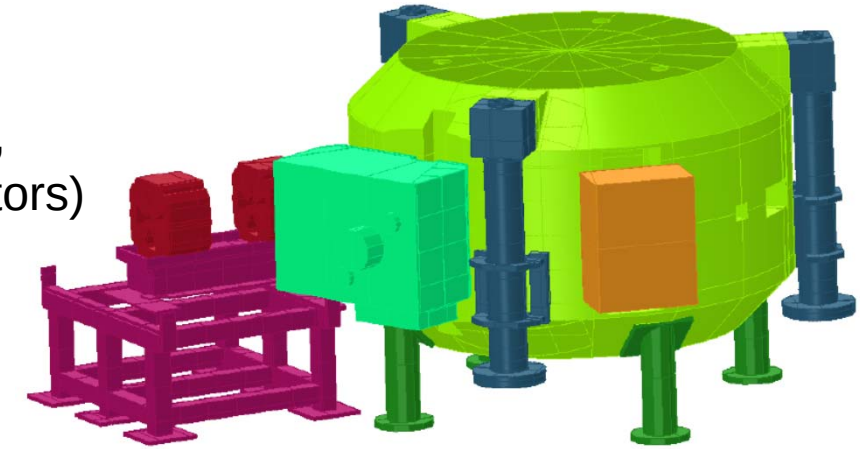
General macro structure for a cyclotron model in OPERA3D



Advantages:
- Easy to modify subsystems
- Easy to add new subsystems

Elements included in an OPERA3D model

i. Yoke+poles+coils
ii. Yoke penetrations
iii. Extraction system (regenerator, channels, first harmonic correctors)
iv. Harmonic coils
v. External systems
   a) Cyclotron feet
   b) Yoke lifting system
   c) Shields (cryo-coolers + rotco)
   d) External quadrupoles



Two poster presentations about OPERA modeling of the S2C2

Due to saturation of yoke iron:
- external systems have to be included in the magnetic design studies
- Cryo-coolers and rotco must be shielded

Tracking and beam dynamics tools specifically related to the synchro-cyclotron

Comparison between isochronous and synchro-cyclotron

	AVF-isochronous	synchro-cyclotron
magnetic field	isochronous with flutter	rotational-symmetric and decreasing with radius
revolution frequency	(almost) constant	decreasing during acceleration
RF frequency	constant	periodically modulated
RF voltage	constant	periodically modulated
beam injection	continuous	limited time window for capture
beam extraction	different ways	regenerative extraction
operation	cw	pulsed
beam intensity	high	low
transverse focusing	alternating	weak
multi-pactor	often no-problem	suppressed by bias-voltage
central region size	normal	very compact
longitudinal dynamics	meta-stable	energy-phase oscillations bound by a separatrix

Has impact on simulation tools

Modifications to the IBA in-house tracking code AOC

- Include the pulsed character of the RF-frequency and voltage
  - Change of independent variable to total RF phase advance:

$$\tau = \omega t \implies \tau = \int \omega dt$$

  - Interpolate in RF-tables to get frequency and voltage as function of τ

$$\omega = \omega(\tau) \text{ and } V = V(\tau)$$

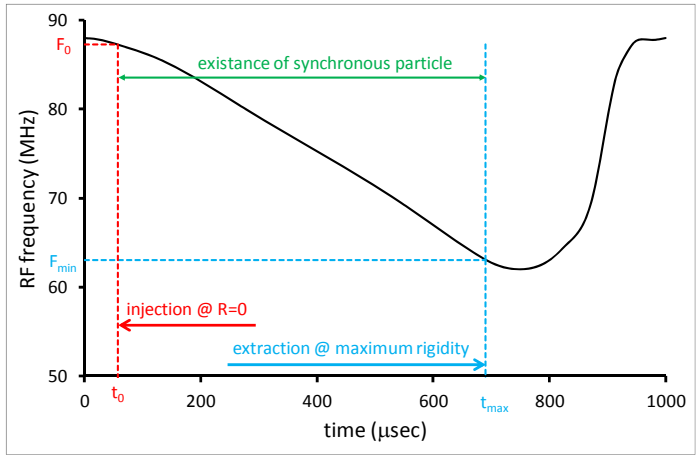
  - Make necessary modification to the equations of motion
- Allow an option to formulate the equations of motion in cartesian coordinates instead of polar coordinates
  - For s2c2 orbit scales to much lower size in the center and polar coordinates may be problematic
  - however, same results were obtained for both cases
- Include the multi-pactor bias electrode voltage as a separately adjustable parameter in the electric field maps
- In progress => nonlinear vertical motion

