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UNIVERSITÀ DEGLI STUDI DI CATANIA

Investigation on the spiral inflector and central region of the IsoDAR test-bench cyclotron

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for IsoDAR / DAEδALUS collaboration

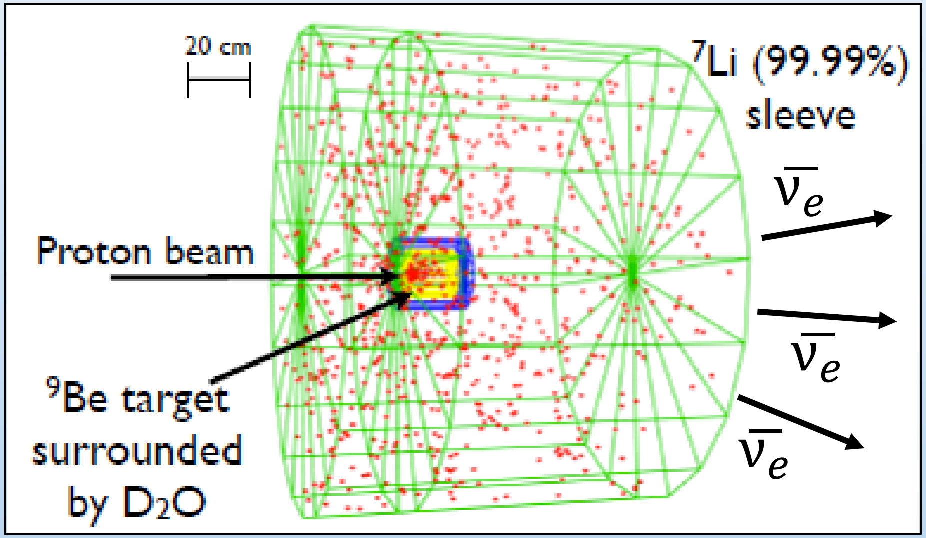
IsoDAR project
(ISOtope Decay-At-Rest)

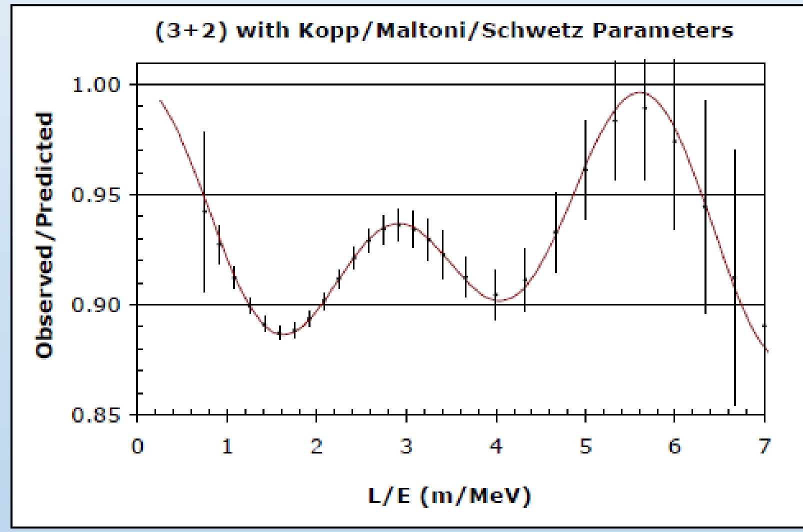
- Goal
- Experimental set-up
- Requirements
- Injection test and test-bench cyclotron

IsoDAR (ISOtope Decay-At-Rest)

Goal: look for the existence of sterile neutrinos

New physics beyond the Standard Model?





- Proton beam into neutron-producing target: p + ^{9}Be -> ^{8}Li + 2p + n
- Secondary neutrons into ~50 kg pure ^{7}Li blanket: ^{7}Li + n -> ^{8}Li

} Production of ^{8}Li isotopes

- ^{8}Li decay produces $\bar{\nu}_e$ with $<E_{\bar{\nu}_e}>$=6.4 MeV: ^{8}Li -> ^{8}Be + e^- + $\bar{\nu}_e$
- $\bar{\nu}_e$ detected by inverse beta decay (IBD) in liquid scintillator-based detector: $\bar{\nu}_e$+ p -> e^+ + n

IsoDAR requirements

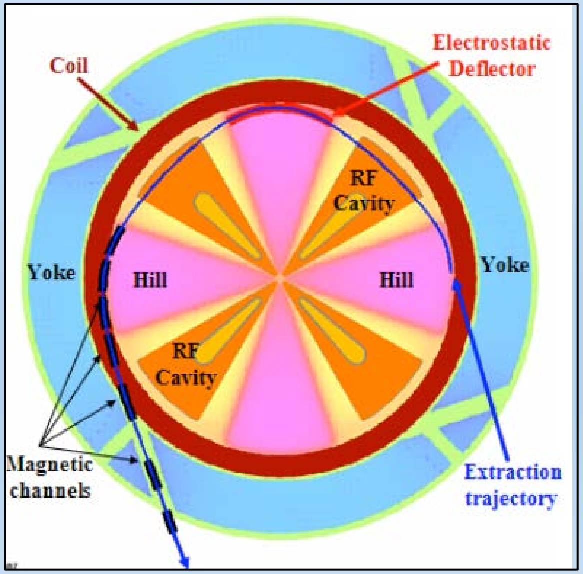
Experiment decisive in 5 years ($\approx 8 \cdot 10^5$ IBD events) → High electronic antineutrinos flux → High proton beam intensity

IsoDAR requires 10 mA proton beam at 60 MeV

How to obtain the beam?

Cyclotron able to deliver a 5 mA H_2^+ beam at 60 AMeV:

- 4 sectors
- Harmonic four
- Extraction through electrostatic deflector
- Stripping of the H_2^+ ions in protons outside the machine

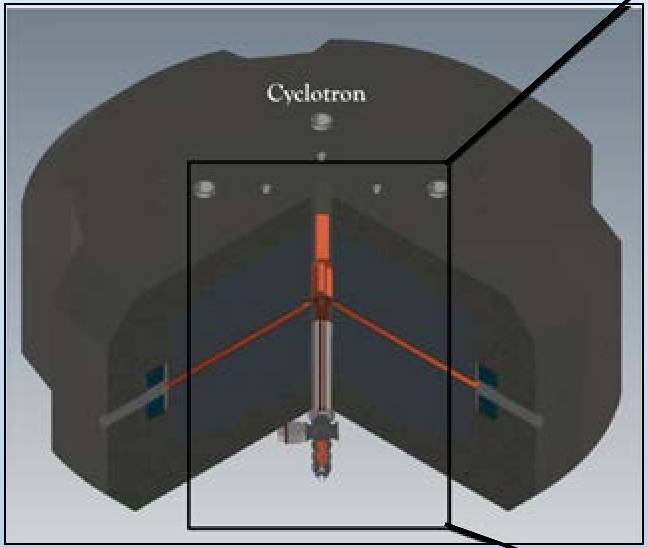


Courtesy of Daniela Campo

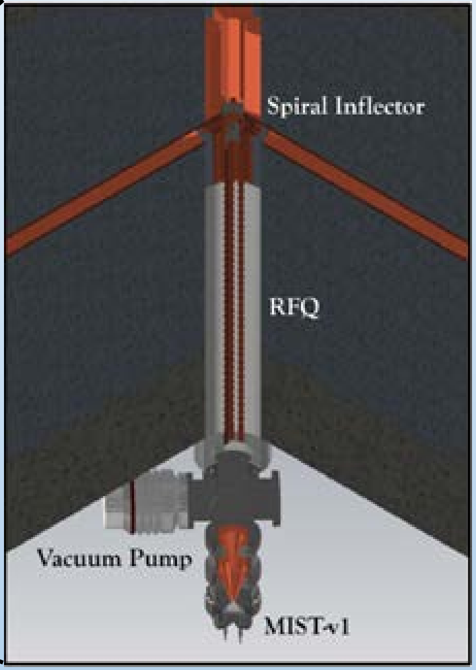
IsoDAR test-bench cyclotron H_2^+ 1 AMeV

Main critical issue: beam injection from the ion source into the cyclotron due to the **high beam current** and correlated serious **space charge effects**

➡ Injection test



IsoDAR cyclotron



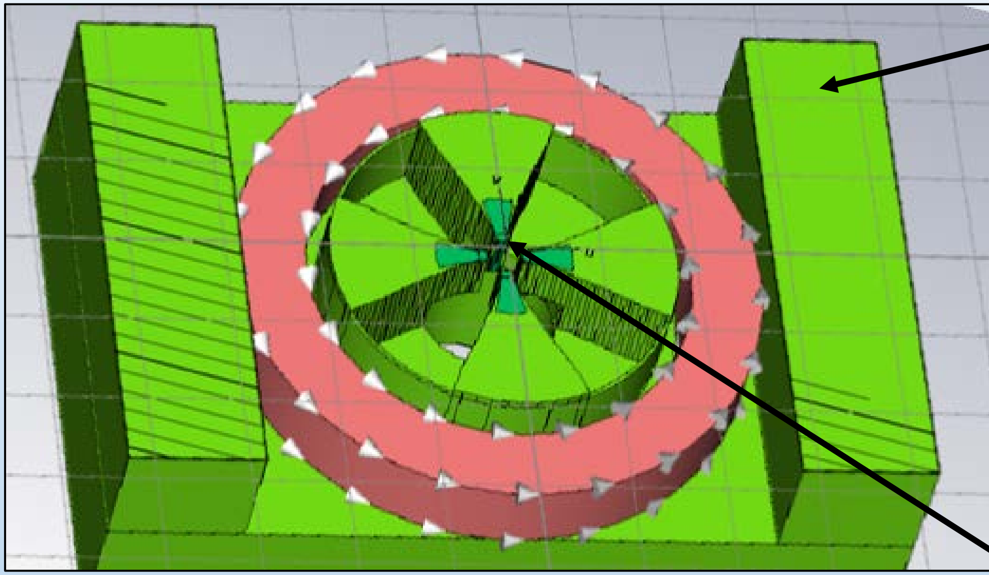
Main parts:

- Ion source (Multicusp source)
- Focusing lense
- Vacuum pump
- RFQ
- Spiral inflector
- Central region

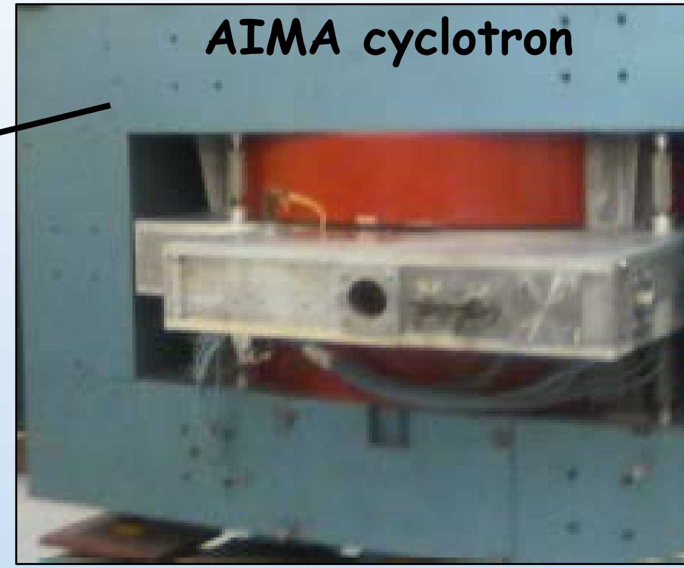
First design of the test-bench cyclotron already realized at INFN-LNS

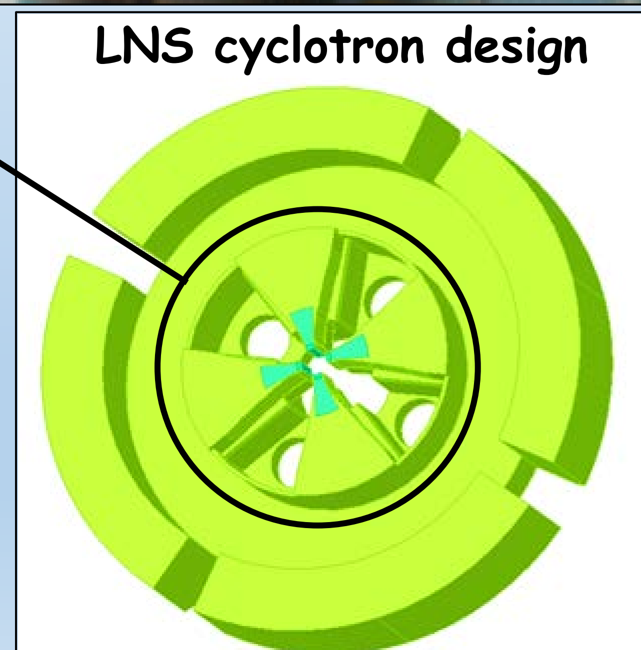
Study of the spiral inflector and central region in progress in collaboration with IBA

Possible injection test at AIMA



Courtesy of Matthieu Conjat





IsoDAR test-bench cyclotron with the AIMA return yoke and coils

DEVELOPPEMENT

The use of the AIMA cyclotron would allow to reduce the costs!

Design of the spiral inflector and central region of the IsoDAR test-bench cyclotron

- Goals
- Constraints
- Calculation code used
- Method used

Goals & constraints

Goals:

- **Good horizontal and vertical beam centering**
- **Vertical focusing**
- **Good longitudinal acceptance**
- **Minimization of the losses**
- **Orbit turn separation**

Very important to avoid losses on the electrostatic deflector!

Input parameters considered during the study: see table

Ion	H_2^+
Beam current	5 mA
Injection energy	35 AkeV
RF cavities	4
RF frequency	32.8 MHz (Harmonic 4)
Dee voltage	70 kV
Dee angle	36°

Constraints related to the magnetic structure (LNS cyclotron design):

- Magnetic field level and shape in the cyclotron centre
- Geometrical space available for the central region and spiral inflector

Calculation code AOC

"AOC" (Advanced Orbit Calculations), IBA code for the particle orbit tracking

We used **OPERA3D** to realize the 3D design and to obtain the field maps to import in AOC

AOC tracks accelerator orbits under the combined action of static magnetic and RF electric fields, using time as independent variable.

