



UNIVERSITY OF JYVÄSKYLÄ



K130 central region upgrade

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Ion Beam Applications, Louvain-la-Neuve, Belgium

22nd International Conference on Cyclotrons and their Applications

Cape Town, South Africa, 22-27 September 2019



Jyväskylän yliopiston
Liikunnan rakennus

Alvar Aalto -museo |
Alvar Aalto Museum

Keski-Suomen museo

Agora

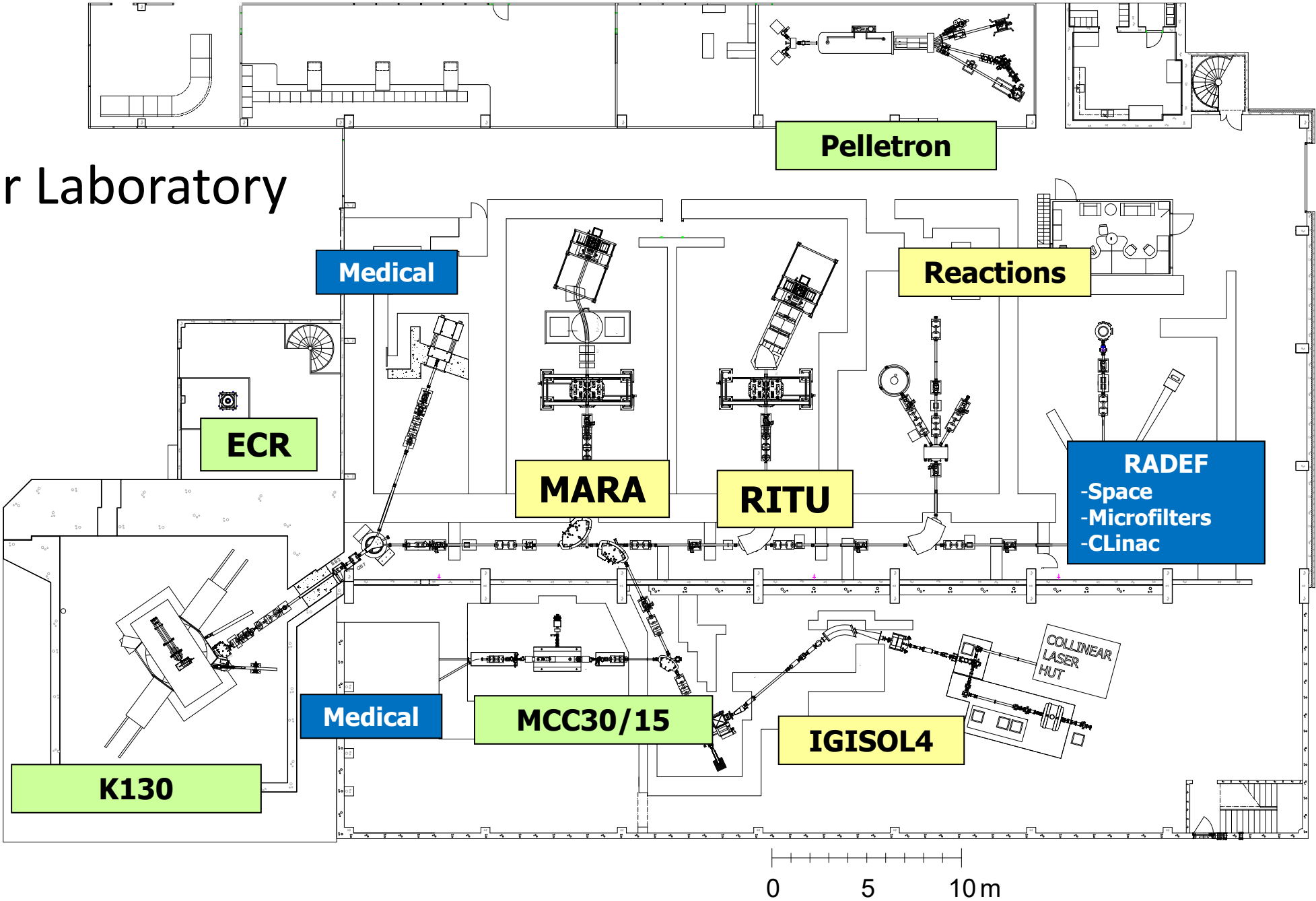
Lounaispuisto

Toivolan Vanha Piha

Rantapuisto

- Jyväskylän...

