NUMERICAL ORBIT TRACKING IN 3D THROUGH THE INJECTOR CYCLOTRON FOR HEAVY IONS AT ITHEMBA LABS

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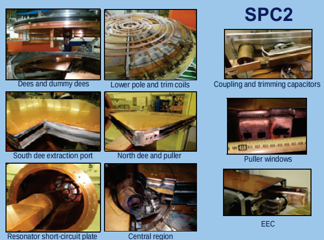
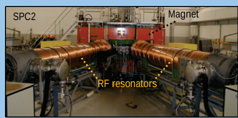
INTRODUCTION

The electric and magnetic fields of the second injector cyclotron (SPC2) [1] were modelled in 3D with finite element methods, using OPERA-3d [2], in an effort to determine the cause of the relative poor 5% beam transmission through the machine in the 8-turn mode. Simulation of the particle motion in SPC2 was done using parameters for acceleration of a $^{20}Ne^{3+}$ beam. Using TOSCA [2], the isochronous magnetic field was calculated from a complete cyclotron magnet model and the electrostatic field distribution from a dee electrode model. The SOPRANO-EV [2] modelling of the RF resonance conditions of the resonators provided radial electric field profiles in the acceleration gaps. A command line program was developed to combine the information of the three models and implement time-dependent control of the electrostatic fields during the particle tracking. Multi-particle orbit calculations were done with two different optimization methods and at two harmonic numbers. In addition, based on calculated data from OPERA-3D [2], the parallel particle-in-cell code OPAL-CYCL [3, 4] was used to calculate a beam track for comparison.

SPC2

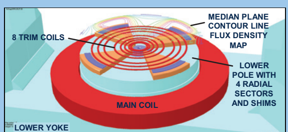


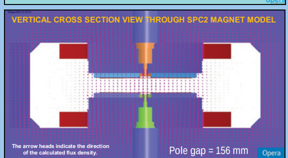


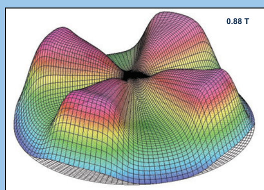
Spiral Inflector

SPC2 pre-accelerates heavy ion beams before injection into the separated sector cyclotron. Beam from one of two external ion sources is axially injected from below into SPC2 through a spiral inflector. It is a solid pole cyclotron with 4 radial magnet sectors and 8 trim coils. The electric fields in the 4 acceleration gaps are provided by two horizontal λ/4 co-axial rf-resonators with 90° dees that operate in the frequency range 8.6 MHz to 26 MHz [5].

MAGNET MODELLING







The calculated isochronous magnetic flux density in the median plane.

The finite element model of the SPC2 magnet includes all geometrical detail of the iron and coils, together with the axial hole in the yoke that, amongst others, contains the solenoids and steerer magnet in the lower half of the yoke (not shown). The known magnetic material BH-characteristics of the iron is used in the simulation. The nominal magnetic field is 0.88 T.

ISOCHRONOUS FIELD PREDICTION [6]

(a): Select a particle from a list in the dropdown box.

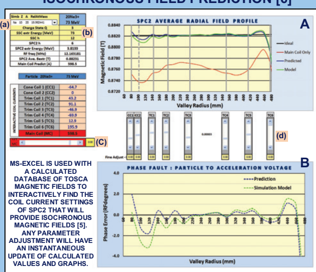
(b): Enter the charge state, extraction energy from the separated sector cyclotron and its harmonic number (yellow cells)

Some calculated parameters of SPC2 are shown in the white cells. The black line in window **A** shows the calculated isochronous average radial field profile for the selected particle rigidity.

(c): The main coil current is set with the red slider (SET MC) to the predicted value.

The calculated magnetic field contribution of the main coil is shown as the red line profile in window **A**.

(d): Use the vertical sliders for individually adjusting the trim coil values until the prediction graph (blue) best fits the isochronous graph (black).



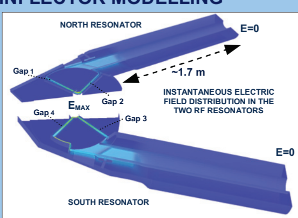
The predicted total magnetic field profile from all the slider settings is shown in window A in blue.

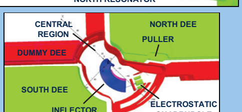
Any change in a slider position automatically updates the associated coil current value, shown in the group of cells middle left. The coding prevents current settings outside the respective ranges of the power supplies.

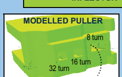
The predicted currents were use as input values to calculate the isochronous field with TOSCA for the $^{20}Ne^{3+}$ beam simulations in the SPC2 model and its radial field profile show good agreement (green graph).