Space charge effects have been included in our simulations. A particle-to-particle method is used (self-field acting on one particle is obtained as the sum of contributions of all other particles)

Stepwise approach used to design the central region and the spiral inflector

Step 1: Initially decouple between central region and spiral inflector to find the matching point

The **matching point** is the particle starting position that allow to achieve the best orbit centering looking at the forward tracked particle orbit in the central region.

Step 2: Design the centroid curve of the spiral inflector intercepting well the matching point

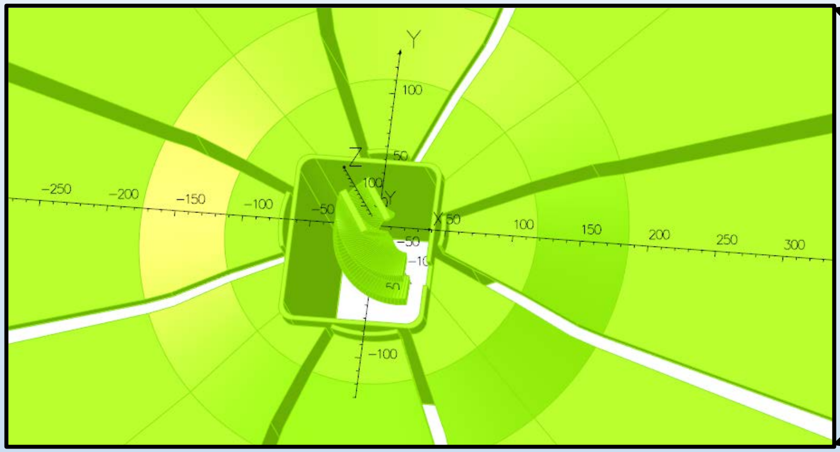
Step 3: Make a full 3D electric/magnetic model (inflector + c.r.)

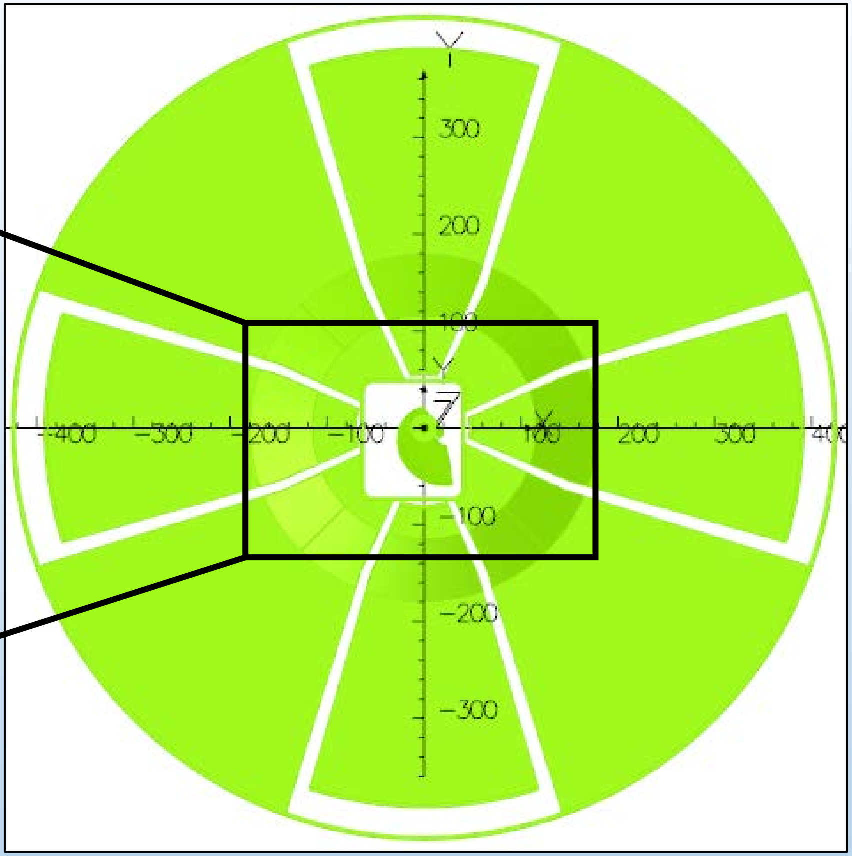
Step 4: Fine tuning of the 3D geometry of the spiral inflector

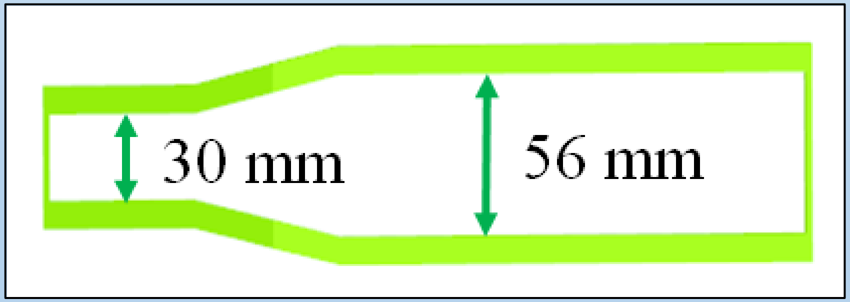
Step 5: Verify the beam dynamics, also considering space charge calculations

Results of the simulations

Central region







Two vertical apertures of the dee-tips (**30 mm** and **56 mm**)

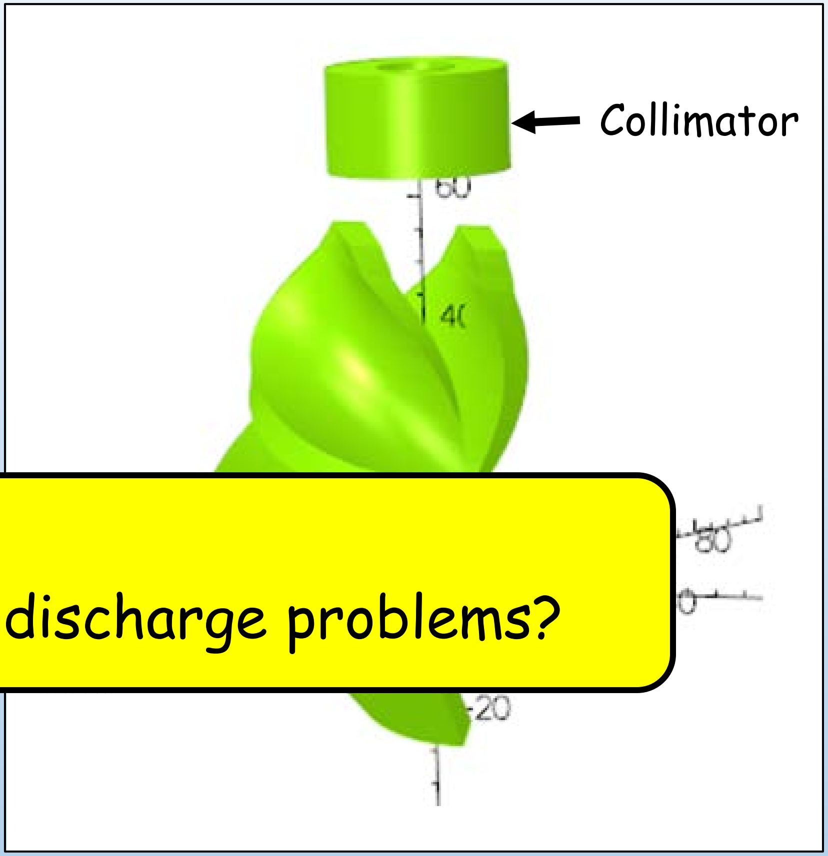
The smallest vertical gap has been chosen taking into account the presence of the transit time factor effects on the beam dynamics especially in the first turn.

The spiral inflector

- Inflector parameters:
  - Bending radius A_0: 50 mm
  - L=79.74 mm
  - Tilt-parameter k′: -1
  - Rotation angle α: -150.86°
  - Constant gap: 14 mm
  - Voltage: ± 18.88 kV
  - Aspect-ratio: 2.5

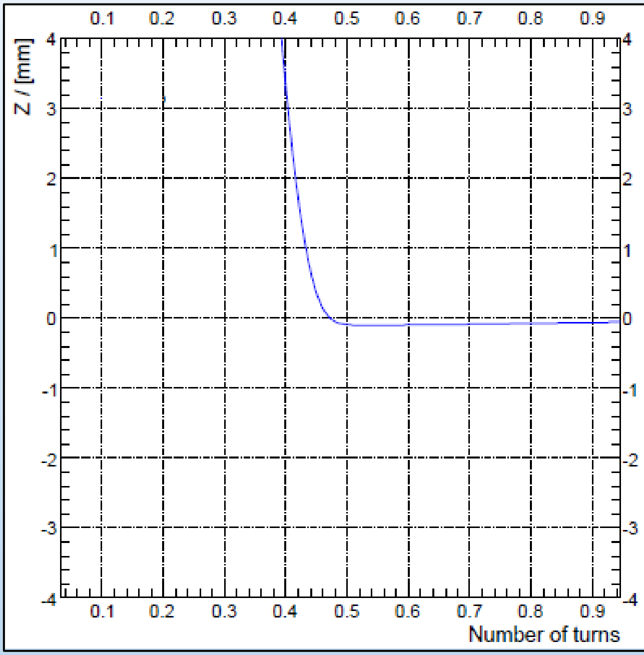
1) Is this value high?
2) Could it produce electrical discharge problems?

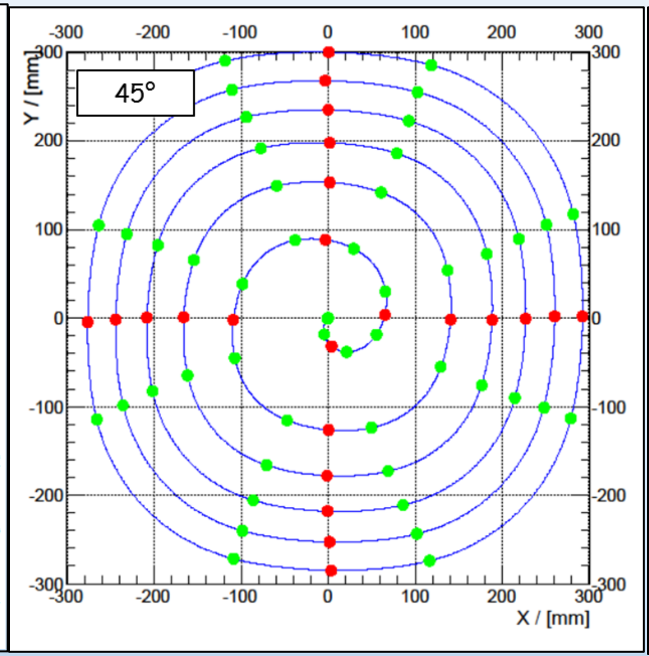
- Internal radius: 6 mm
- Thickness: 16 mm
- Distance from SI: 10 mm

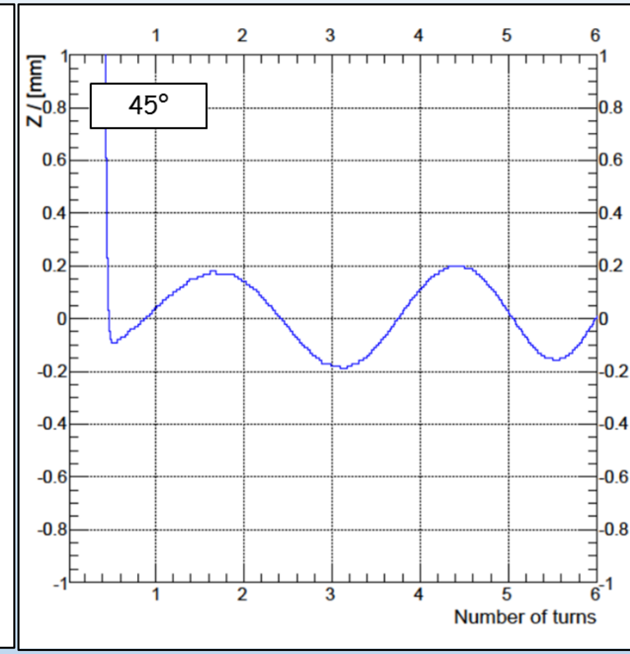


The collimator reduces the fringing field effects at the inflector entrance.

Features of the central orbit in the full model





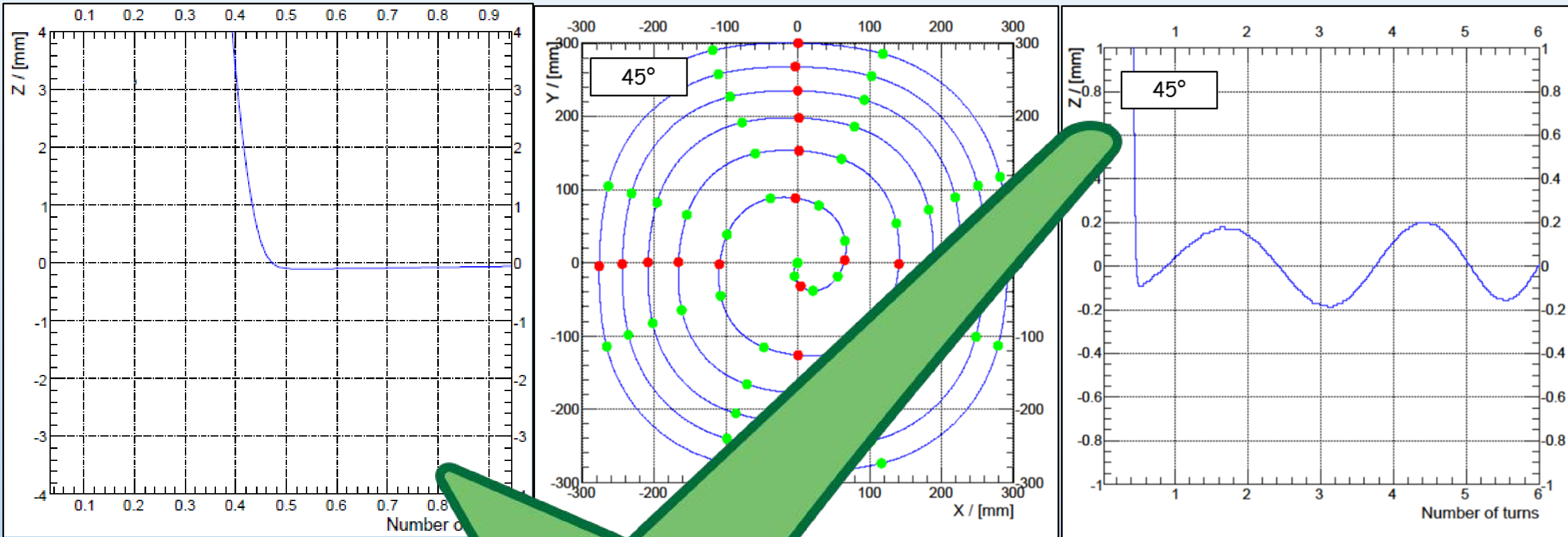


Red dots: particle position when $V_{dee}=0$
Green dots: particle position when $V_{dee}=V_{max}$

At the inflector exit, the central orbit is onto the median plane and its vertical momentum is near to zero.
The centroid curve is well centered with respect to the inflector electrodes.