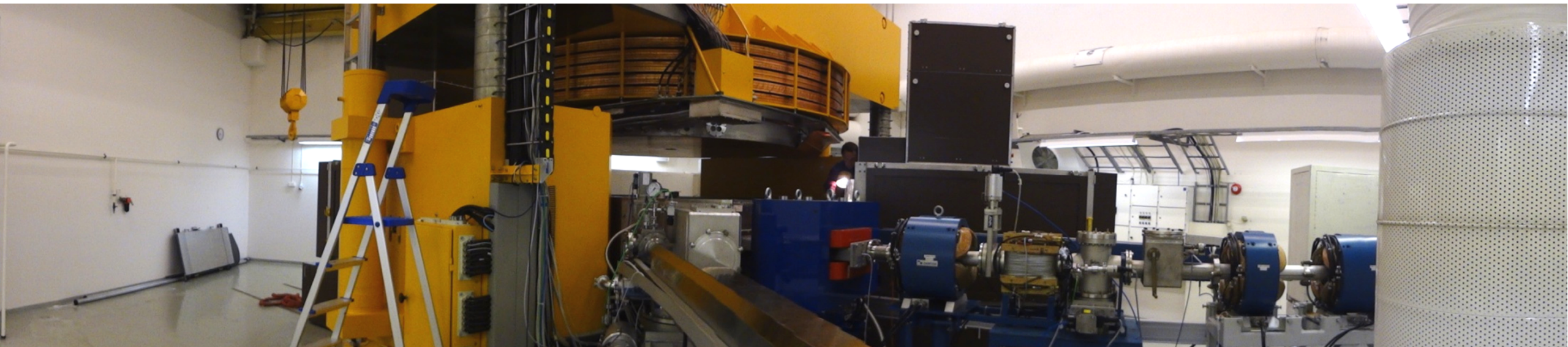
Jyväskylä Accelerator Laboratory



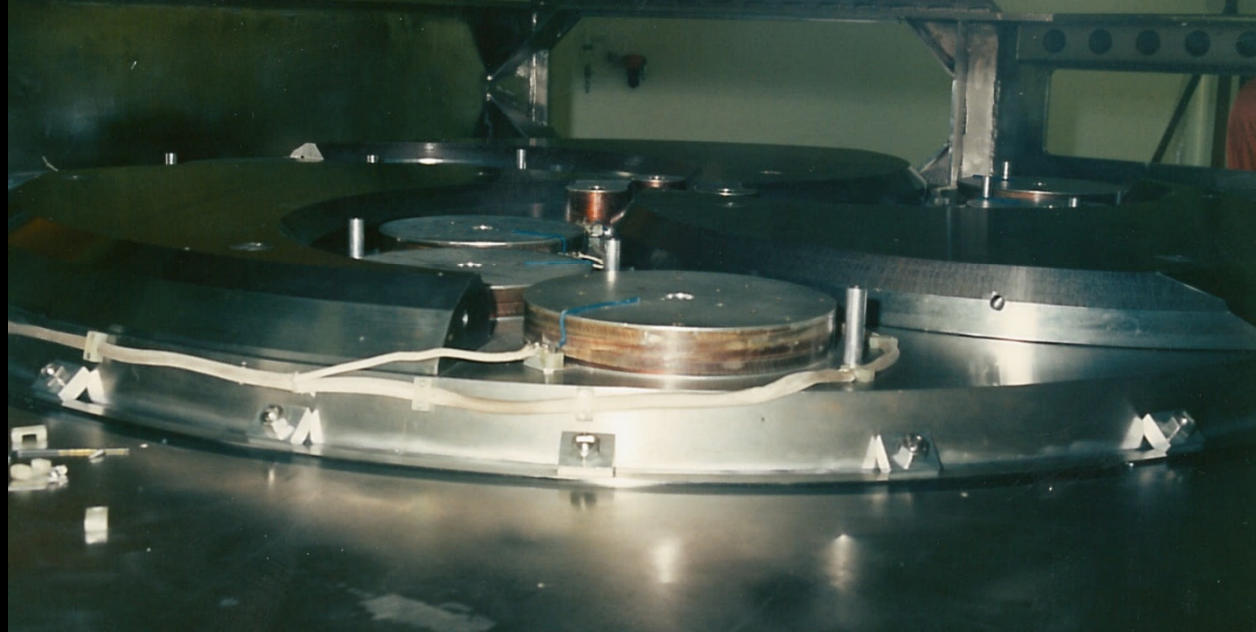
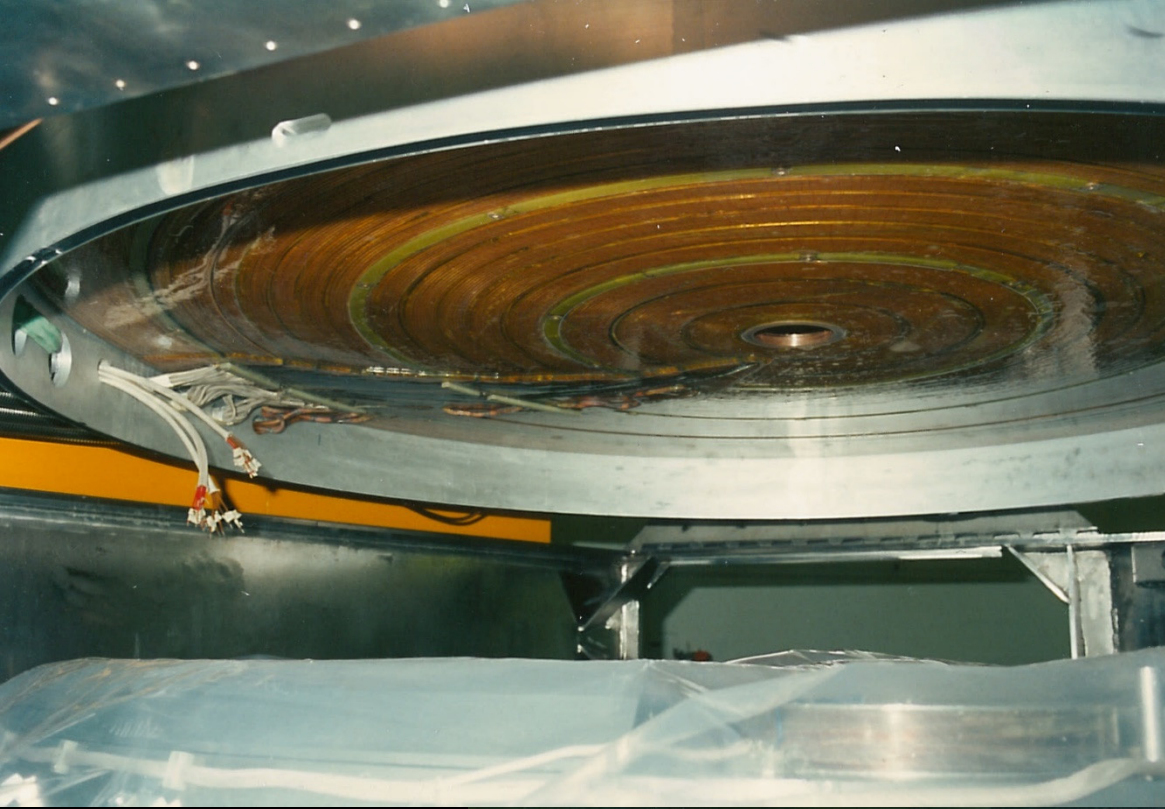
Scanditronix K130 cyclotron

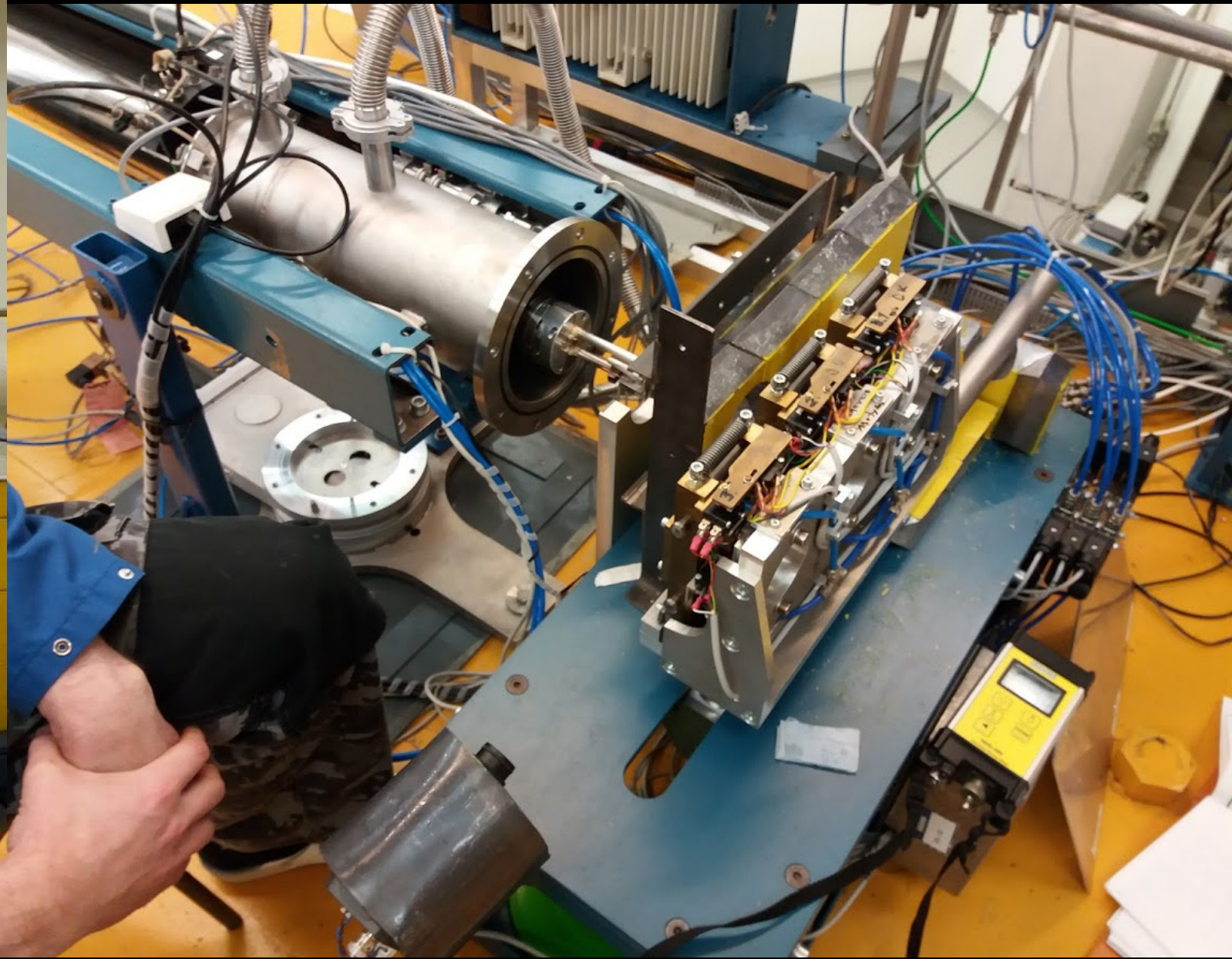
Multi-particle, multi-energy machine, designed 1986-, built and installed 1987-1991

- Pole diameter of 2.4 m
- Pole gap 0.33 / 0.174 m
- Three spiral sectors, 58° max angle
- Normal conducting, 150 kW main coils and 35 kW circular trim coils
- Extraction at 0.95 m with 1.83 T average field at 1170 A
- Bending limit 137 MeV, focusing limit 90 MeV
- Acceleration with two 78° dees with 10-21 MHz RF at 50 kV max, using harmonics 1-3
- Stripping extraction for H⁻, electrostatic deflector, EMC + 2 passive channels for heavy ions