The synchronous particle

Synchronous particle => A particle for which the revolution frequency is equal to the RF frequency at all times during the acceleration

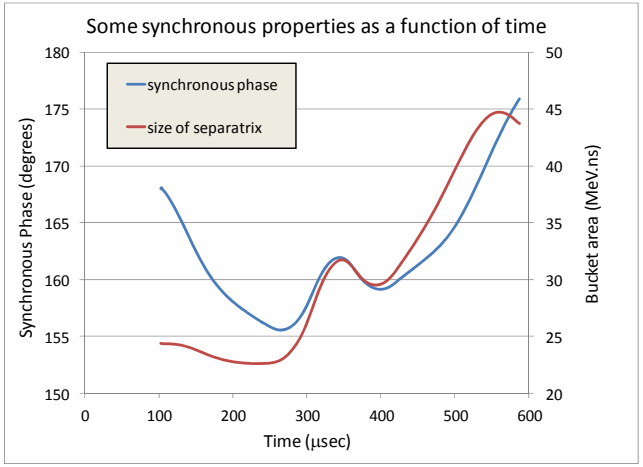
Equilibrium solution of the longitudinal motion (comparable to equilibrium orbit for radial motion)

Pulsed RF-frequency



The program synchronous_particle calculates the properties of this particle such as synchronous-phase and energy, separatrix etc as function of time

Synchronous phase and bucket area



Calculation of the synchronous particle

Mathematical definition of the synchronous particle

$$\frac{q\hat{V}N\sin\varphi_s}{E_s} = -\frac{2\pi}{K\omega_s^2}\frac{d\omega_s}{dt}$$

$$K = -\frac{\Delta\omega/\omega}{\Delta E/E} = 1 + \frac{n}{\beta^2(1-n)}$$

V, N, dω/dt => RF properties

K, ω => magnetic field properties

φ_s => synchronous phase

Following steps are made:

i. For given time value find the RF-properties such as RF-frequency ω_{RF}, rate of frequency change $d\omega_{RF}/dt$ and dee-voltage *V*

ii. For resulting RF-frequency find the corresponding radius in the magnetic field *r*.

iii. For resulting radius *r* find the magnetic field properties *n* and *K*.

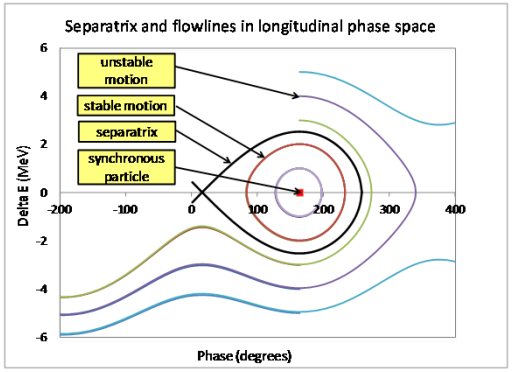
iv. Calculate all required properties of separatrix

Main action of program is interpolating in frequency table and magnetic field map

Longitudinal phase motion code

Decouple the 2D-longitudinal phase motion from the general 6D-motion studied by particle tracking in order to speed up calculations. This allows to study:

- capture of particles in the RF bucket
- stability of RF bucket during acceleration
- following particles during many RF-pulses and study if lost particles may be recaptured in the bucket in a later pulse
- As function of:
  - RF-frequency and voltage table
  - Magnetic field properties (*K*-value)
- Independent variable is time t
- Dependent variable are RF-phase and particle energy (or deviation)
- Properties of synchronous particle are obtained from the previous program