The injection system model (spiral inflector + central region) allows to obtain a good orbit centering and a small vertical excursion of the reference trajectory in the central region

Features of the central orbit in the full model



article position when V_{dee}=0
s: particle position when $V_{dee}=V_{max}$

At the inflector exit, central orbit is onto the med plane and its vertical momentu is near to zero.
The centroid curve is well centered with respect to the inflector electrodes.

The injection system model (spiral inflector + central region) allows to obtain a good orbit centering and a small vertical excursion of the reference trajectory in the central region

What happens when we inject a beam in the designed injection system?

Verify the beam dynamics

Track an emittance

Number of particles	5000
Starting energy	70 keV
Energy spread	±2 %
x,y	5 mm
Norm. Emittance in the planes x-x′ and y-y′	1 π mm mrad
Geometrical emittance	115 π mm mrad
β_x, β_y	0.217 mm
α_x, α_y	2.065

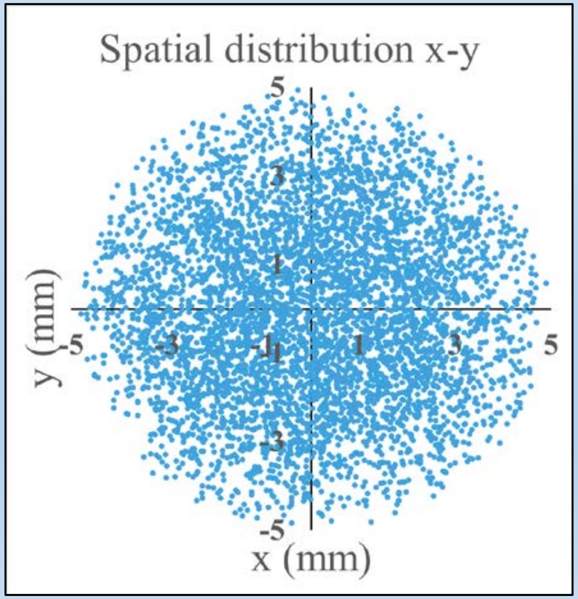
Round beam => same for x and y

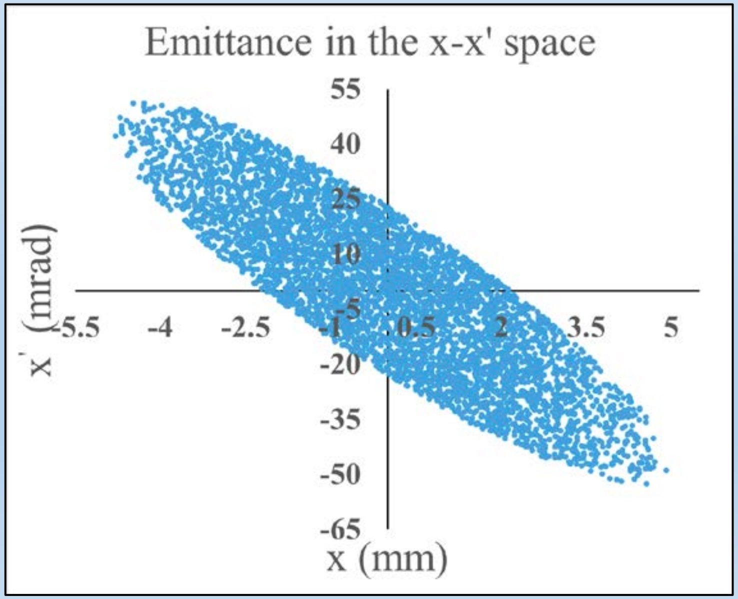
Uniform distribution in the spaces x-x′ and y-y′

Starting position: 100 mm from the median plane

Space charge effect included in the simulations (<I>=5 mA)

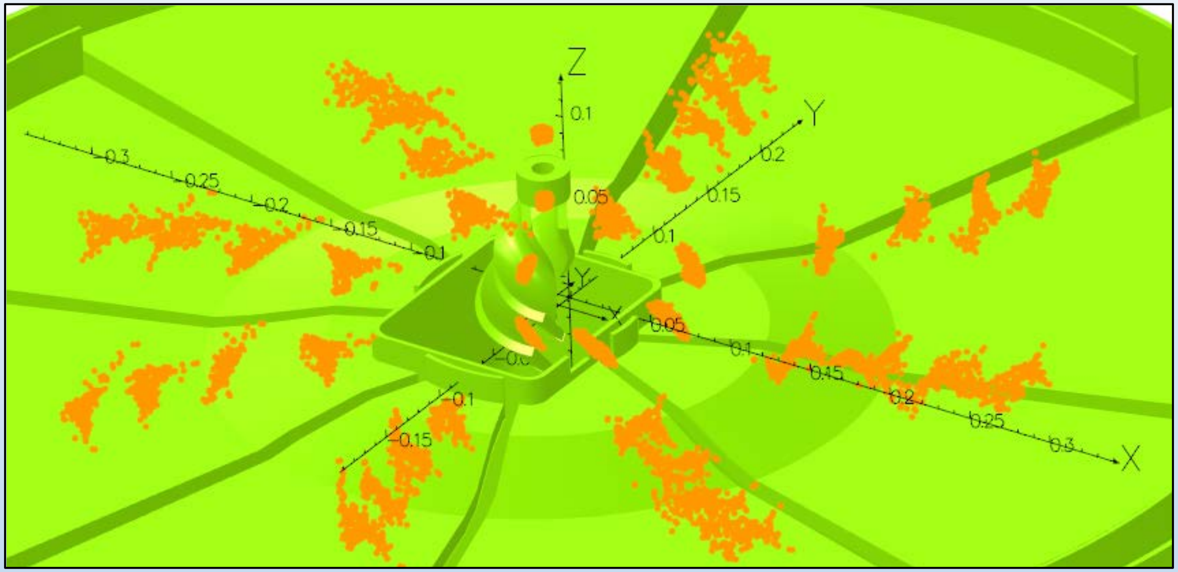
Different bunch lengths: 30°, 20°, 10°, 5°

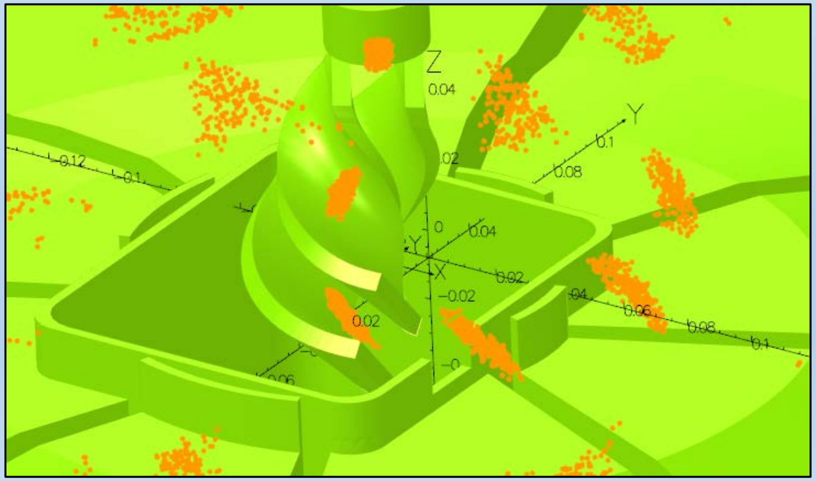




Bunch length (deg)	Bunch length (mm)
30	6.6
20	4.4
10	2.2
5	1.1

Bunch during its motion through the spiral inflector and in the central region



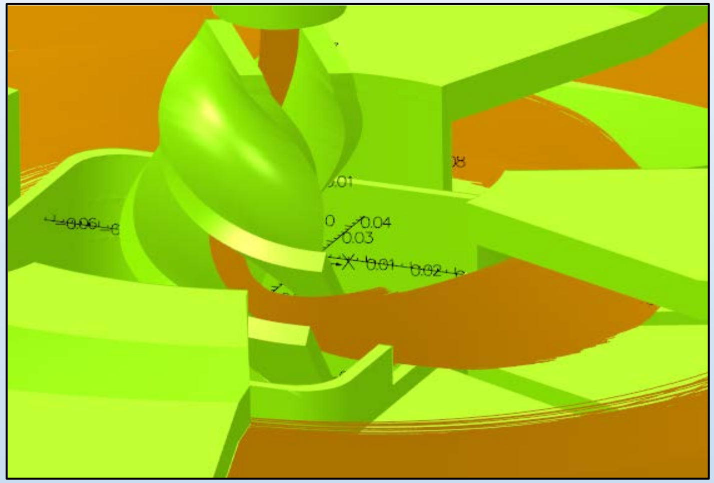


For simplicity, not all particles of the bunch are showed in the figure

Verify the beam dynamics

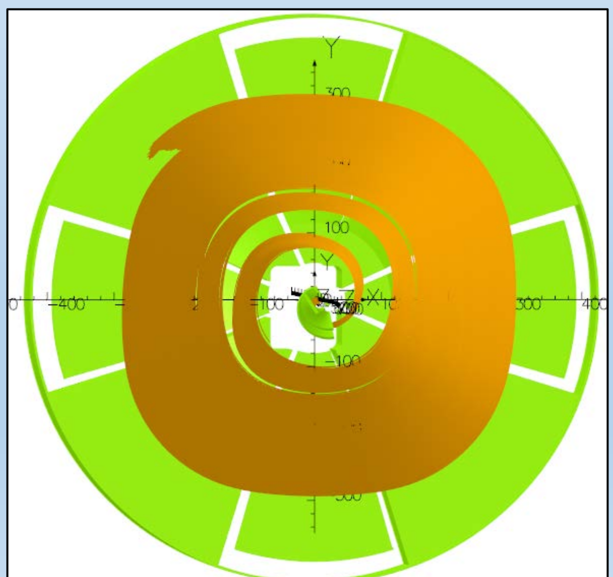
Track an emittance

Losses on the exit housing and in the first turn



This occurs in presence of the space charge effects and for all bunch lengths considered and also in absence of the space charge effects.

No orbit turn separation

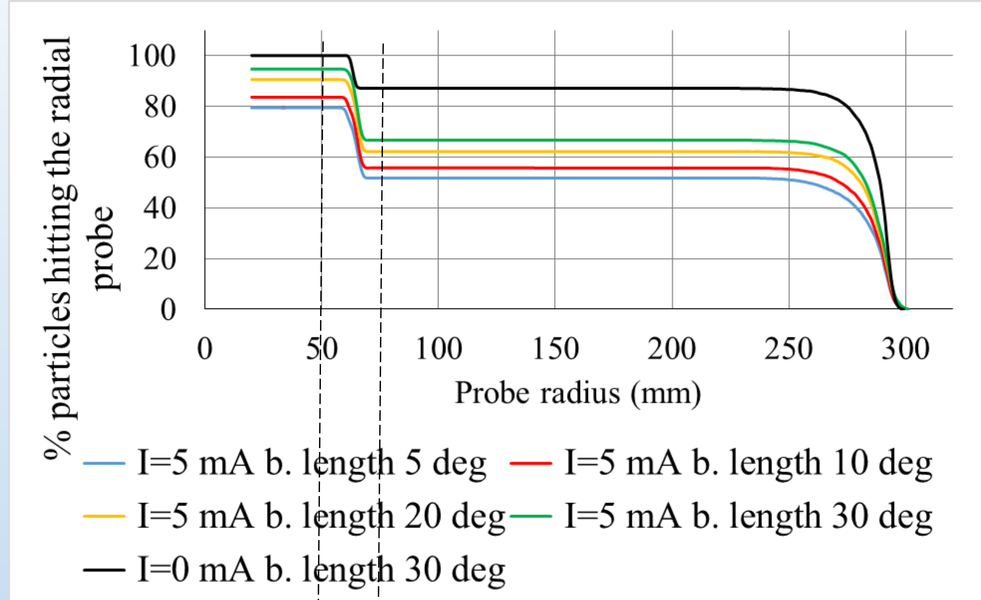


Work in progress

Transmission and losses evaluation

Starting position: 100 mm from the median plane

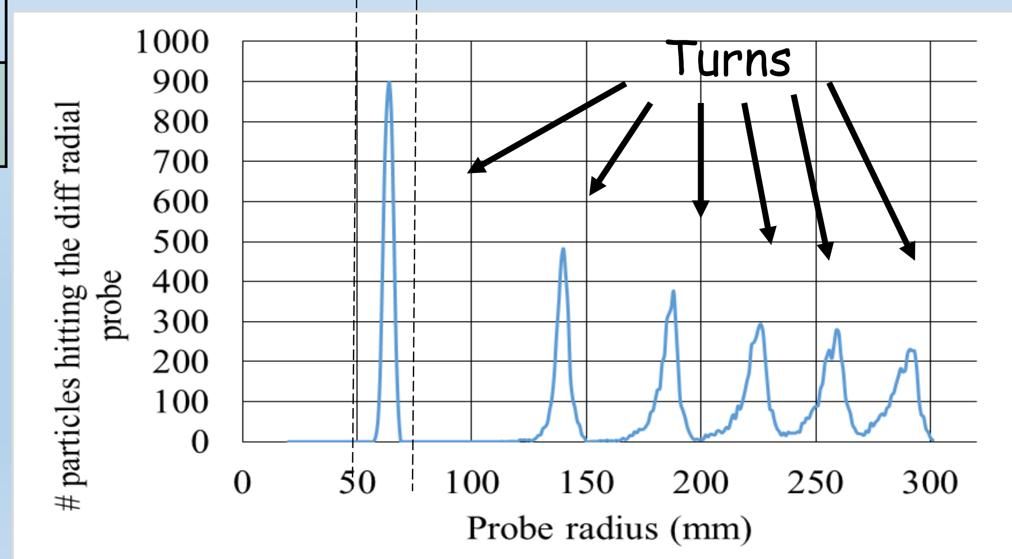
	Losses (#particles and %)	Trasmission (%)
I=0 mA,30 deg	645 (12.9)	87.1
I=5 mA, 30 deg	1667 (33.3)	66.7
I=5 mA, 20 deg	1891 (37.8)	62.2
I= 5 mA, 10 deg	2216 (43.3)	55.7
I= 5 mA, 5 deg	2414 (48.2)	51.8