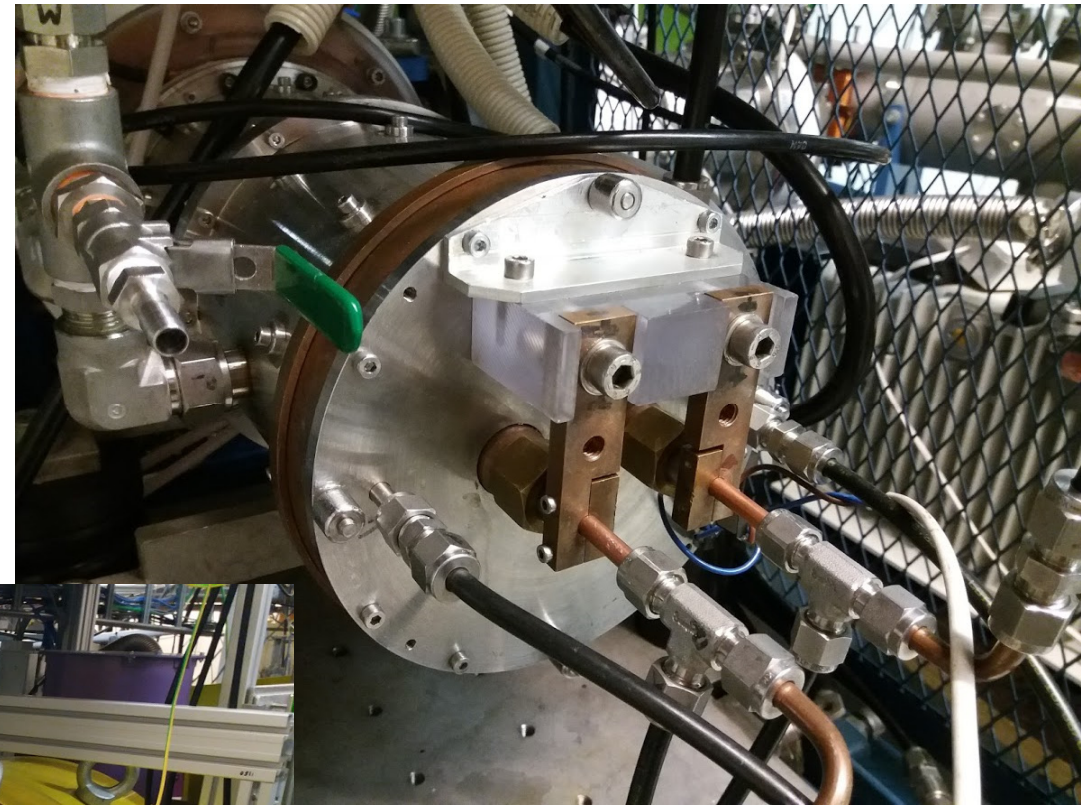
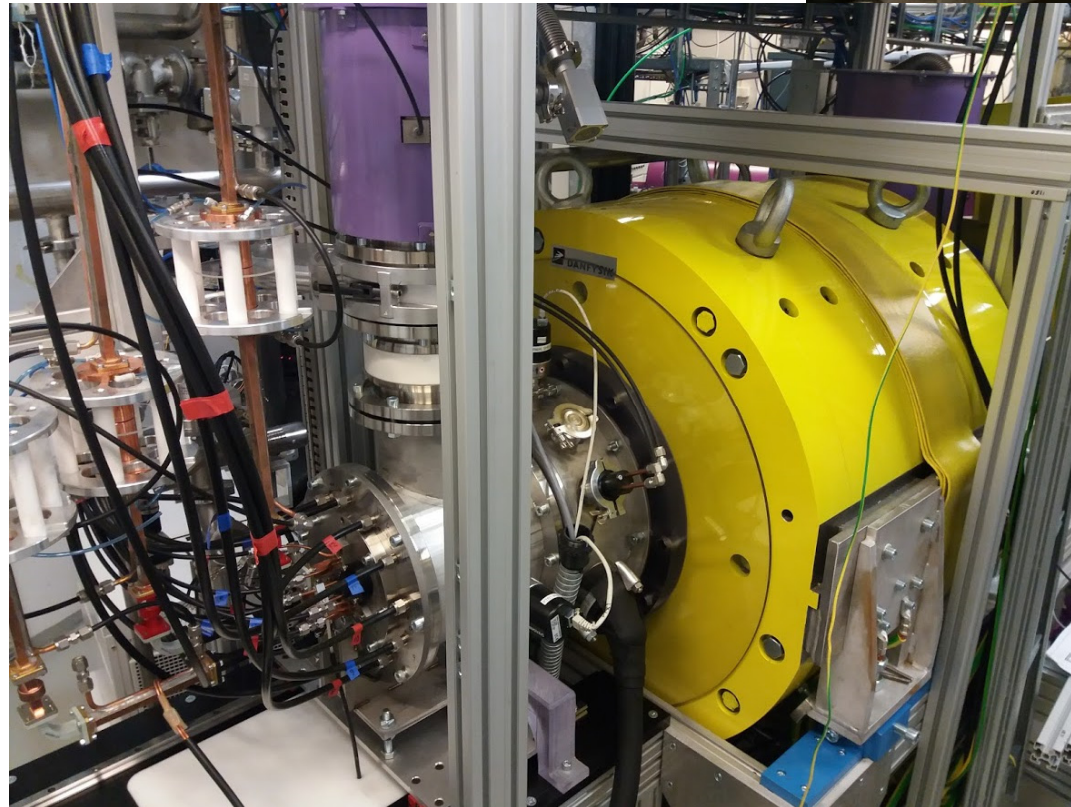




Ion sources

Four ion sources driving the K130

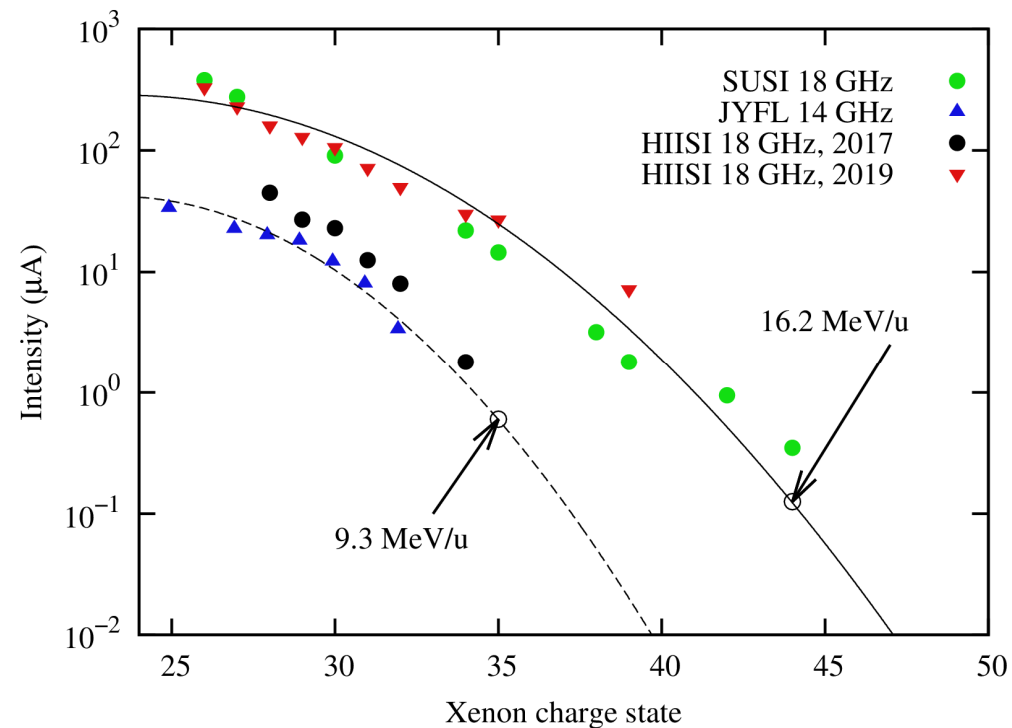
- **18 GHz ECRIS, 2014-2018**
- 14 GHz ECRIS, 2000
- 6.4 GHz ECRIS, 1991
- TRIUMF-type filament-driven H⁻ ion source, 1999