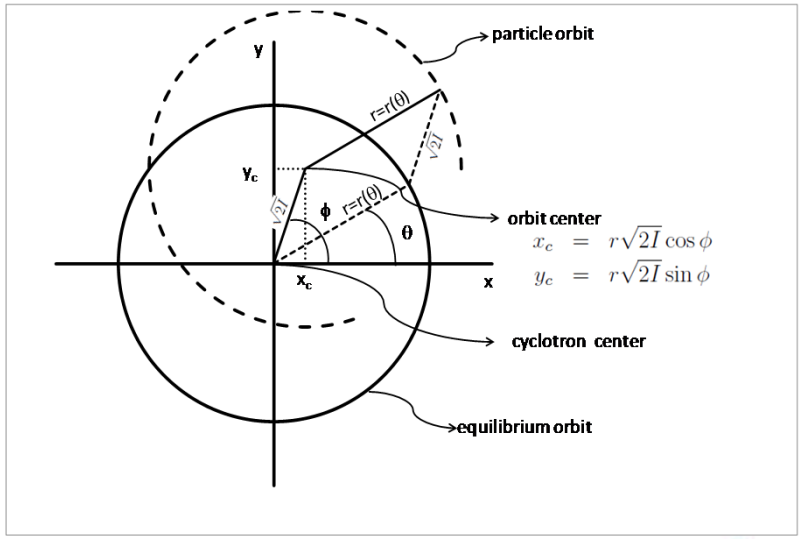
$$\frac{d\varphi}{dt} = 2\pi F_{RF}\left(1 - \frac{hF_p}{F_{RF}}\right) \cong 2\pi F_{RF} K \frac{\Delta E}{E_s}$$

$$\frac{d\Delta E}{dt} = F_{RF}\frac{Nq\hat{V}}{h}(\sin\varphi - \sin\varphi_s)$$

Two poster-presentations based on this subject

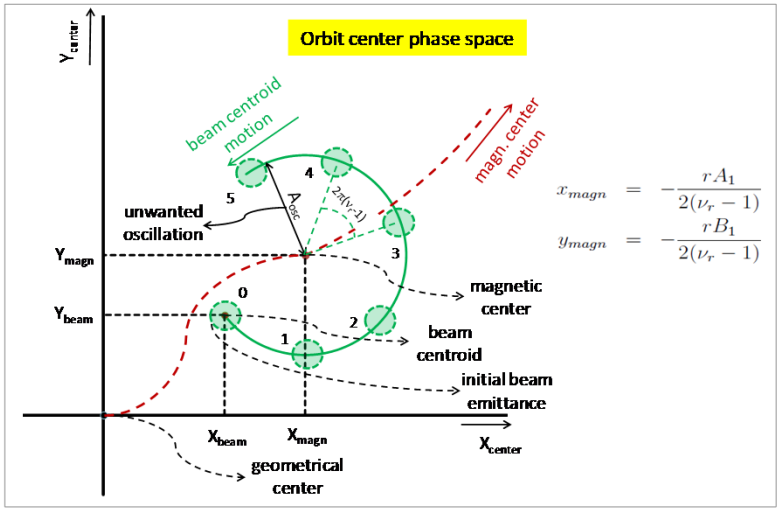
A tool for the study of radial beam optics in orbit-center phase space

- Radial betatron oscillations in a cyclotron can be represented by an amplitude and a phase, but also by the coordinates of the orbit centre.
- The latter can be more convenient because the orbit centre oscillates slowly (frequency ν_r-1) as compared to the betatron oscillation itself (frequency ν_r)
- In the orbit centre representation, the equations of motion can be simplified using approximations that make use of the slowly varying character of the motion and the integration can be done much faster
- The orbit can be re-constructed from the orbit center coordinates, the equilibrium orbit radius r(θ) and the value of the independent variable θ. The canonical orbit center variables can be expressed in a Cartesian form (x_c,y_c) or in a polar form (action-angle variables (ϕ,I)).
- Acceleration is taken into account by smooth increase of the equilibrium orbit radius with increasing azimuth