Bunch length ↓

Space charge forces ↑

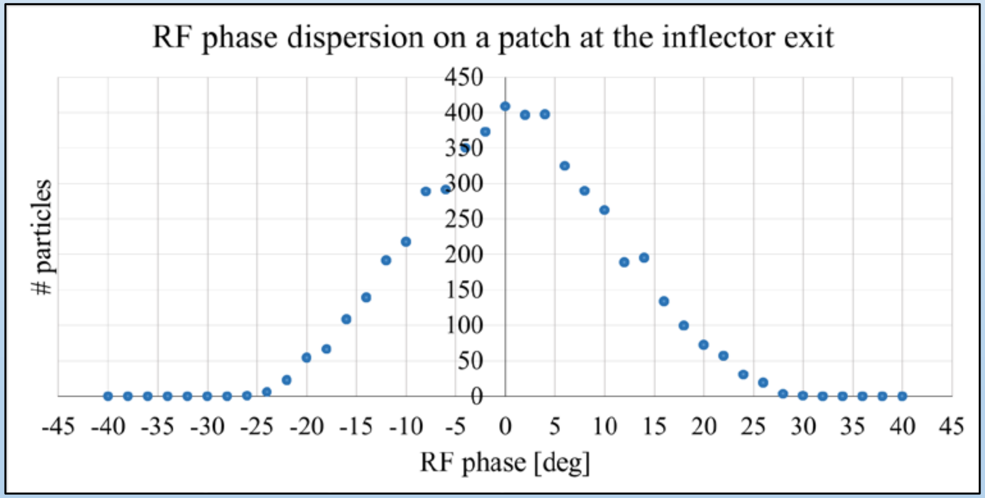
Beam transverse defocusing ↑



RF phase dispersion – spiral inflector

The spiral inflector produces **beam RF phase dispersion**.
It appears due to the different length paths of the ions inside the inflector with respect to the reference particle.

The beam phase dispersion depends on the position of the particles (x and y coordinates) but also on direction (x' and y') (The spiral inflector is a linear device).



No space charge effects

No bunch length (unique RF phase for all particles)

No energy spread

Starting position and beam features equal to that considered previously

Does the tilt parameter influence the beam phase dispersion??

Conclusion and perspectives

The design of the IsoDAR injection system poses serious problems due to the high beam current and the space charge effects non negligible.

It will be needed to improve the injection system design, looking in particular at the orbit turn separation,transmission, beam size, energy spread.

How to do this?

- Look at the beam motion along the vertical axis and spiral inflector to reduce the RF debunching, one of the causes of the absence of orbit turn separation

- Look at the beam motion in the central region (could the pillars help the beam dynamics?)

- Look at the beam motion in the full injection system

Space charge effects have to be included in the simulations.
Simulations considering different bunch lengths, different average currents and different beam size are mandatory to understand their effect on the beam dynamics.

- Investigation on the maximum voltage applicable on the inflector electrodes to avoid electrical discharges.

Thanks for your attention

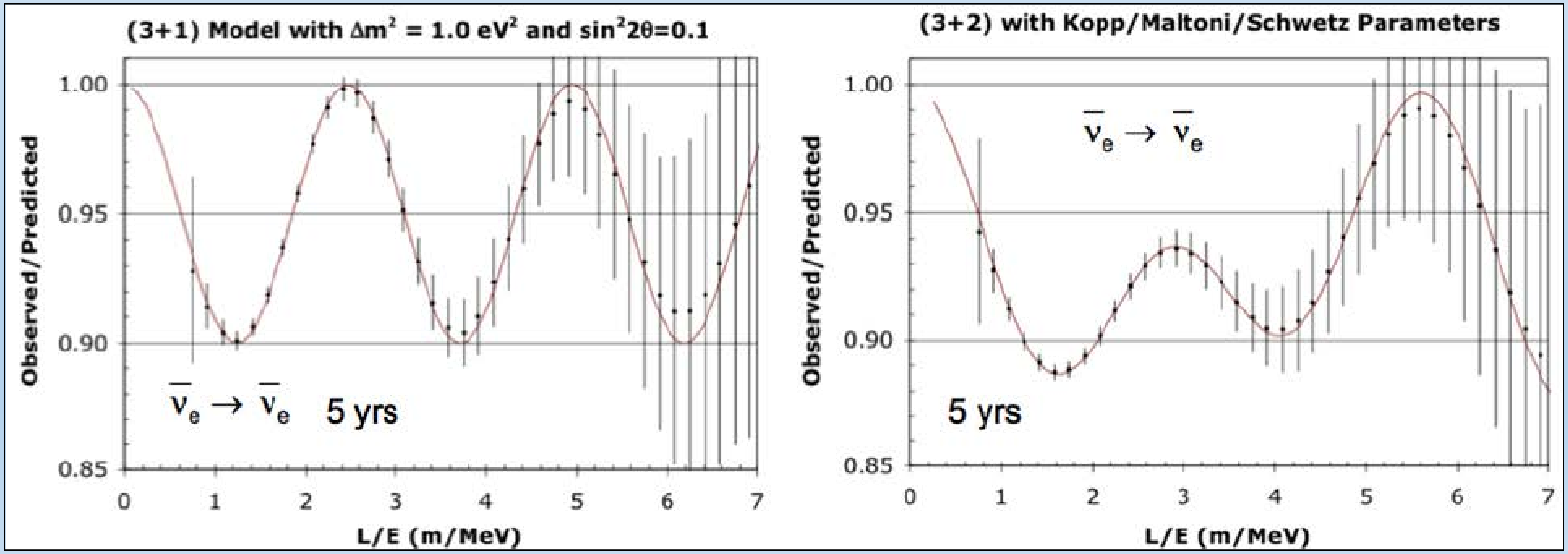
IsoDAR (ISOtope Decay-At-Rest)

$\bar{\nu}_e$ disappearance due to oscillations → Δm^2 anomalies (1 eV)

Anomalies: short baseline accelerator neutrino oscillation experiment,
short baseline reactor experiments,
radioactive source experiments

Sterile neutrinos: (3+1) and (3+2) models can solve the problem

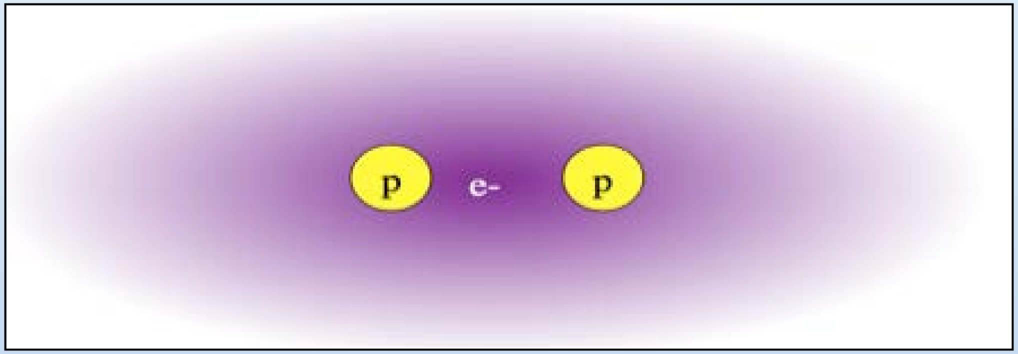
Oscillation L/E waves in IsoDAR → High statistic and good L/E resolution



The H_2^+ cyclotron

Critical point concerning the injection → **Space charge effects**

Acceleration of H_2^+ molecules to produce high intensity proton beam



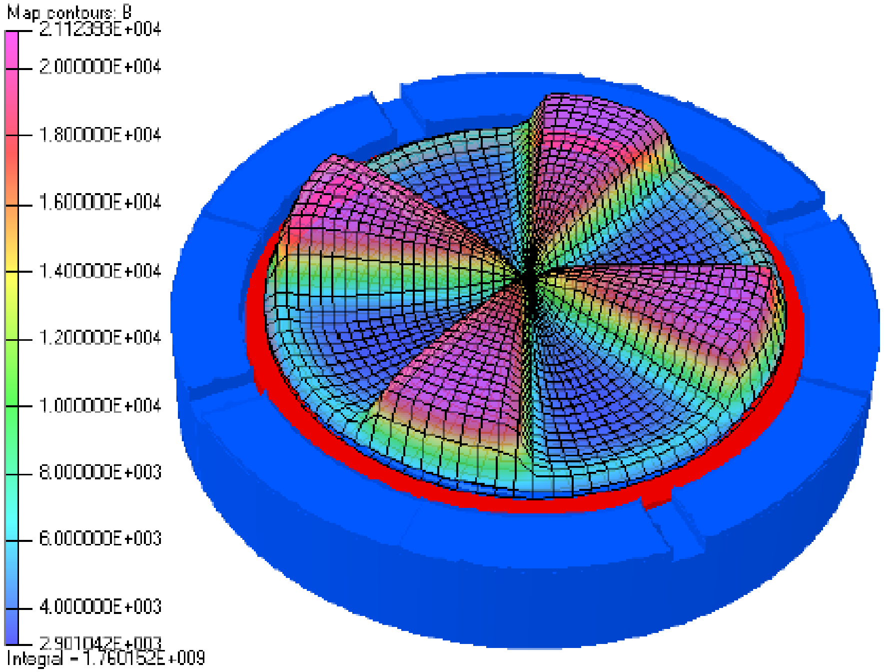
Generalized Perveance
(Reiser's formula)

$$K = \frac{qI}{2 \cdot \pi \cdot \varepsilon_o \cdot m \cdot \gamma^3 \beta^3}$$

2 mA protons @ 30 keV/amu ⟷ **Perveance** ⟷ **5 mA H_2^+ @ 35 keV/amu**

The perveance measures the strength of the space charge effects

The H_2^+ cyclotron

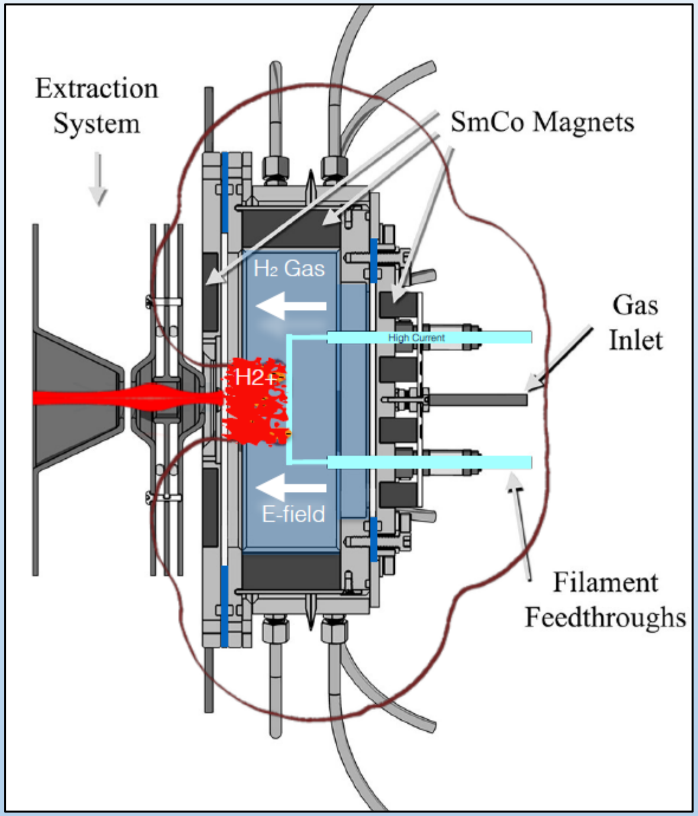


E_{inj}	35 keV/n	E_{max}	61.7 MeV/n
B_0	1.075 T	$\langle B \rangle$ at R_{ext}	1.166 T
$\langle R_{inj} \rangle$	51.58 mm	$\langle R_{ext} \rangle$	2000 mm
N. Sectors	4	Hill width	25.5° ÷ 36.5°
Valley gap	1800 mm	Hill gap	100 mm
Diameter	6240 mm	Full height	2700 mm
N. Cavities	4	Cavities λ/2	Double gap
RF Harmonic	4^{th}	RF frequency	32.8 MHz
Acc. Voltage	70 ÷ 250 kV	Power cavity	<160 kW
Coil size	200x250 mm^2	Current density	3.17 A/mm^2