Two goals for 18 GHz ECRIS: 1. RADEF beam cocktail

16.2 MeV/u cocktail

Ion	E (MeV)	$\Delta m/q$ (%)
$^{17}\text{O}^{6+}$	284	-0.75
$^{20}\text{Ne}^{7+}$	329	0.06
$^{40}\text{Ar}^{14+}$	657	0
$^{57}\text{Fe}^{20+}$	941	-0.27
$^{83}\text{Kr}^{29+}$	1358	0.16
$^{126}\text{Xe}^{44+}$	2059	0.25



Application and development of ion-source technology for radiation-effects testing of electronics



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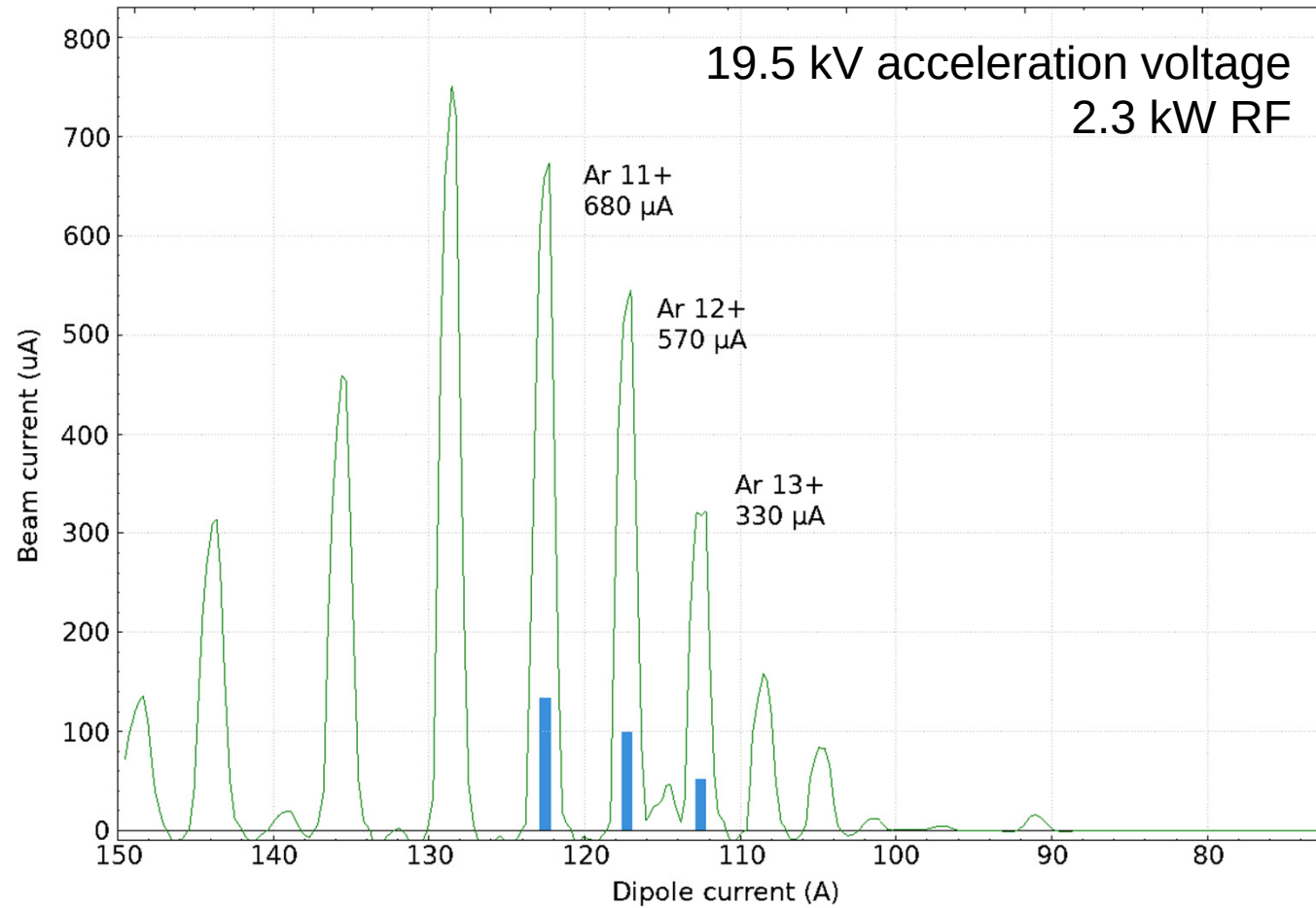
^b Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN 37235, USA

ABSTRACT

Studies of heavy-ion induced single event effect (SEE) on space electronics are necessary to verify the operation of the components in the harsh radiation environment. These studies are conducted by using high-energy heavy-ion beams to simulate the radiation effects in space. The ion beams are accelerated as so-called ion cocktails, containing several ion beam species with similar mass-to-charge ratio, covering a wide range of linear energy transfer (LET) values also present in space. The use of cocktails enables fast switching between beam species during testing. Production of these high-energy ion cocktails poses challenging requirements to the ion sources because in most laboratories reaching the necessary beam energies requires very high charge state ions. There are two main technologies producing these beams: The electron beam ion source EBIS and the electron cyclotron resonance ion source ECRIS. The EBIS is most suitable for pulsed accelerators, while ECRIS is most suitable for use with cyclotrons, which are the most common accelerators used in these applications.