Example: effect of a first harmonic during acceleration

- A First harmonic field error, displaces the magnetic center of the cyclotron relative to the geometrical center.
- Particles *execute a betatron-oscillation around the magnetic center.*
- *With acceleration, the magnetic center itself is also moving and the total motion is a complicated superposition of the two separate motions*
- *The beam quality will degrade when the centroid of the beam is shifting with respect to the magnetic center of the cyclotron.*

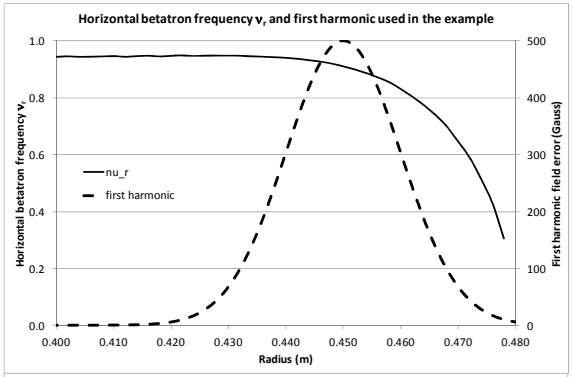


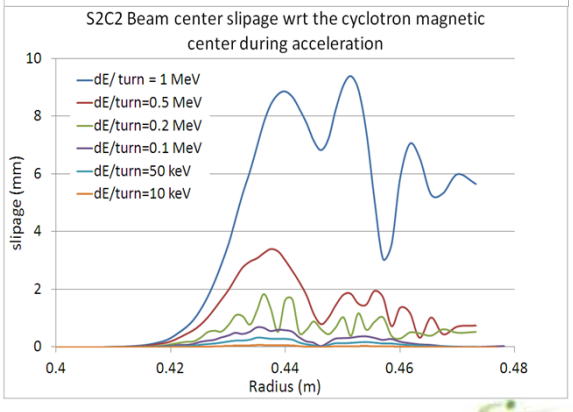
- *This will occur when the acceleration is very fast and/or the gradients of the first harmonic field error are large.*
- *The distance A_{osc} is the amplitude of the betatron oscillation and is a good measure for the harmful effect of the first harmonic field error. Numbers indicate subsequent turns*

Example: effect of a first harmonic during acceleration

- Slippage between the beam centroid and the magnetic center of the S2C2 as calculated numerically with the program orbit_center_motion.
- The beam is accelerated from 15 MeV up to extraction.
- Initially the beam is well-centered and the magnetic center coincides with the magnetic center.
- During acceleration a coherent oscillation A_{osc} is building up.
- For fast acceleration, this amplitude becomes large and the beam quality is destroyed.
- For slow acceleration, the beam adiabatically follows the magnetic center and no or very little oscillation amplitude is generated.
- For the S2C2 the orange curve (dE/turn=10 keV) is applicable and the loss of beam quality is negligible.

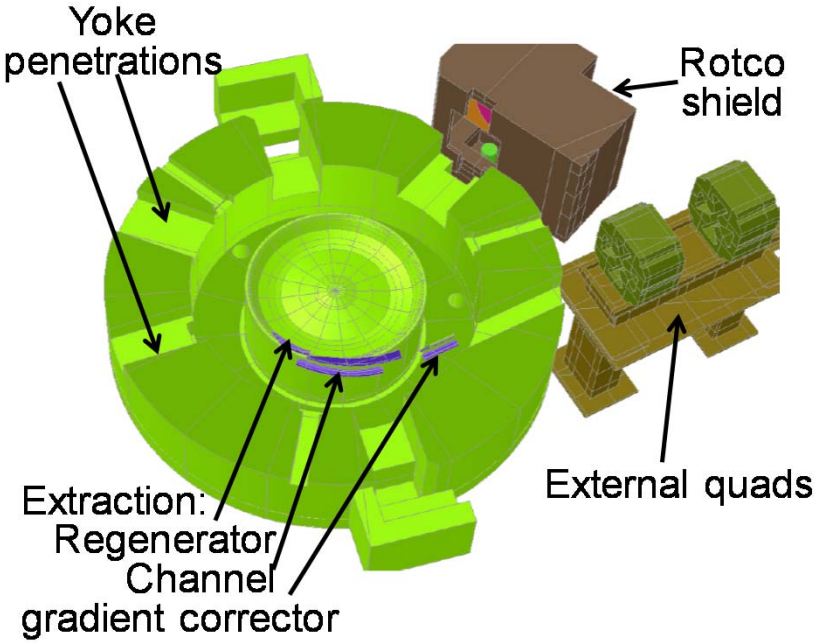
One poster presentation about this subject