Courtesy of Daniela Campo

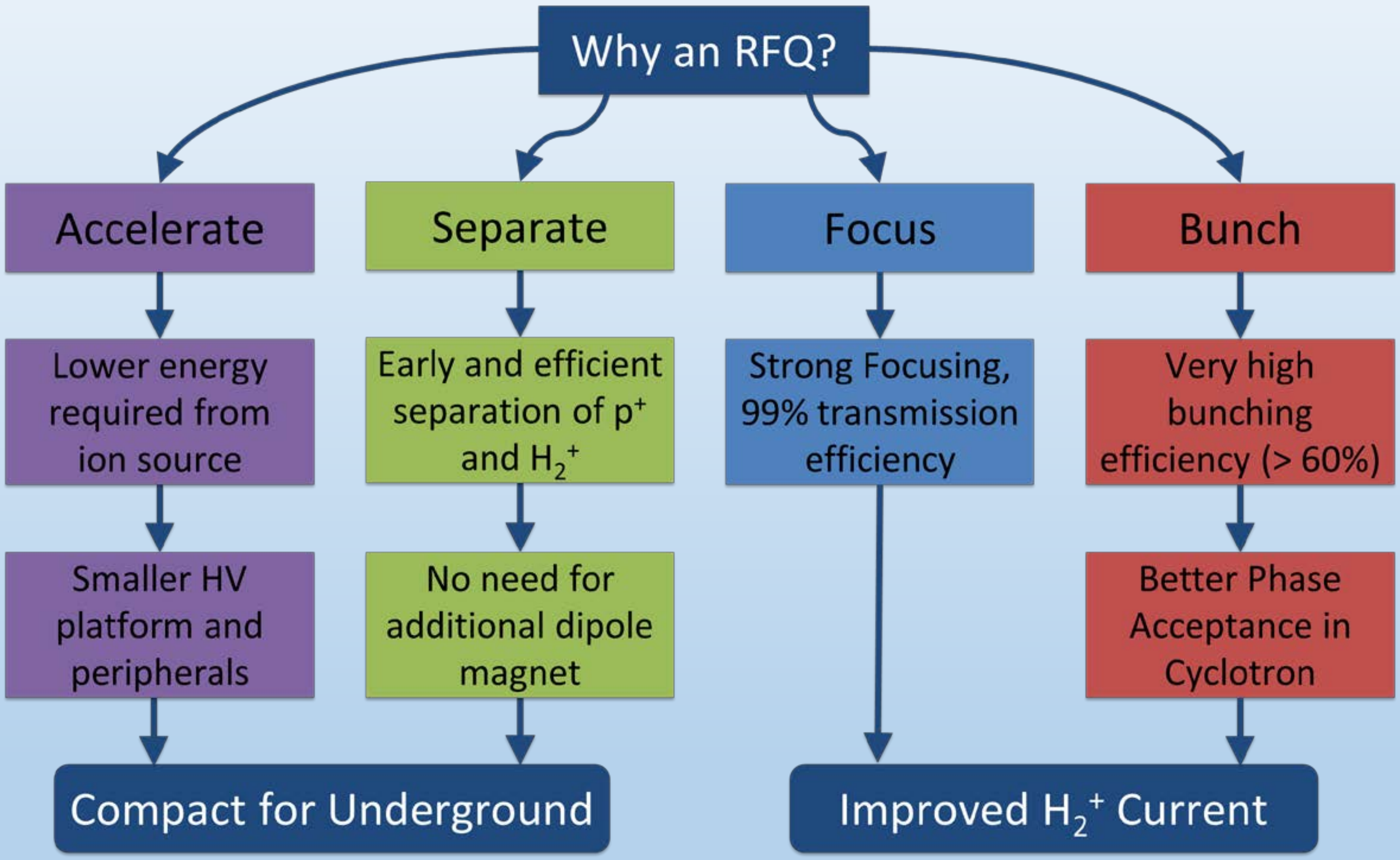
MIST-1 Ion Source

- Confinement in multicusp field generated by permanent magnets
- Electrons are created through thermionic emission from filament
- Electrons are accelerated towards front plate
- Electron impact collision with molecules, atoms and ions leads to ionization
- Ions drift through extraction hole and are accelerated in extraction system → beam



Courtesy of Daniel Winklehner

RFQ direct injection



Courtesy of Daniel Winklehner

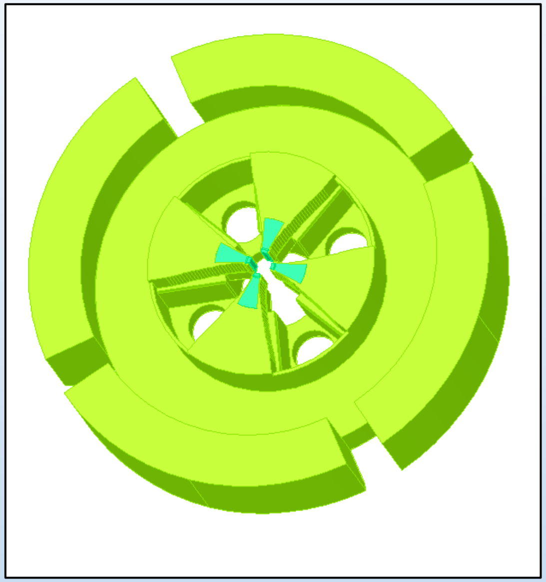
Some data concerning the ion source and the RFQ

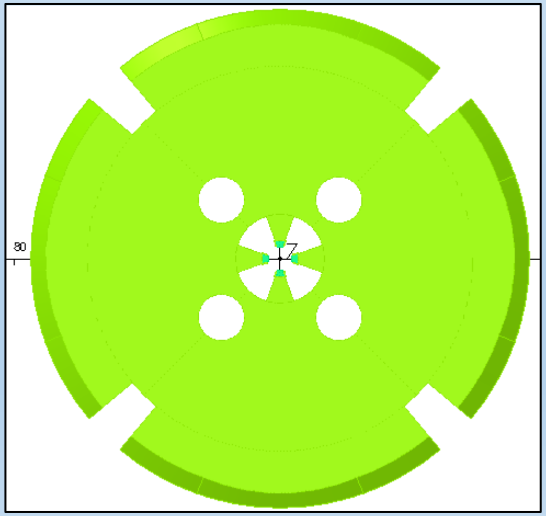
- Ion Currents (worst case): H_2^+: 12 mA, p, H_3^+: 5mA each

- RFQ:
  - Alignment: Vertical
  - Cyclotron Bore hole: < 30 cm
  - Frequency: 32.8 MHz (harmonic 4)
  - Length: 120-130 cm
  - Injection Energy: 15 keV
  - RFQ final Energy: 70 keV
  - Maximum Energy spread: +- 2%
  - Distance of RFQ exit to Cyclotron mid-plane: 20 cm
  - Bunching efficiency: 50 %

    Exit ion current: 7-7.5 mA

IsoDAR test-bench cyclotron - Info

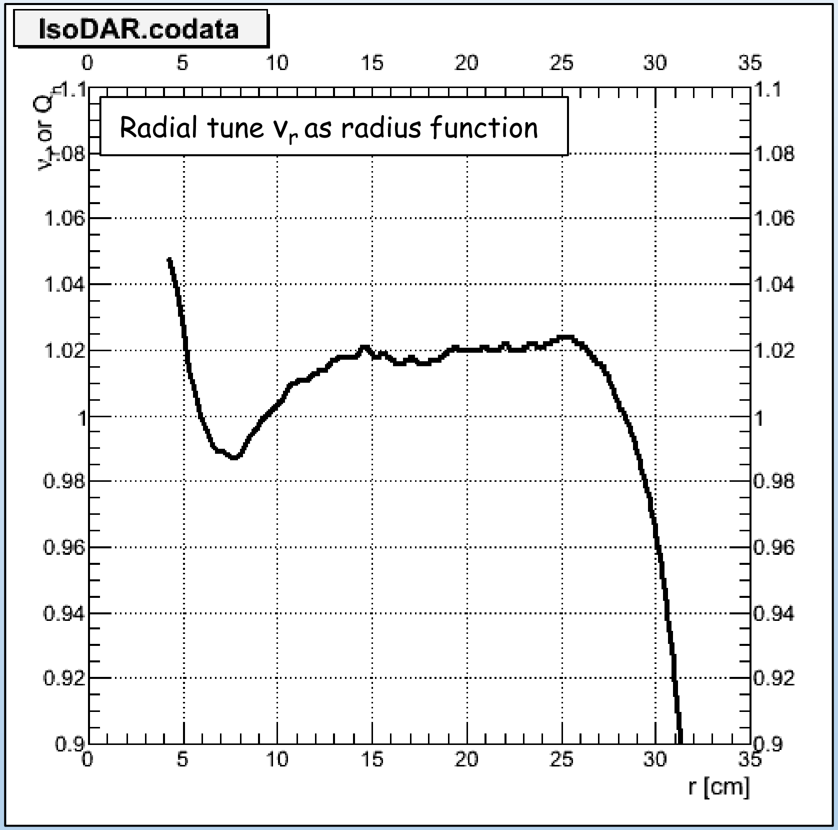


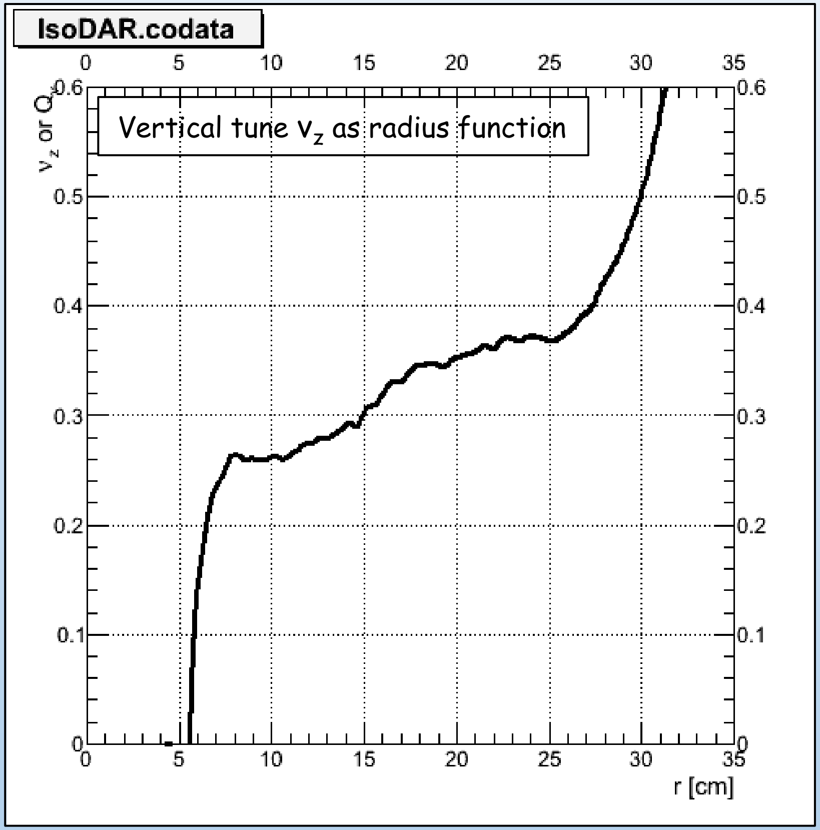


what	value	units
external radius of the yoke	75	cm
semi-height of the cyclo	37	cm
total weight	6.321	Tons
coil cross-section	r16xz18	cm2
current density	224	Amp/cm2
electrical power per coil w/out and with cooling (to get the total: this numberx2)	5.62-6.8	kW
pole radius	37	cm
1 MeV radius at the center of the hill	27	cm
energy of the last closed orbit found w/ GENSPE	1.4	AMeV
internal radius of the skirt valley	36	cm
externall radius of the skirt valley	37	cm
internal radius of coil	40	cm
external radius of the coil	56	cm
internal radius of the yoke	58	cm
coil distance in z	3.6*2	cm
distance between coil and iron in the z direction	0.8	cm
valley height	22.5x2	cm
volume of the semi-sector (1/16 of the model)	50083	cm3
iron specific weight	77300	N/m3
weight x volume	3871.42	N
weight of the semi- sector	395.04	kg
residual field at (0,0,57) cm	145	Gauss
residual field at (80,0,0) cm	<5	Gauss