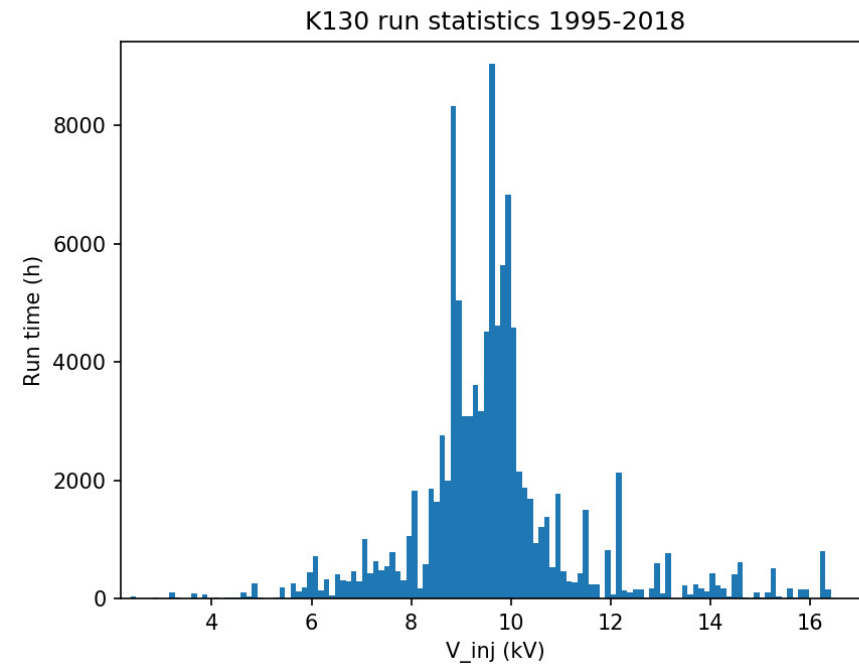
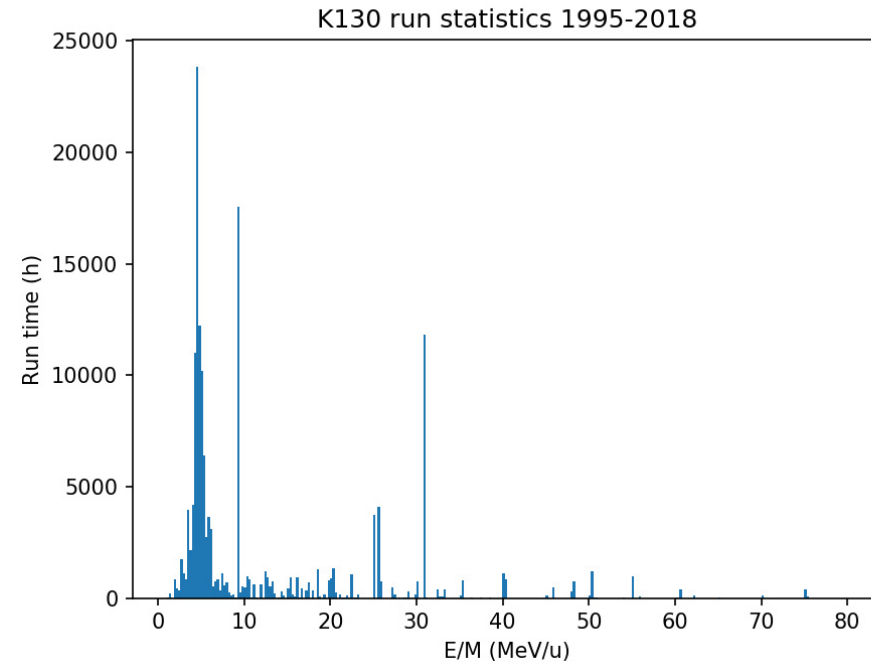
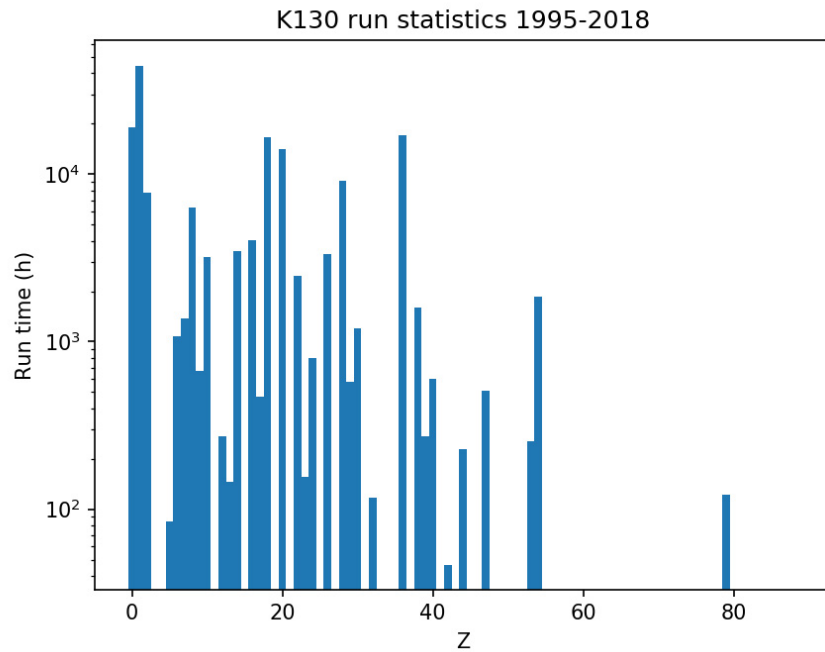
At the Accelerator Laboratory of the University of Jyväskylä (JYFL), radiation effects testing is currently performed using a K130 cyclotron and a 14 GHz ECRIS at a beam energy of 9.3 MeV/u. A new 18 GHz ECRIS, pushing the limits of the normal conducting ECR technology is under development at JYFL. The performances of existing 18 GHz ion sources have been compared, and based on this analysis, a 16.2 MeV/u beam cocktail with 1999 MeV $^{126}\text{Xe}^{44+}$ being the most challenging component to has been chosen for development at JYFL. The properties of the suggested beam cocktail are introduced and discussed.

2. Intensity gains for nuclear physics



Run statistics

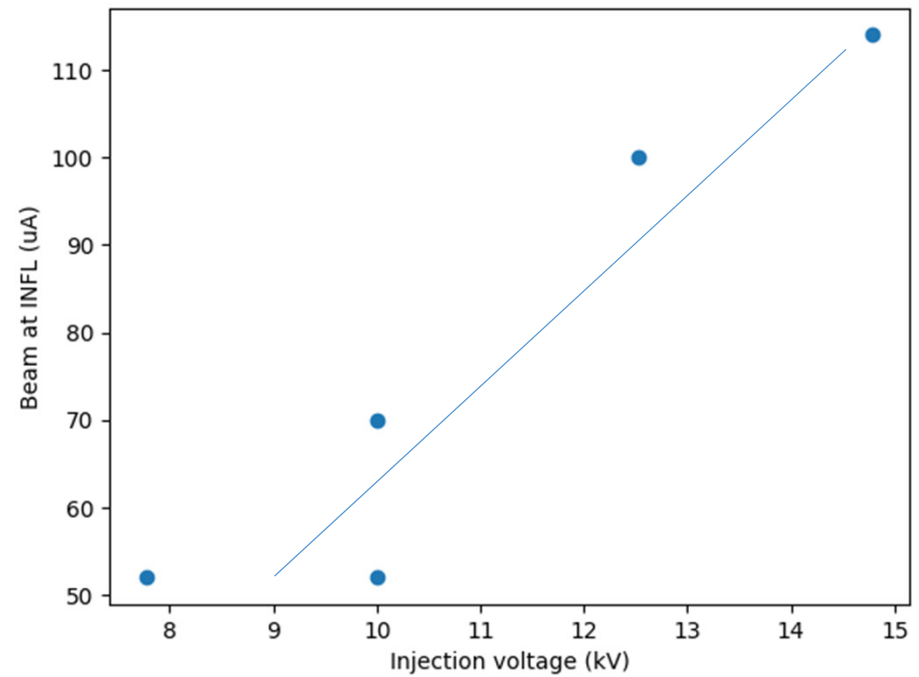
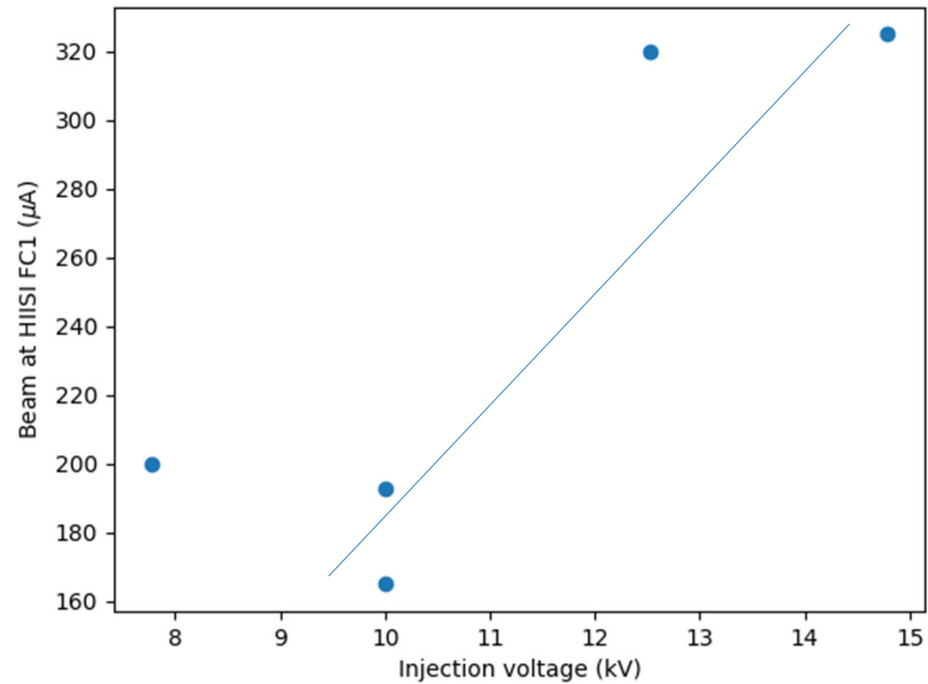
163 000 hours, 6812 hours/year average



Transport measurements

Measurements with Ar 11+ show an increase of

- 50 % from 10 kV to 15 kV
- 100 % from 10 kV to 20 kV (FC1)