Fast computation of magnetic shimming in a high field environment

- Asymmetric features in the design of the S2C2 create large first harmonic field errors that may have adverse effects on the beam
  1) orbits approaching extraction may be so much off-centered that they hit the dees
  2) orbits in the cyclotron center may be not well-accelerated due to large off-centering
  3) Beam quality may degrade during acceleration
- A calculation tool was made to compensate such errors by multiple sector shaped or rectangular iron shims that are assumed to be uniformly magnetized



Iron shims considered as two opposite monopoles

- A small iron shim placed in a very high magnetic field immediately becomes completely saturated and uniformly magnetized parallel to the external magnetic field .
- It can be considered as the sum of a positive magnetic monopole attached to the lower surface and a negative magnetic monopole attached to the upper surface.
- The magnetic charge density is equal to the polarization strength J_0 (about 2 Tesla for iron)

MAGNETIC MONOPOLE POTENTIAL FUNCTION

$$d^2\psi = \frac{J_0 \Delta A}{4\pi\mu_0 r}\cos\alpha$$

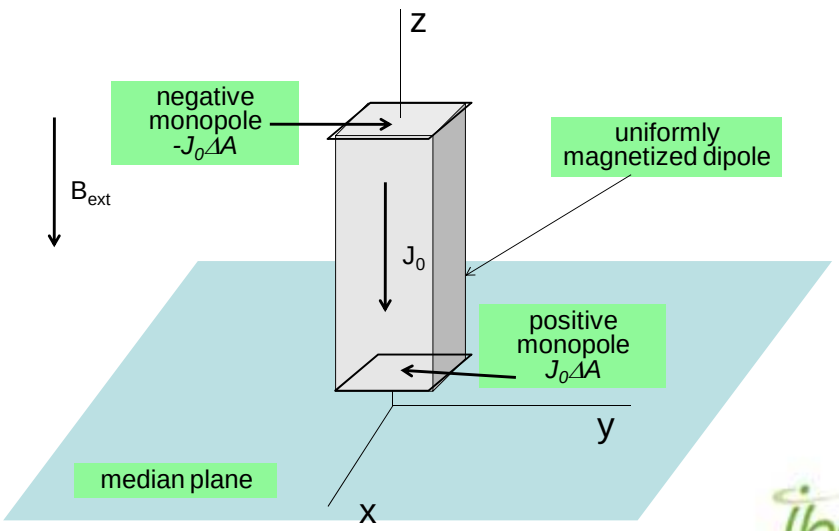
MEDIAN PLANE MAGNETIC FIELD CONTRIBUTION