IsoDAR test-bench cyclotron - Properties

Focusing

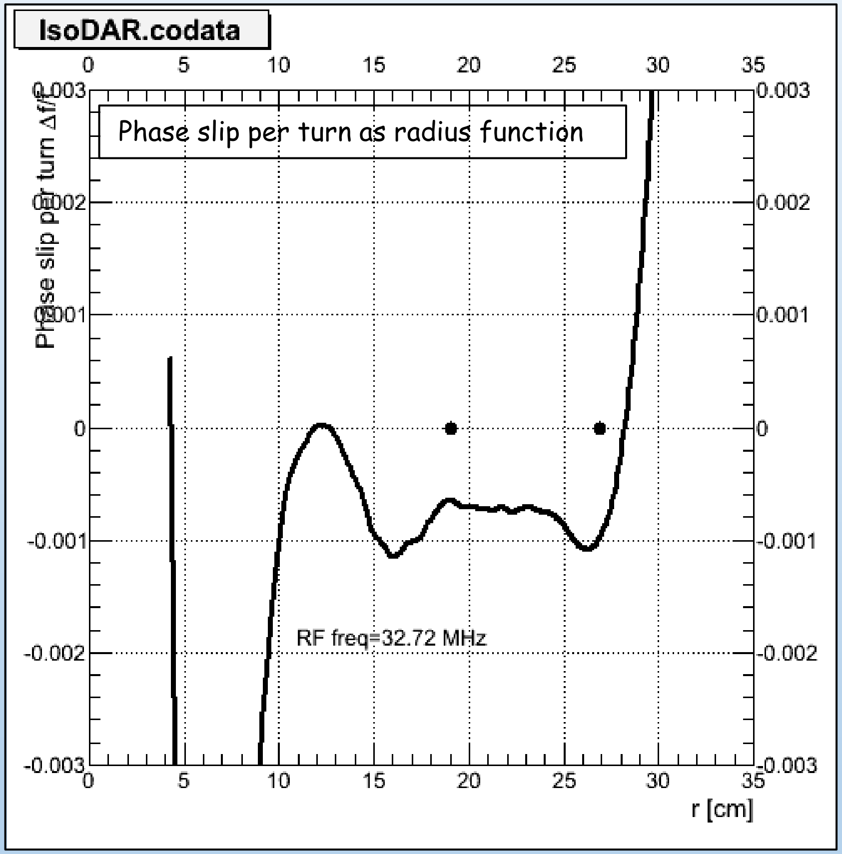


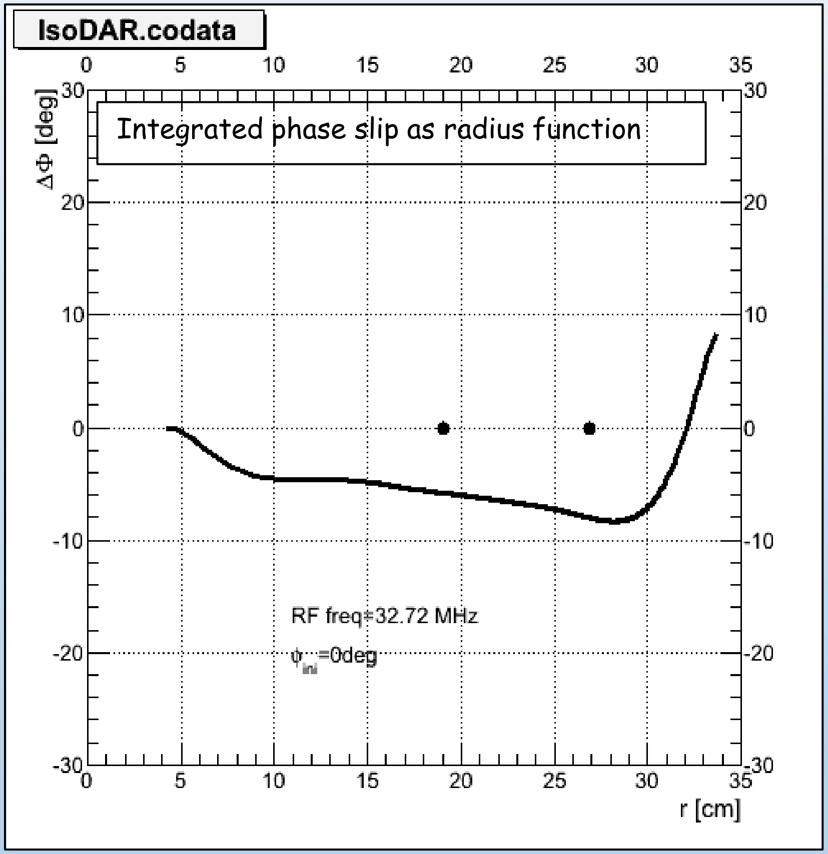


The cyclotron has **good vertical focusing properties**

IsoDAR test-bench cyclotron - Properties

Isochronism

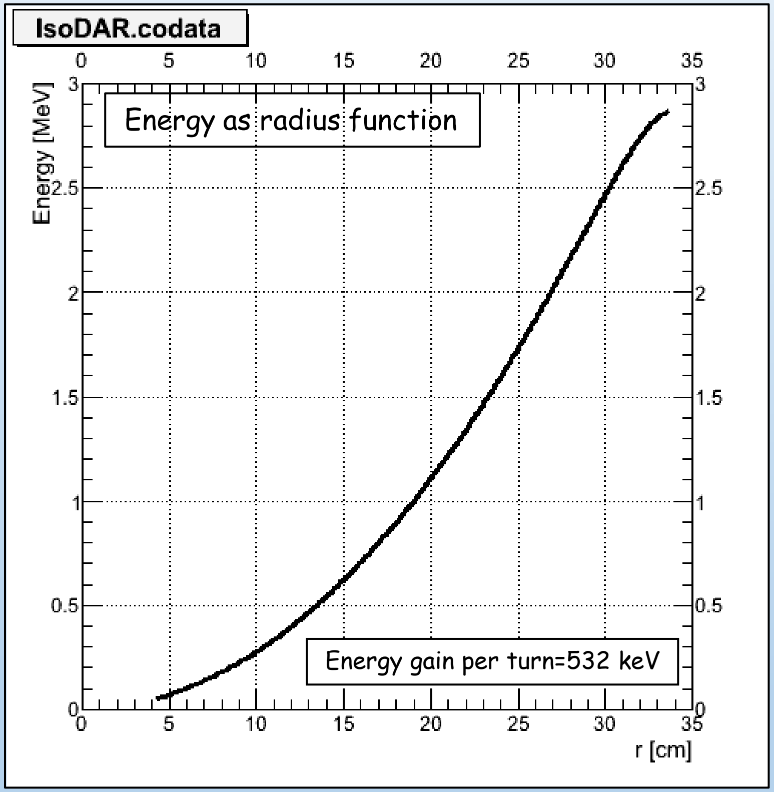


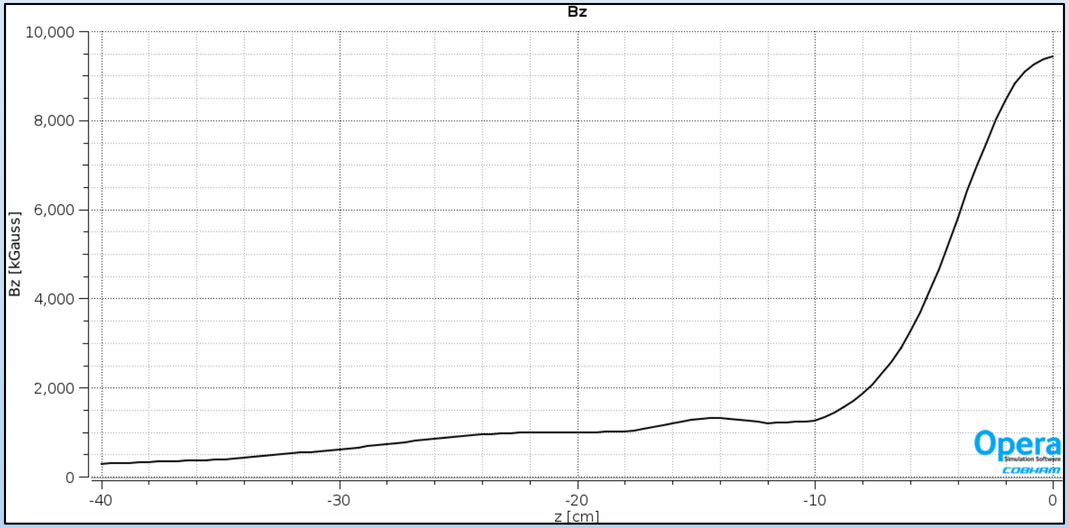


In addition, it presents a good isochronism (the integrated phase slip is < 10 deg)

IsoDAR test-bench cyclotron - Properties

Energy and magnetic field along the vertical axis





Possible injection test at AIMA - Costs

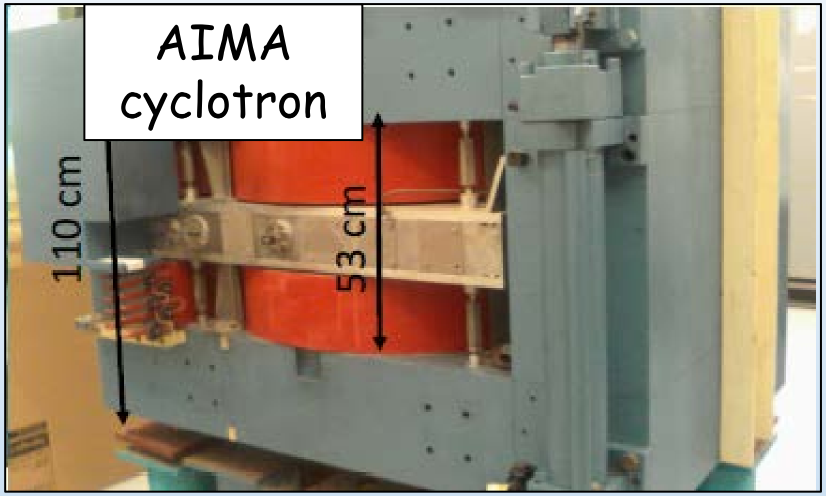
- Coil construction (30 k€)
- Power supply for the coil (30 k€)
- Hydraulic piston and crane (100 k€)
- Return yoke iron (60-80 k€)
- Support pillars, cables (15 k€)
- Pumping system (30 k€)
- Cooling system for the cyclotron (20 k€)
- Mapping system (15 k€)

Total 300-320 k€
(Saved)

- Cyclotron poles machining (30 k€)
- Axial hole drilling (15 k€)
- Vacuum chamber (20-30 K€)
- Labor cost for field mapping and shimming (5 k€)
- 4 RF cavities (160 k€)
- RF amplifier for the cavities (160 k€)
- Ancillary costs (30 k€)

Total 435 k€

Possible injection test at AIMA - Images



Distance between the median plane and the bottom/top return yoke is 26.5 mm in AIMA cyclotron, in the LNS design is 22.5 mm. → New poles design

Cyclotron support and bottom space to install the RFQ and ion source

The 12 T crane of the accelerator vault

Calculations code AOC

"AOC" (Advanced Orbit Calculations), the IBA code for the particle orbit tracking

AOC tracks accelerator orbits under the combined action of static magnetic and RF electric fields, using time as independent variable.
OPERA3D can be used for the 3D design of the electrodes and to obtain the 3D field maps to import in AOC

AOC allows to calculate the design orbit of a cyclotron spiral inflector considering the electric fringing field at the entrance and exit and 3D dependence of the magnetic field in the volume occupied by the inflector.

AOC is able to monitor beam losses on RF electrodes or magnetic iron. In addition, there are several tools in AOC, to process the calculated beam, as radial probes or patches.

REFERENCE: AOC, A beam dynamics design code for medical and industrial accelerators at IBA, W. Kleeven et al., Proceedings of IPAC2016, Busan, Korea

Calculations code AOC

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SCOPE OF APPLICATIONS
Cyclotrons (isochronous, synchronous) FFAG's, Rhodotrons, PT-gantries Static magnetic fields, RF and/or static electric fields
EQUATIONS OF MOTION SOLVED
3D-trajectories, Twiss-functions, inflector design orbits
INTEGRATION METHOD
Time domain, Runge-Kutta 5th order, adaptive step
SPACE CHARGE CALCULATIONS
Fully relativistic, fully 3D centroids E- and B-self fields, iterative or single-step solution
OTHER IMPORTANT FEATURES
Cyclotron injection (axial, internal source) Cyclotron extraction (stripping, ESD), Multi-threading Detection of beam-losses, orbit back-tracking Choice between cartesian and polar coordinate systems Application of angular kicks, Dee-voltage ripple
MAGNETIC AND ELECTRIC FIELD INPUT
Linear or non-linear expansion from 2D B-maps 3D B-maps of multiple magnets on multiple grids 3D E-maps on multiple grids, or simplified dee-gaps
POST-PROCESSING OPTIONS
Beam rms-analysis, radial probe tracks patch intersections, cyclotron Smith-Garren analysis

AOC features

Stepwise approach used to design the central region and the spiral inflector

Step 1: Initially decouple between central region and spiral inflector to find the matching point

The **matching point** is the particle starting position that allow to achieve the best orbit centering looking at the forward tracked particle orbit in the central region.

Forward tracking from 70 keV, corresponding to the injection energy, towards the outer radius of the cyclotron

Design of the 3D dees and dummy-dees

Method used to design the central region and the spiral inflector

Step 2: Design the centroid curve of the spiral inflector intercepting well the matching point

AOC simulates the inflector by an electric field that is always perpendicular to the orbit. The matching point is used to optimize the inflector parameters.
The spiral inflector is specified by:
- its electric bend radius A_0
- its length L (along the orbit)
- its tilt parameter k′
- its entrance height z_0
- its rotation a around the z-axis
- width of fringe fields at the inflector entrance and exit.

✓ Varying 3D magnetic field
✓ Electric fringing field at the inflector entrance and exit

The code optimizes L and z_0, such that the particle is injected exactly onto the median plane.
The code optimizes the angle a such that the injected orbit passes through the matching point. Optimization of the injected orbit angle at the matching point is done by changing k'.

Method used to design the central region and the spiral inflector

Step 3: Make a full 3D electric model

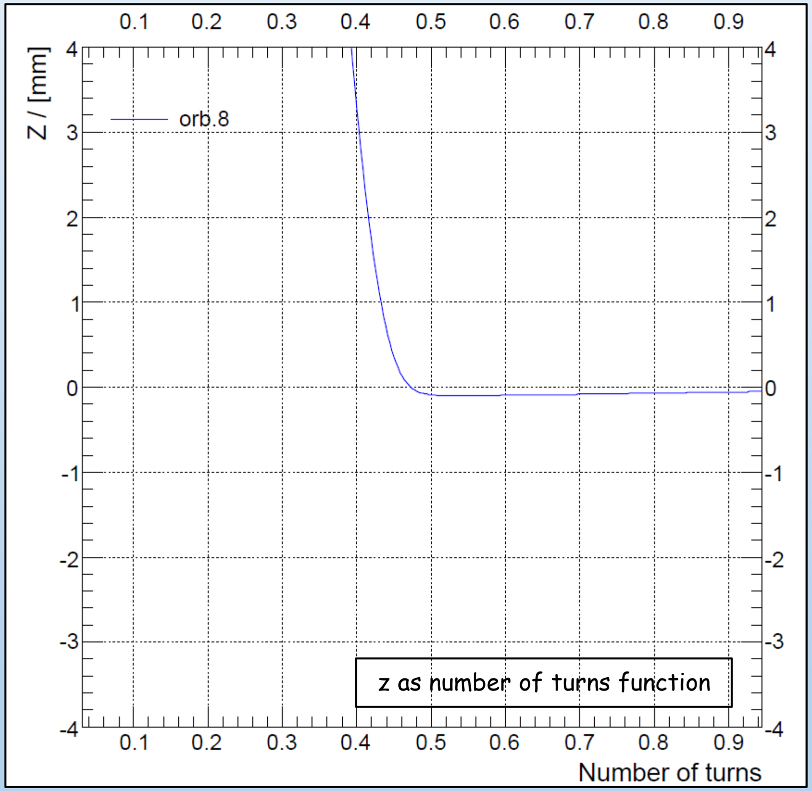
The real 3D inflector electrode have been designed around the estimated reference orbit using a tool in OPERA3D.