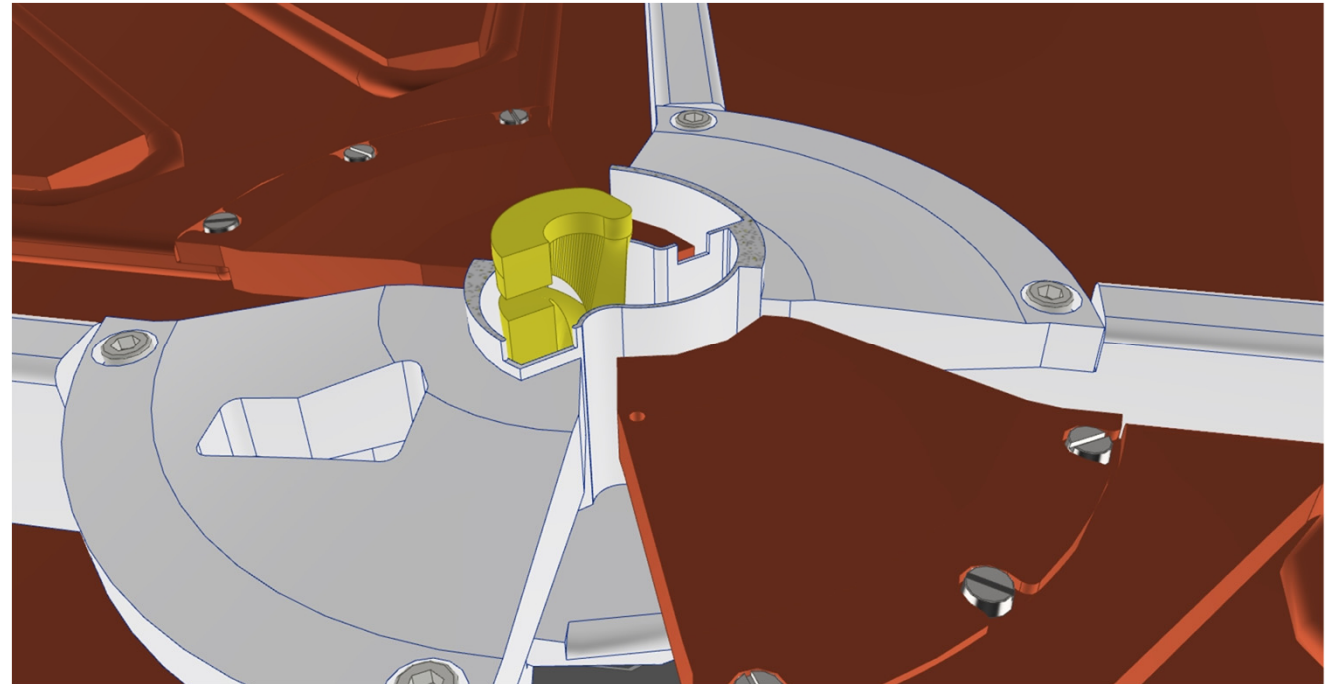


Redesign of central region for double injection voltage

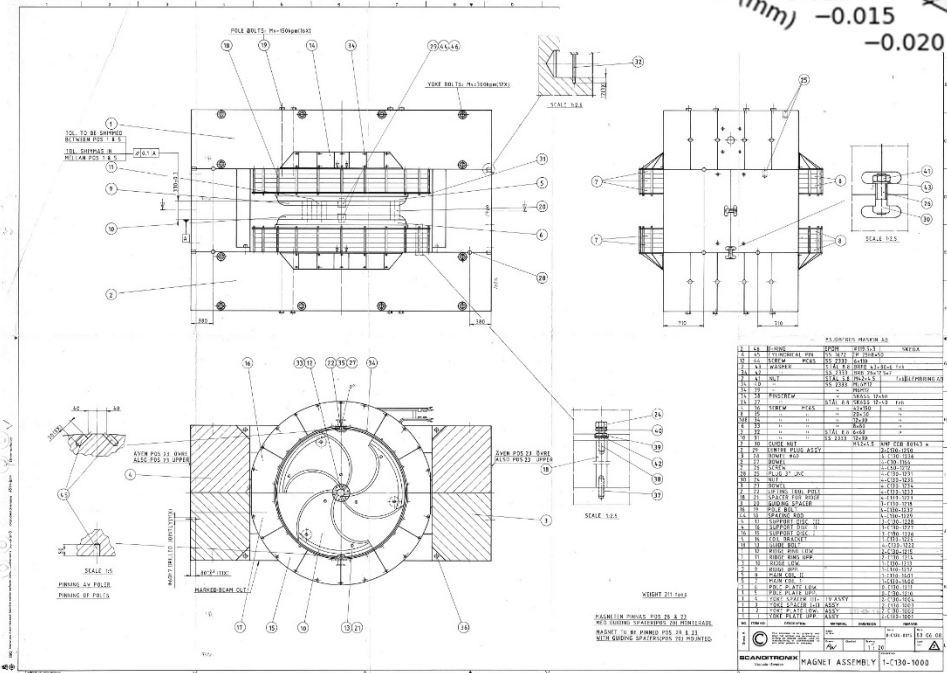
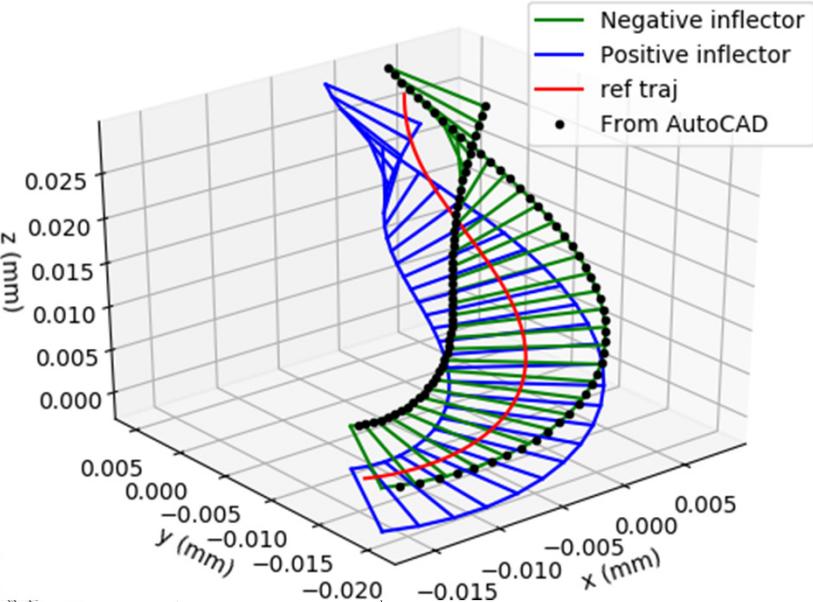
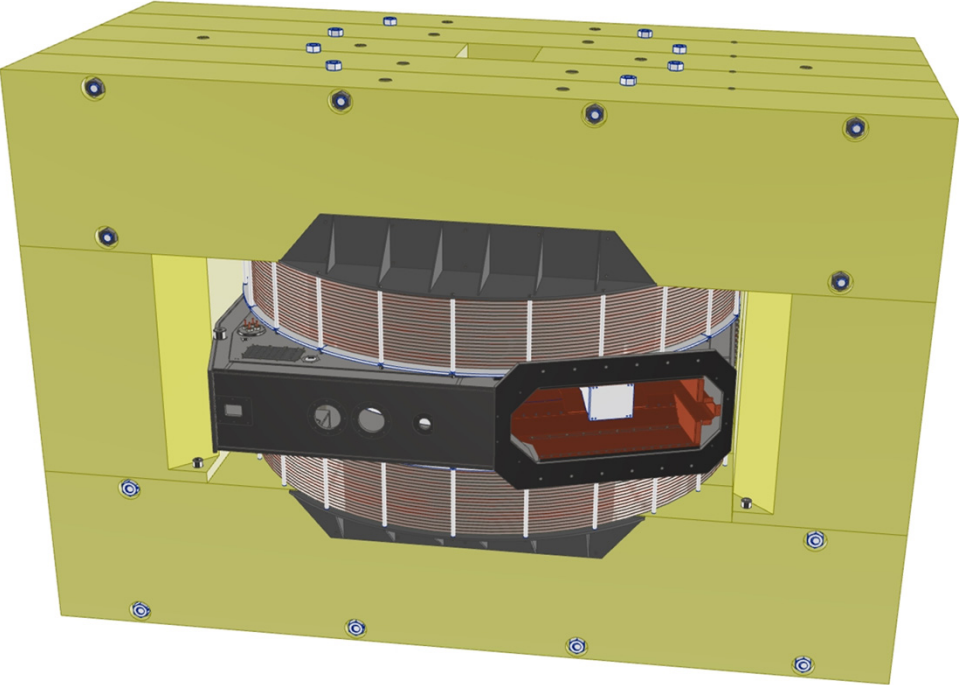
- Redesign the central region and inject to larger radius -> higher injection voltage
- Problem: 16.2 MeV/u cocktail runs already at 18.8 kV, doubling the voltage would need a major upgrade to the injection line infrastructure