$$d^2 B_z = \frac{J_0 \Delta A}{4\pi}\frac{z}{|\vec{x}-\vec{x}_0|^3}\cos\alpha$$

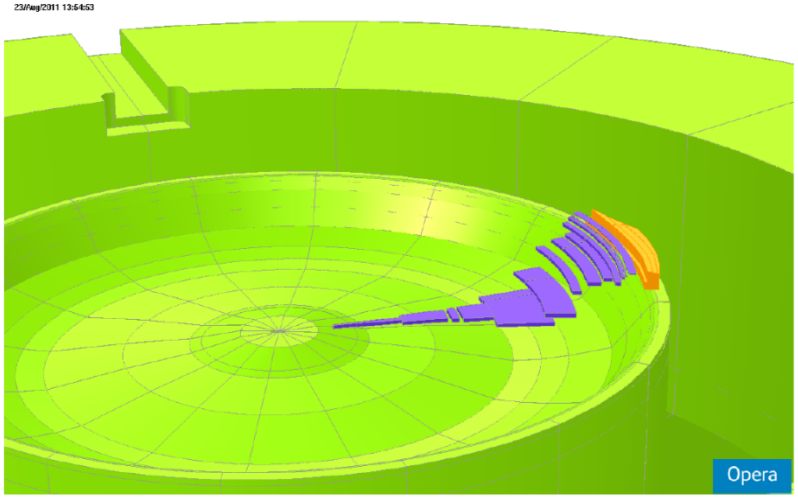
INTEGRATE OVER SURFACE OF MONOPOLE

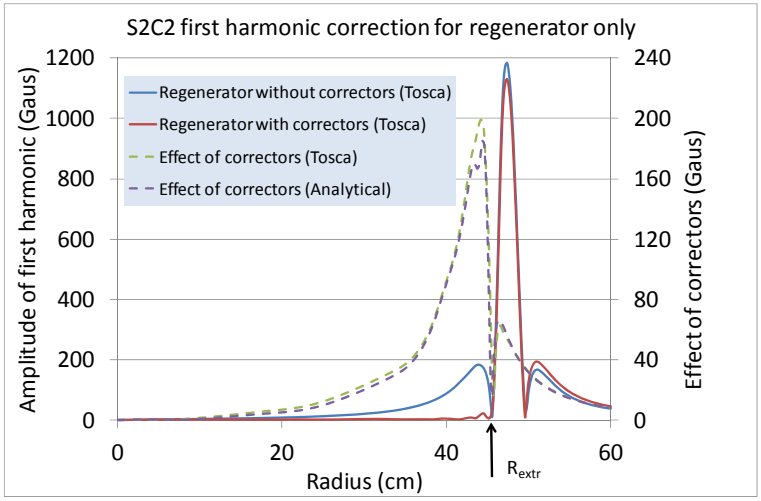
SECTOR SHAPED SHIM

$$d^2 B_z = \frac{J_0}{4\pi}\frac{zrdrd\theta\cos\alpha}{\sqrt[3]{(r-r_0\cos(\theta-\theta_0))^2 + r_0^2\sin^2(\theta-\theta_0)+z^2}}$$



Calculation example: S2C2 regenerator compensation





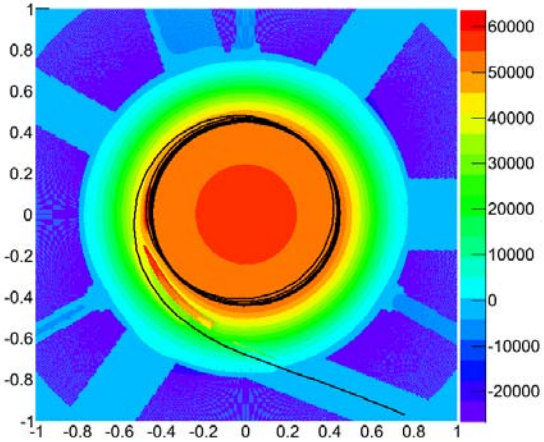
- The left scale shows the first harmonic calculated with OPERA3D (blue solid line without compensation and red solid line after compensation).
- The right scale shows the effect of the correctors (green dashed line for OPERA3D and black dashed line for the analytical program)

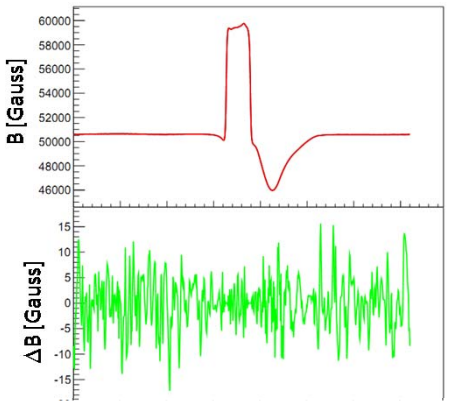
One poster presentation about this subject