Step 4: Fine tuning of the 3D geometry of the spiral inflector

- Previous step 2 repeated using the more precise width of the fringing field obtained from the 3D model of the spiral inflector;
- Optimization of the inflector voltage
- Movement the spiral inflector along the vertical direction.

Step 5: Verify the beam dynamics in the full injection system, also considering space charge calculations

Inflector central orbit features by tracking in the 3D full model



The inflector voltage that deflects the particle on the median plane is **V_{infl} = ± 18.88 kV**

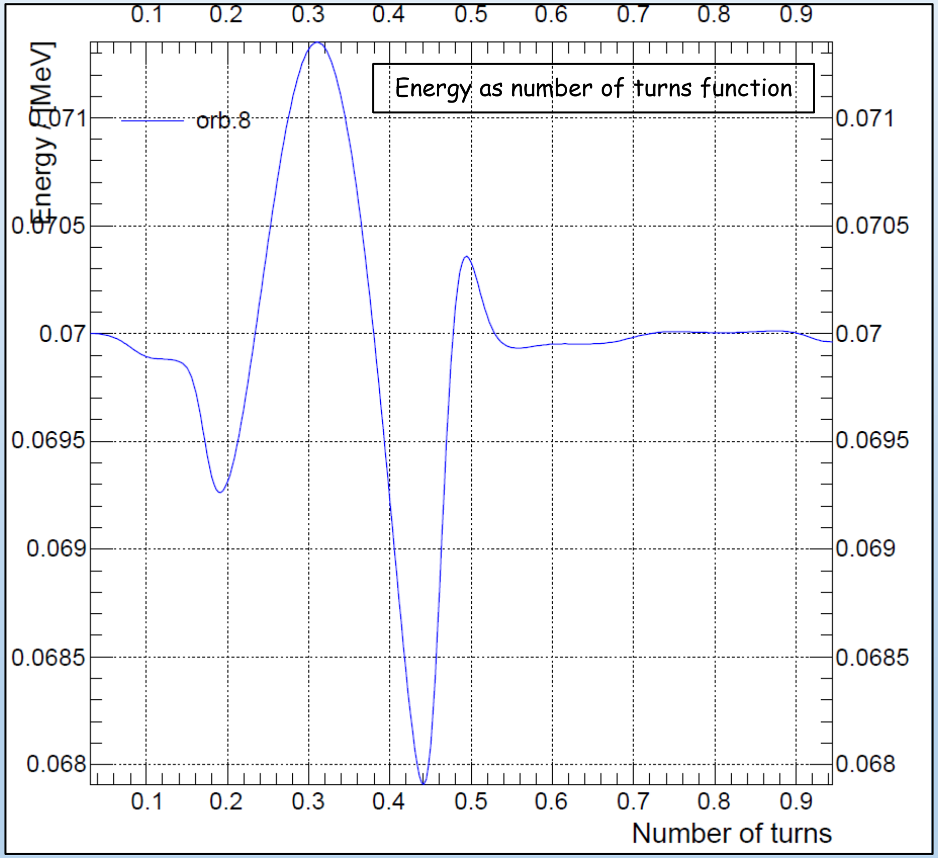
The theoretical value is ± 19.6 kV:

$$V = E_{inf} \cdot gap = 2 \cdot \frac{V_{inj}}{A_0} \cdot gap = 2 \cdot \frac{70\ kV}{50\ mm} \cdot 14\ mm$$
$$= \ 39.2\ kV = 2 \cdot 19.6\ kV$$

It was needed to decrease the voltage on the electrodes to reduce the vertical momentum of the reference particle at the exit of the spiral inflector.

In addition, the spiral inflector has been moved along the vertical direction of 0.7 mm to put the reference orbit perfectly onto the median plane.

Inflector central orbit features by tracking in the 3D full model

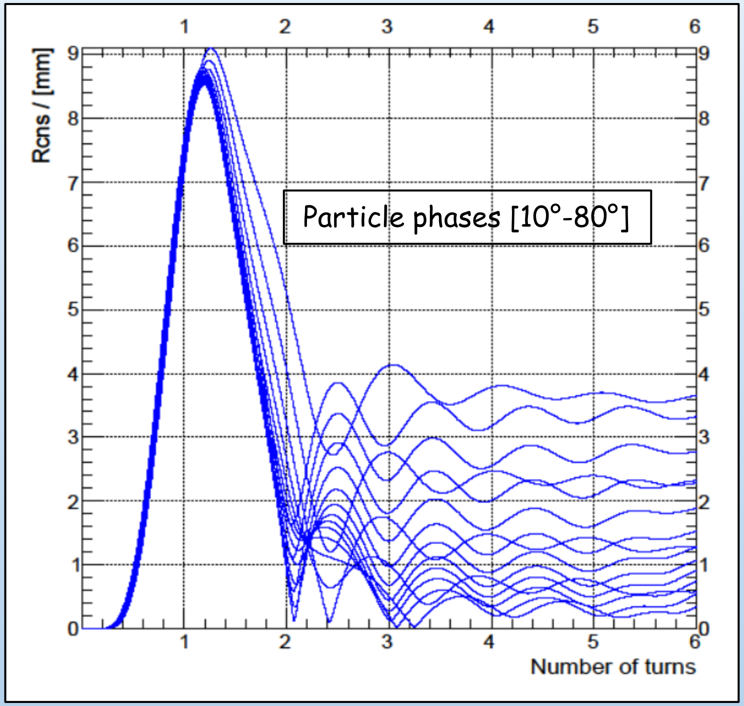


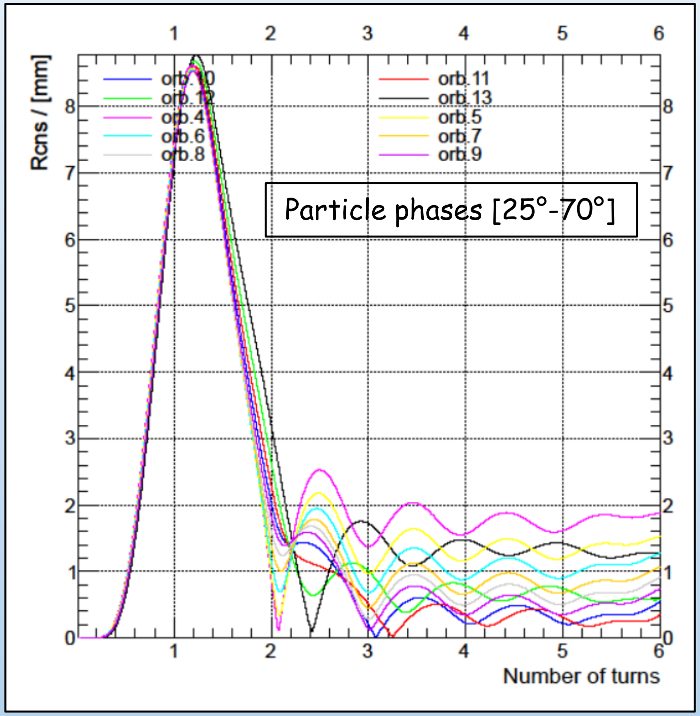
The energy variation in the inflector is 2 keV which means that the particle follows pretty well the central orbit.

The max displacement wrt to the central orbit is d ≈ 0.8 mm:

$$d = gap \cdot \frac{\Delta E}{qV} = 14\ \text{mm} \cdot \frac{2\ keV}{1e*37.76\ kV} \approx$$
$$\approx 0.8\ \text{mm}$$

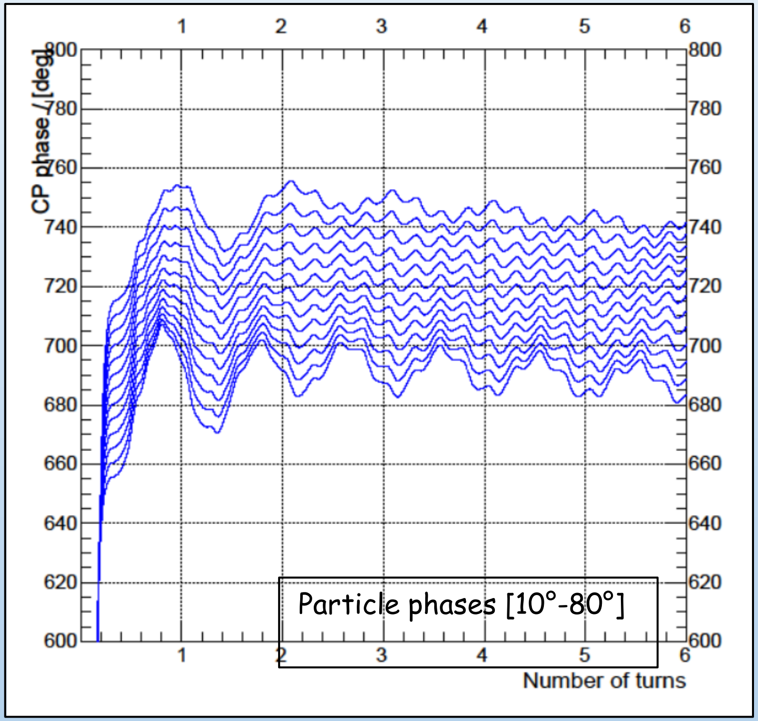
Accepted particle phases of the central region for the centering (< 2 mm)

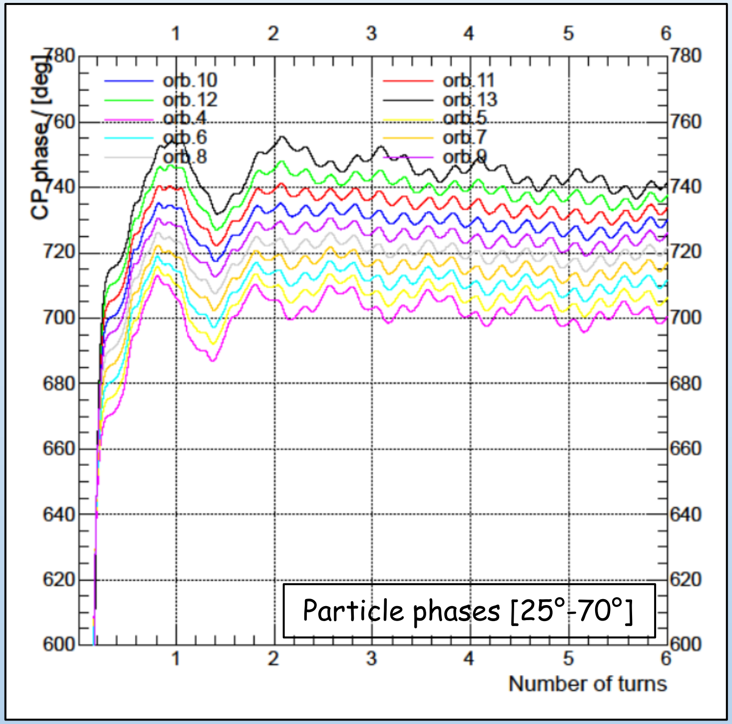




The orbit center amplitude is < 2 mm for the phases included in the interval **[25°-70°]**

Accepted particle phases of the central region for the CP-phase

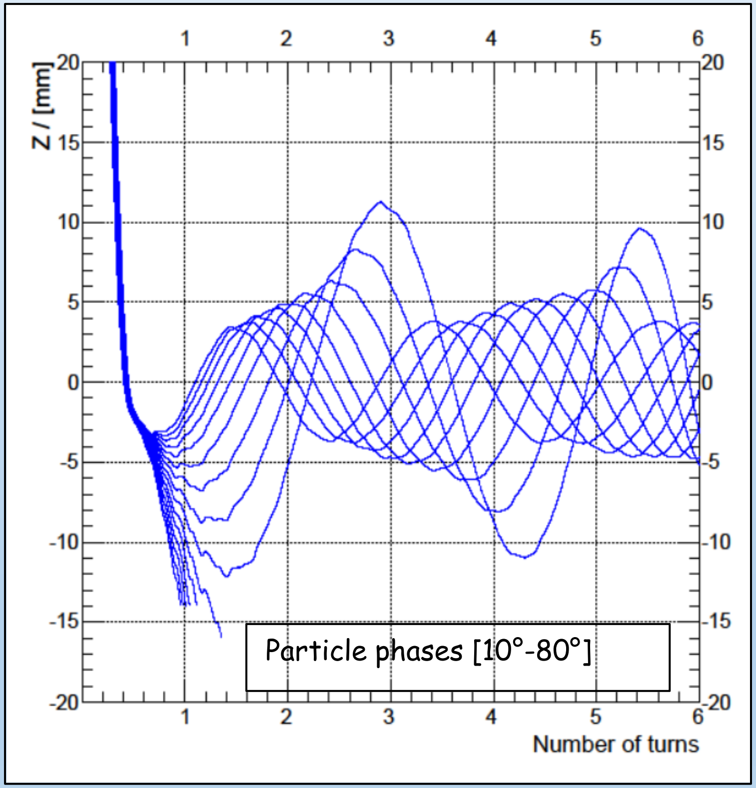


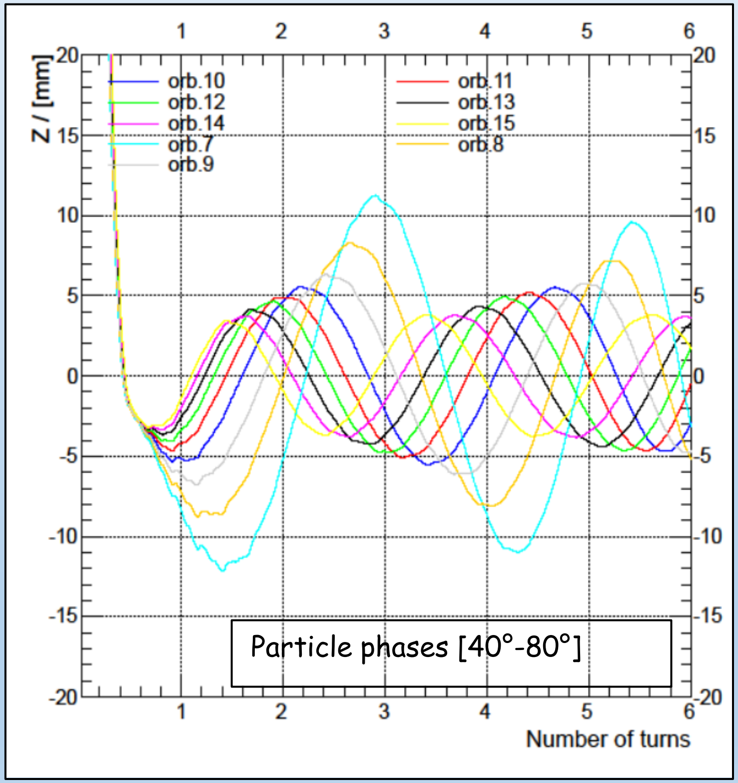


For the phases included in the interval [25°-70°] the CP phase is < **20°**

Accepted particle phases of the central region for z-stability

A variation of the inflector voltage (±0.5 kV) has been used to individuate the accepted particle phases for the z-stability