Plan:

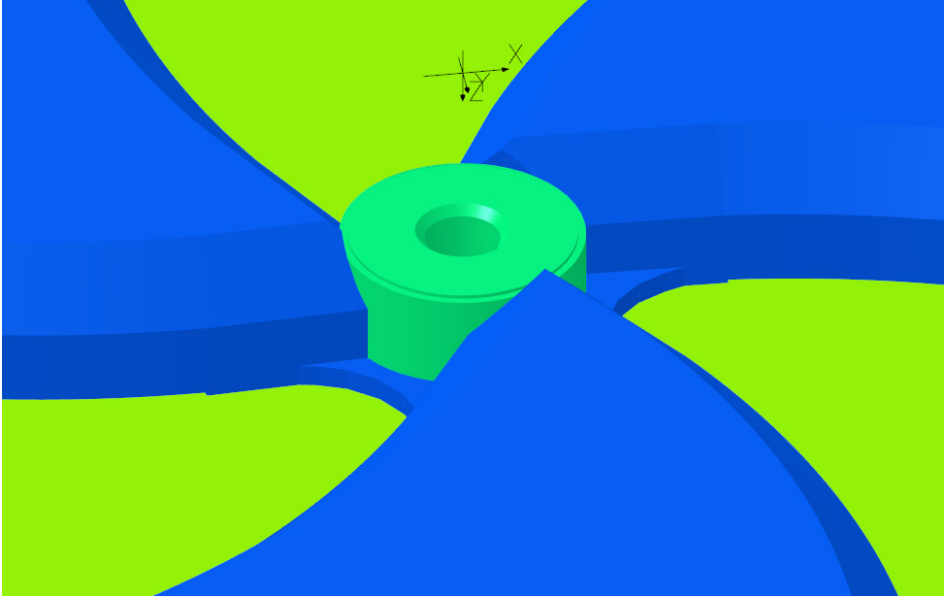
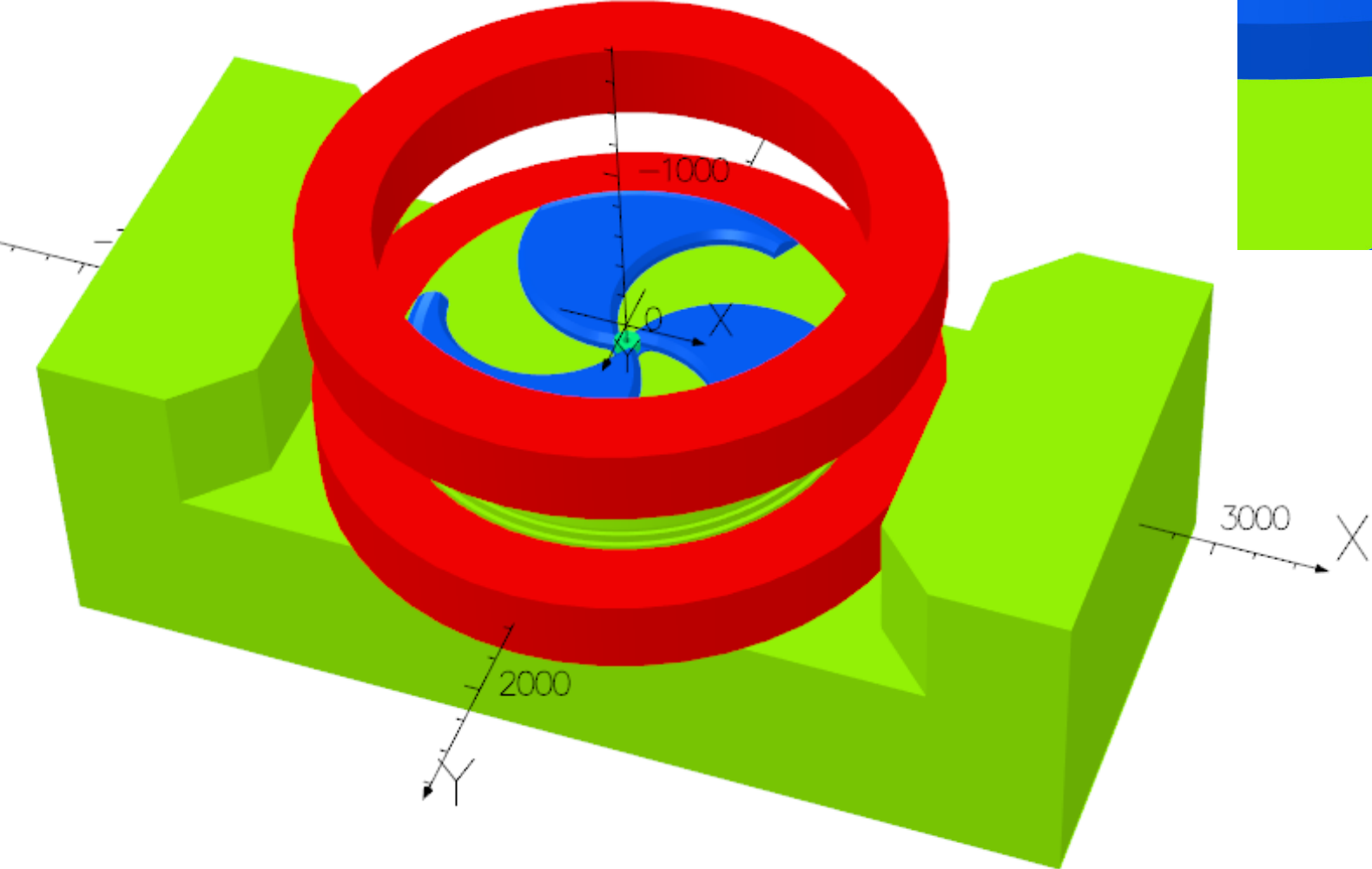
- Changeable central regions
 - One for high intensity runs
 - One for other runs
- Runs to be scheduled in blocks
- Central region is relatively easy to change
- Avoid activating runs before change