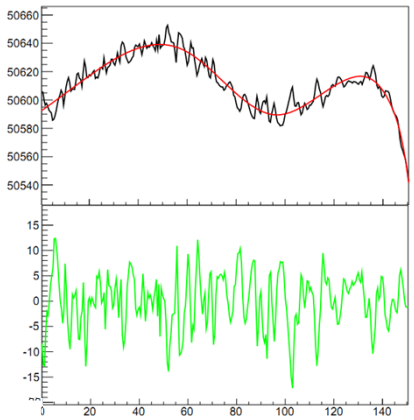
Tools for smoothing of magnetic field maps

- OPERA3D calculated field maps can be very noisy especially in the extraction region were the vertical gap is small
- In such region the vertical beam optics is strongly non-linear
- To simulate extraction in AOC, nonlinear field-expansion with respect to the median plane is needed which will require up to third order derivatives of the field
- This is only possible after careful smoothing of the field data
- Two methods are used:
  - Least square cubic spline fitting (De Boor method)
  - least square fitting of polynomial functions to grid of points (Savitzky-Golay filtering)

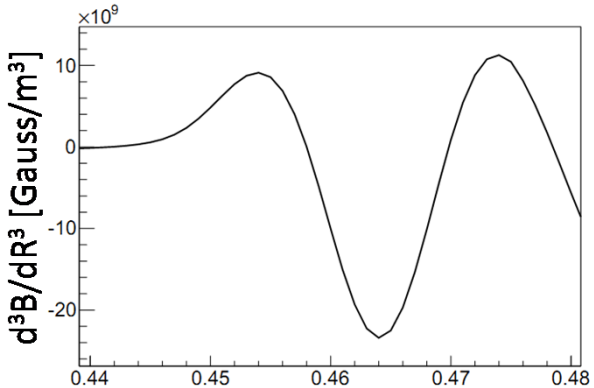
Eaxample smoothing of s2c2 fieldmaps







Perfectly smooth 3rd order derivatives are obtained



Made by Jarno Van de Walle

Related poster presentations

1. Fast computation of magnetic shimming in a high field environment
2. IBA S2C2: coil forces and median plane errors due to coil displacements
3. Median plane error compensation in the S2C2
4. IBA S2C2: The influence of first harmonic field errors on the beam quality
5. Phase motion: a program for studying longitudinal beam optics in a synchrocyclotron
6. A longitudinal phase space study of H^+ recapture in a synchrocyclotron
7. Developments on the S2C2 mapping system
8. Status of the Proteus One S2C2 RF System
9. IBA S2C2 Quench Study: Induced forces on Dees and Liner

Thank you

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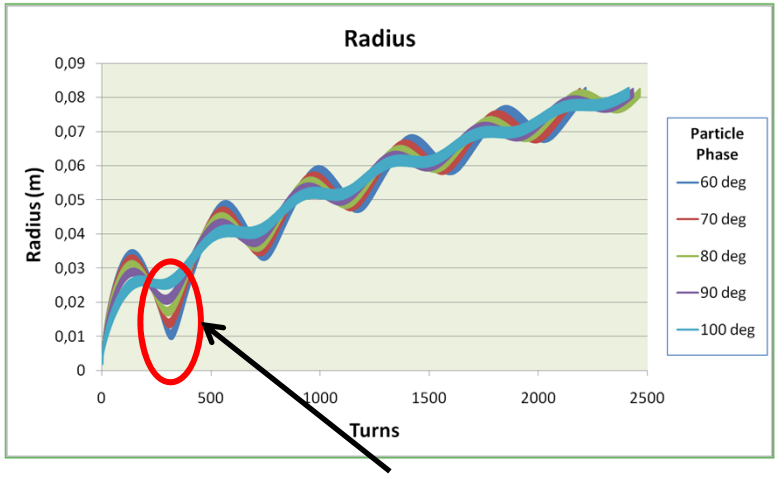
Illustration of some specific features calculated with AOC

Synchrotron oscillations of particle radius



Backward -deceleration towards the source

Particle bunches followed during many turns