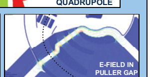
The calculated phase errors from the predicted and modelled fields are shown with dashed lines in window **B**, respectively in blue and green. In general the deviation is not more than 1 rf degree. The maximum deviation of 3 rf degrees is still acceptable.

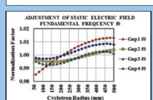
RESONATOR AND INFLECTOR MODELLING

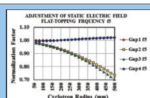












The dees, dummy dees, puller and central region that contain the spiral inflector and electrostatic quadrupole were built into a model to calculate the static electric field distribution with TOSCA. In order to have the real charge distributions on the electrode surfaces under RF conditions, the electric field profile in each acceleration gap was calculated with a model for each of the two rf-resonators, using the eigenvalue solver of SOPRANO. The illustration on the bottom-right shows the calculations with flat-topping at the 5th harmonic of the fundamental RF. Although SPC2 does not have flat-topping resonators, the calculated results agree with measured data of the flat-topping resonators of injector cyclotron 1.

CONTROL PROGRAM

An OPERA-3D command line program is used to combine the calculated information of the simulation models and create parameters for adjusting the conditions during the tracking of the particles through SPC2. The conversion of the calculated static electric field, E_s, to a time- and positional dependent field, is defined by

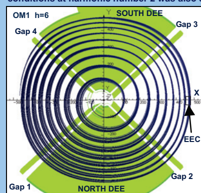
$$E_t = A_R.E_s.\sin(2\pi f t + \phi_0),$$

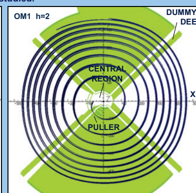
where f is the RF frequency, ϕ_0 the injection phase of the particle to the dee voltage, t the time-of-flight parameter [7] that is inherently available when particle tracking is done with OPERA-3d POST [2]. The radial adjustment of the RF field amplitude in an acceleration gap, A_R, is calculated in-flight from the applicable radial function. Minor adjustments in the control program permit calculations at other harmonic numbers, implementation of alternative optimization methods and, if needed, to have flat-topping included.

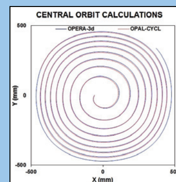
Simulating the 8-turn orbit mode in SPC2 requires cyclotron settings such that a particle crosses 34 acceleration gaps before reaching the electrostatic extraction channel (EEC), followed by another acceleration gap crossing before exiting the machine. The horizontal width of the EEC gap at the entrance is 14 mm and its radial centre position is adjustable between 456 and 470 mm. The calculations reported here are based on the machine operational parameters for a $^{20}Ne^{3+}$ beam with extraction energy of 3.81 MeV, which requires acceleration at harmonic number 6 with a peak dee voltage of 37.4 kV at 12.16 MHz. The spiral inflector voltage and ion source extraction voltages are respectively 4.3 kV and 13.37 kV.

3D TRACKING CALCULATION RESULTS

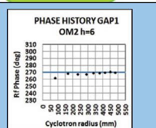
A bunch length of 14 RF degrees was defined by three reference particles, of which one is leading the injection phase of the central particle by 7 RF degrees and the other lags by 7 RF degrees. For multi-particle analysis transversal phase ellipses with an emittance of 10 π mm.mrad were used for each of the three reference particles. Two beam optimization methods were used for the orbit calculations. For optimization method 1 (OM1), the injection phase and dee voltage were adjusted to minimize the energy spread at extraction. Optimization method 2 (OM2) comprises of an iterative process of improving the beam centring, field isochronization and injection phase corrections, and finally by changing of the injection angles of the leading and lagging particles in the beam bunch, respectively, by +1° and -1° from that of the central particles. The last step of differentiated injection angles with OM2 cannot be implemented in SPC2 at this stage. Although the RF-system of SPC2 permits only harmonic number 6 for acceleration of a 3.81 MeV $^{20}Ne^{3+}$ beam, the intrinsic better beam dynamic conditions at harmonic number 2 was also studied.







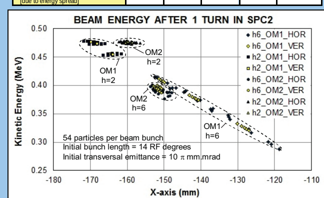
Starting on the median plane from a point between the inflector and puller, the central particle orbit for OPERA-3d was also calculated with OPAL-CYCL and the orbits are in good agreement, as shown above. Identical input parameters were used, except that the radial correction factor on the acceleration voltage, A_R, was not implemented for OPAL-CYCL.



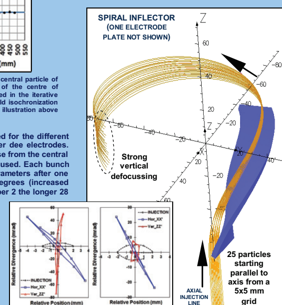
The calculated phase history of the central particle of the beam bunch, at the crossing of the centre of acceleration gap number 1, was used in the iterative process to optimize the centring, field isochronization and injection phase corrections. The illustration above is for OM2 with harmonic number 6.