The z oscillation is < 10 mm for the particle phases included in the interval **[40°-80°]**

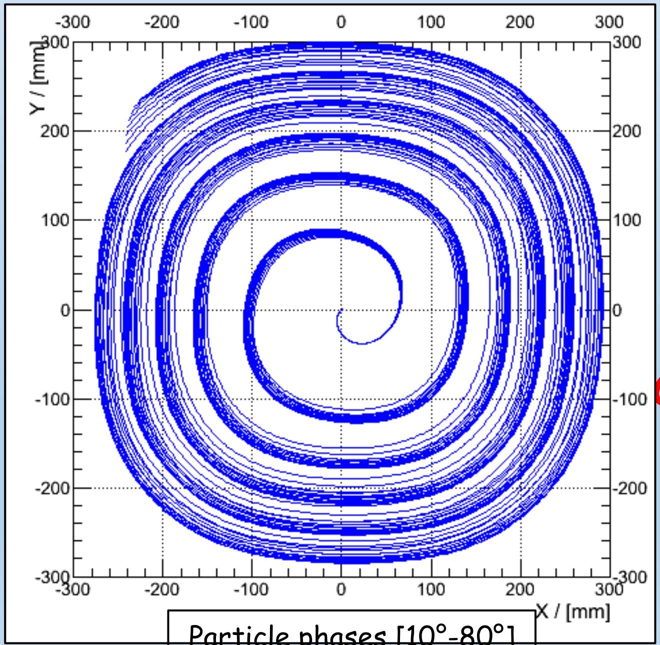
Accepted particle phases for centering, CP phase and z-stability

Accepted particle phases by central region → [10°-80°]

Accepted particles phases for centering (< 2 mm) → [25°-70°]

Accepted particles phases for CP-phase → [25°-70°]

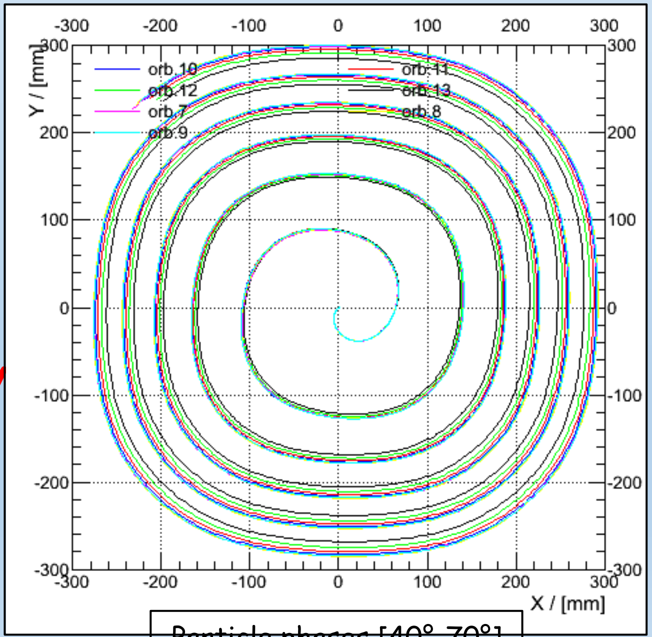
Accepted particles phases for z stability → [40°-80°]



Particle phases [10°-80°]

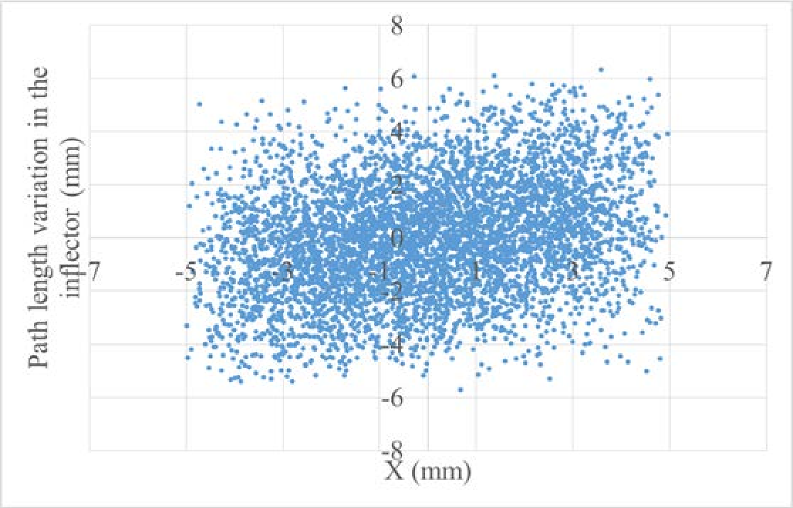
Phase acceptance in degrees for centering, CP-phase and z-stability

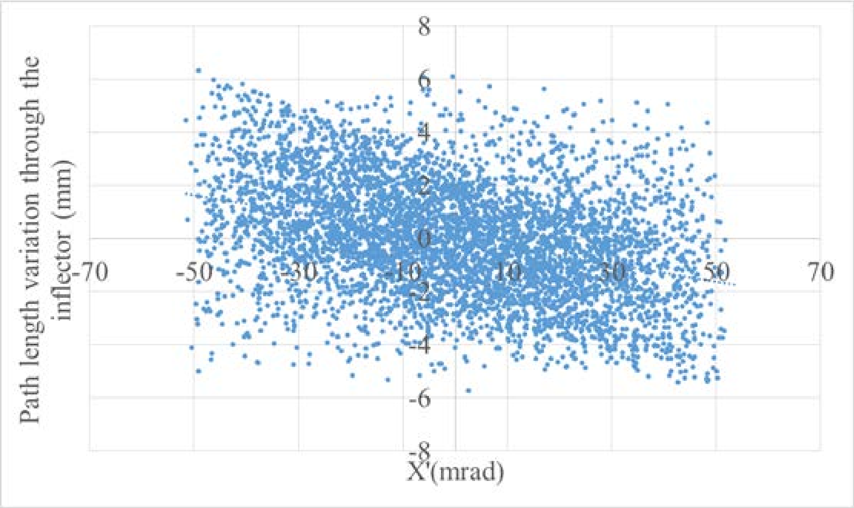
[40°-70°]

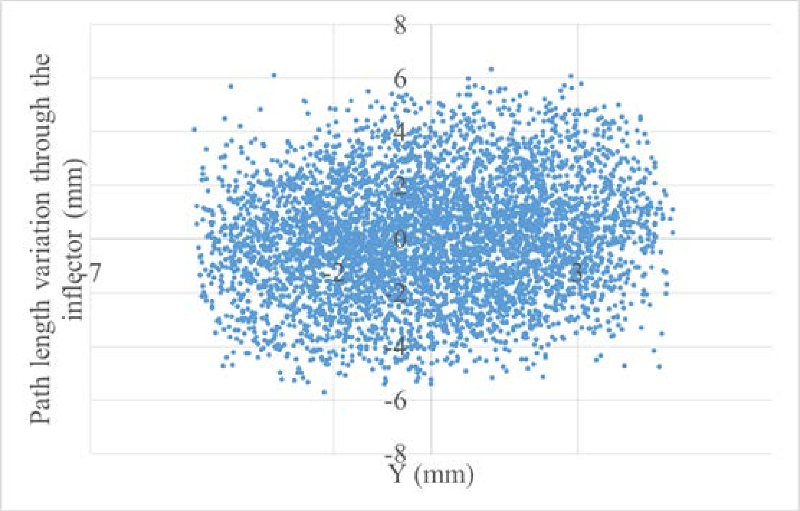


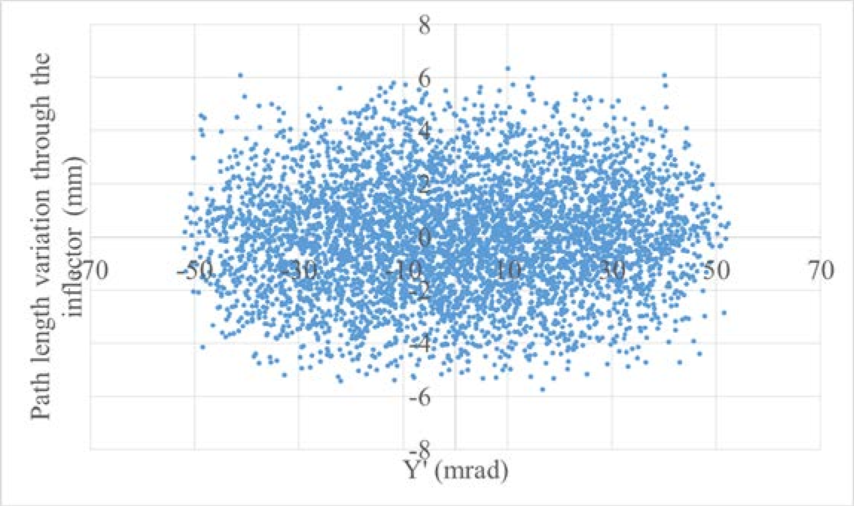
Particle phases [40°-70°]

Beam phase dispersion – spiral inflector

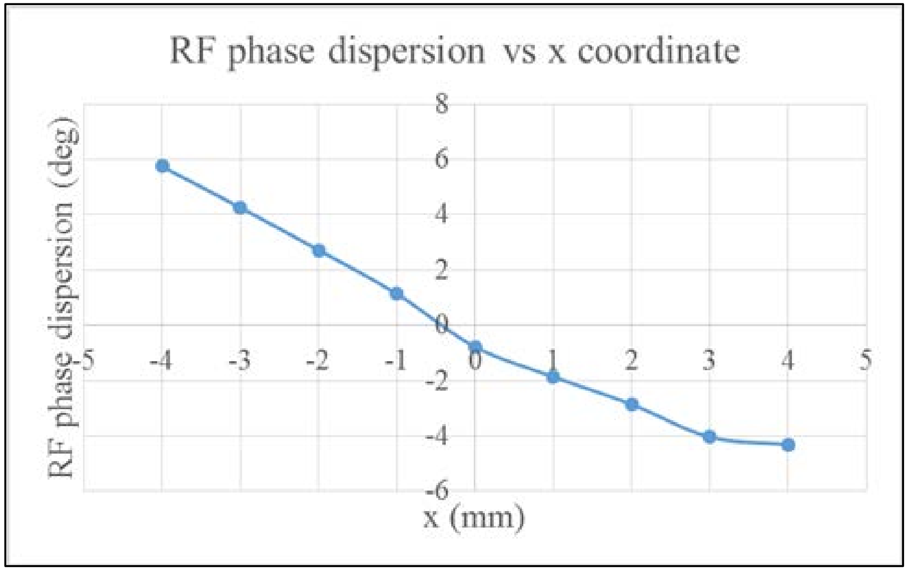


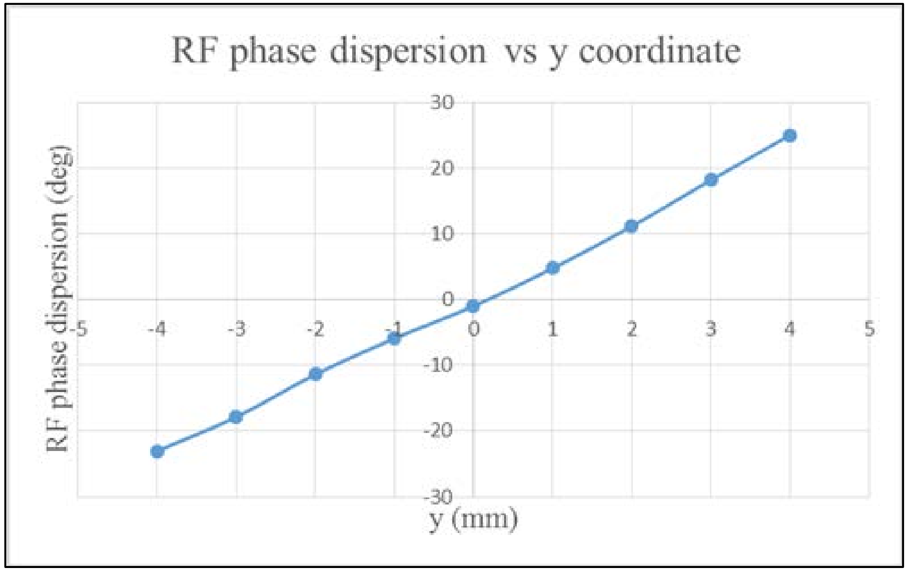






Beam phase dispersion – spiral inflector





The spiral inflector is a linear device