The calculated orbits of the multi-particle 14 RF degree beam bunches were calculated for the different optimization methods and harmonic numbers and shown superimposed on the lower dee electrodes. Each bunch is defined by three reference particles, one leading and one lagging in phase from the central particle and for each reference particle transversal emittances of 10 π mm.mrad were used. Each bunch has a total of 54 particles. A comparison of some calculated cyclotron and beam parameters after one turn, at the EEC and at extraction are tabulated below. Bunch lengths of 28 RF degrees (increased intensity) could also be extracted with OM2 at harmonic number 6. For harmonic number 2 the longer 28 RF degree bunches were extracted with both OM1 and OM2.

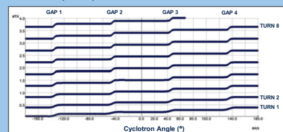
HARMONIC NUMBER	6	6	2	2	UNIT
OPTIMIZATION METHOD	OM1	OM2	OM1	OM2	
Radio-frequency	12.16	12.16	4.053	4.053	MHz
Acceleration voltage	43.9	41.5	38.1	38.1	kV
Bunch length	14	14	14	14	RF deg
Energy after 1 turn	0.417	0.401	0.478	0.478	MeV
Energy spread after 1 turn	30.7	6	4.8	1.3	%
Extraction energy	4.02	4.04	3.97	4	MeV
Extraction energy spread	3	1.5	2.2	0.9	%
Radial width at EEC [due to energy spread + emittance]	11	9	9	5	mm
Radial width at EEC [due to energy spread]	7.2	3.6	5.3	2.2	mm



The kinetic energy of the particles of the beam bunches, calculated and compared after one turn in the cyclotron where it intersects with the ZX plane at Y = 0. The energy spread significantly improved both from OM1 to OM2 and from harmonic number 6 to 2.



Analysis of the beam transmission through the inflector showed large defocussing of the beam, especially in the vertical direction (Z). With larger beam emittances, beam losses can be expected at the 10 mm high puller window, which is located about 60 mm downstream from the inflector. Back-tracking of 10 π mm.mrad horizontal and vertical phase ellipses through the inflector to the vertical injection line showed unattainable injection conditions. The strong vertical defocussing of the inflector is quantified with the calculated phase space transmission results.



The energy gain per acceleration gap of the central particle for harmonic number 6 and OM2 are shown with respect to the angular angle of the particle. The extraction energy (#TK on vertical axis) is 4.04 MeV after a total of 35 acceleration gap crossings. Gaps 1, 2, 3 and 4 are at cyclotron angles -135°, -45°, 45° and 135°, respectively.

CONCLUSIONS

- For better transmission at harmonic number 6, more stringent optimization of the beam quality is required from the first turn to extraction.
    - Implementation of the required diagnostic equipment in SPC2, e.g. a phase probe.
- Defocussing of the beam by the spiral inflector causes losses at the puller window.
    - New spiral inflectors are being calculated.
- Methods and tools for realistic 3D tracking calculations in any cyclotron.
    - Further development.
- User-friendly method for coil current prediction in SPC2.
    - To be improved.
- Space-charge effects not calculated.
    - OPAL-CYCL to be used.

ACKNOWLEDGEMENT

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REFERENCES

[1] Z. B. du Toit *et al.*, "Commissioning of the injector cyclotron for polarised and heavy ions at NAC", in *Proc. 14th Int. Conf. on Cyclotrons and their Applications*, Cape Town, South Africa, 1995, pp. 28-31.
[2] OPERA-3d, http://operafea.com
[3] A. Adelmann, C. Kraus, Y. Ineichen, S. Russel and J. J. Yang, "The OPAL framework - User's reference manual", PSI Technical Report No. PSI-PR-08-02, 2008.
[4] J. J. Yang, A. Adelmann, M. Humbel, M. Seidel, and T. J. Zhang, "Beam dynamics in high intensity cyclotrons including neighbouring bunch effects: model, implementation and application", *Phys. Rev. ST Accel. Beams*, 064201, 2010.
[5] List of cyclotrons and booster-rings, in *Proc. 14th Int. Conf. on Cyclotrons and their Applications*, Cape Town, South Africa, 1995, entry C52, p747.
[6] J. L. Conradie *et al.*,"Status report and new developments at iThemba LABS", in *Proc. 20th Int. Conf. on Cyclotrons and their Applications*, Vancouver, Canada, 2013, MOPPT032, p95.
[7] *OPERA-3d Reference Manual*, Ver. 17R1, pp 887-888.

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