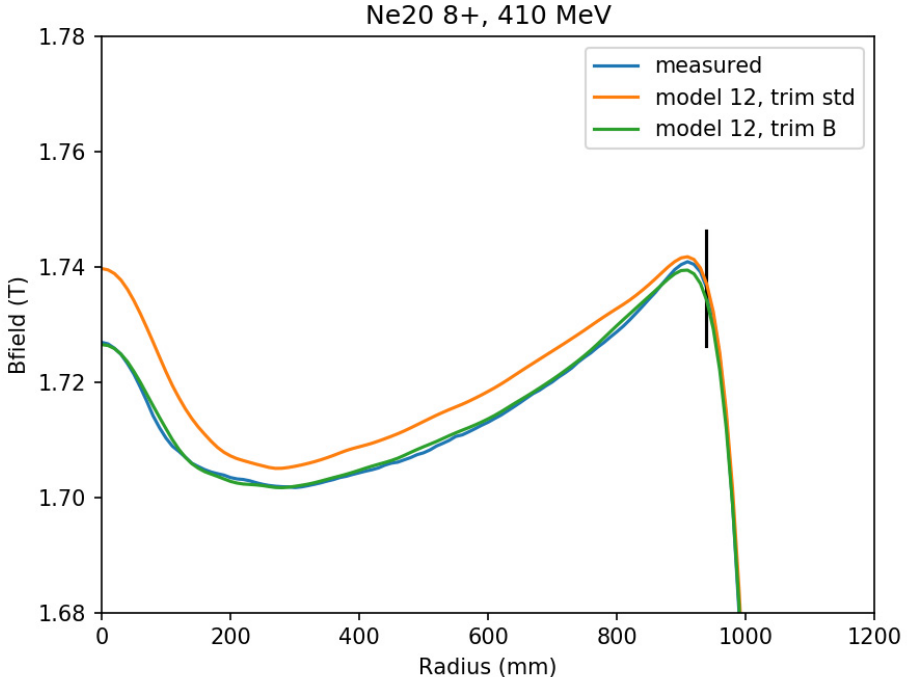
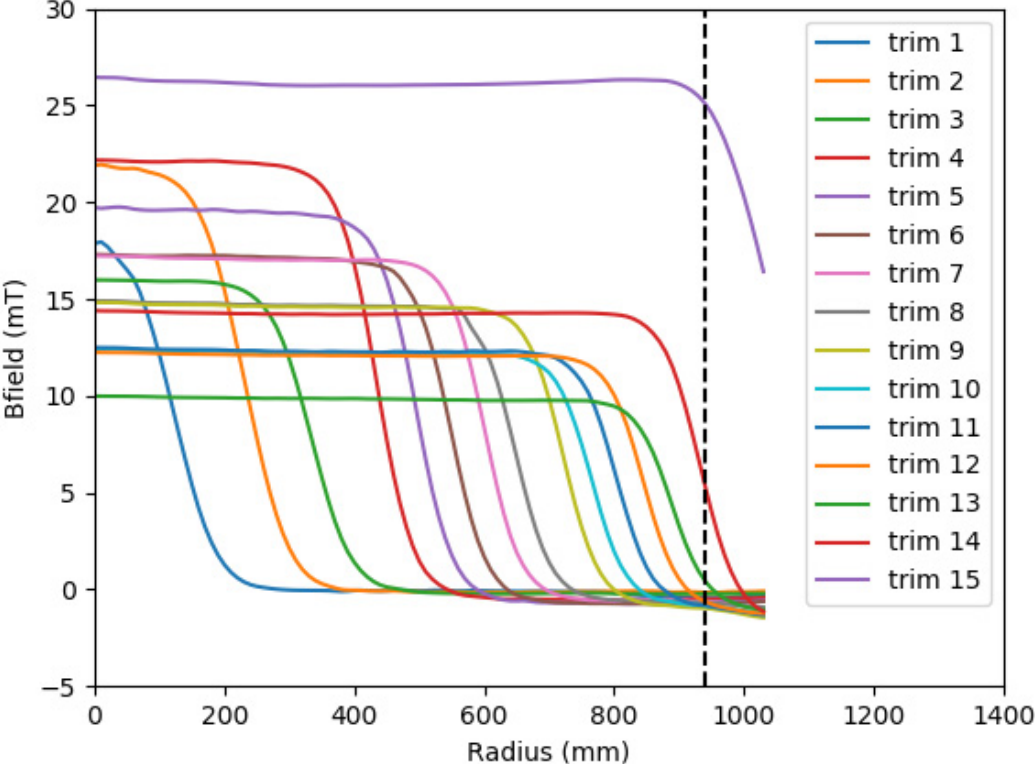
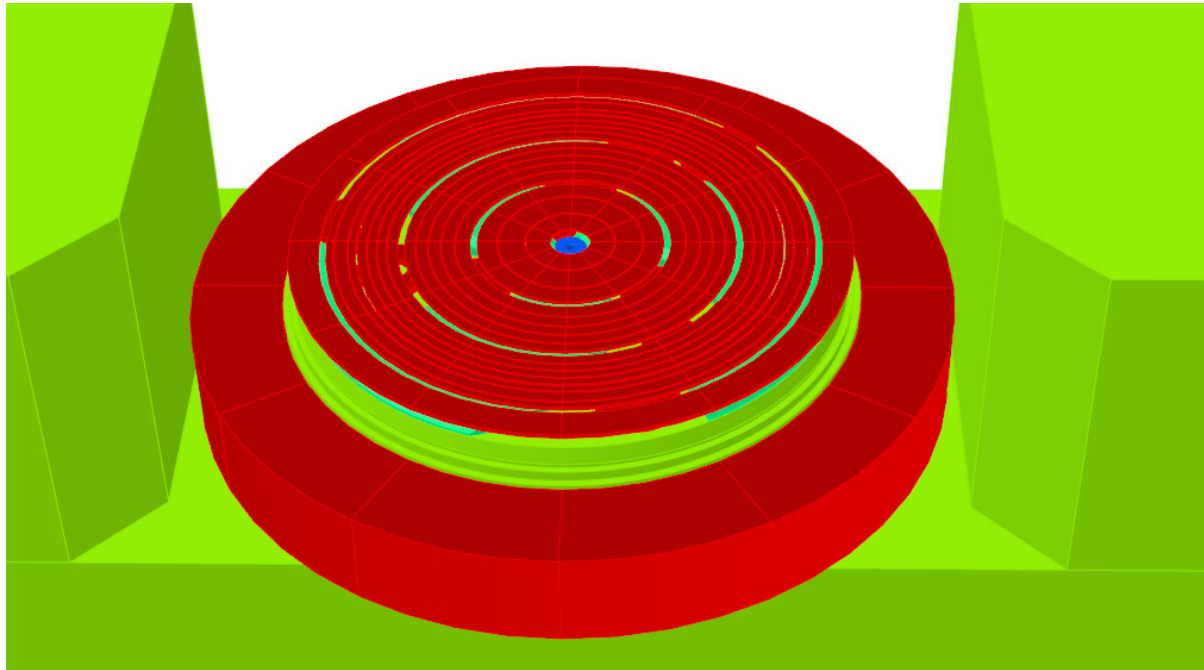
Work started with CAD modelling and data gathering



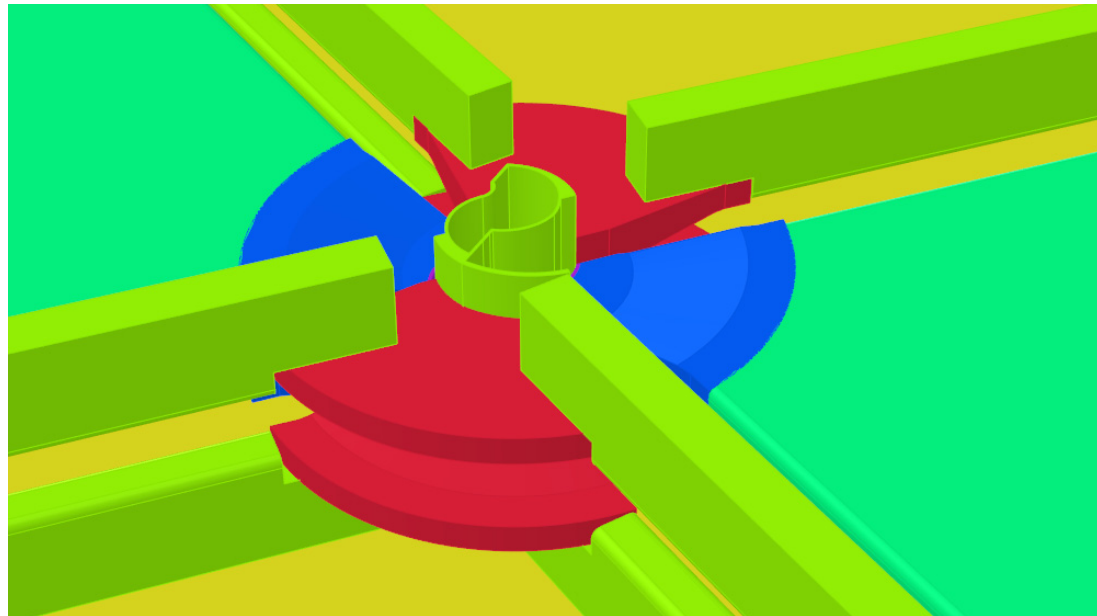
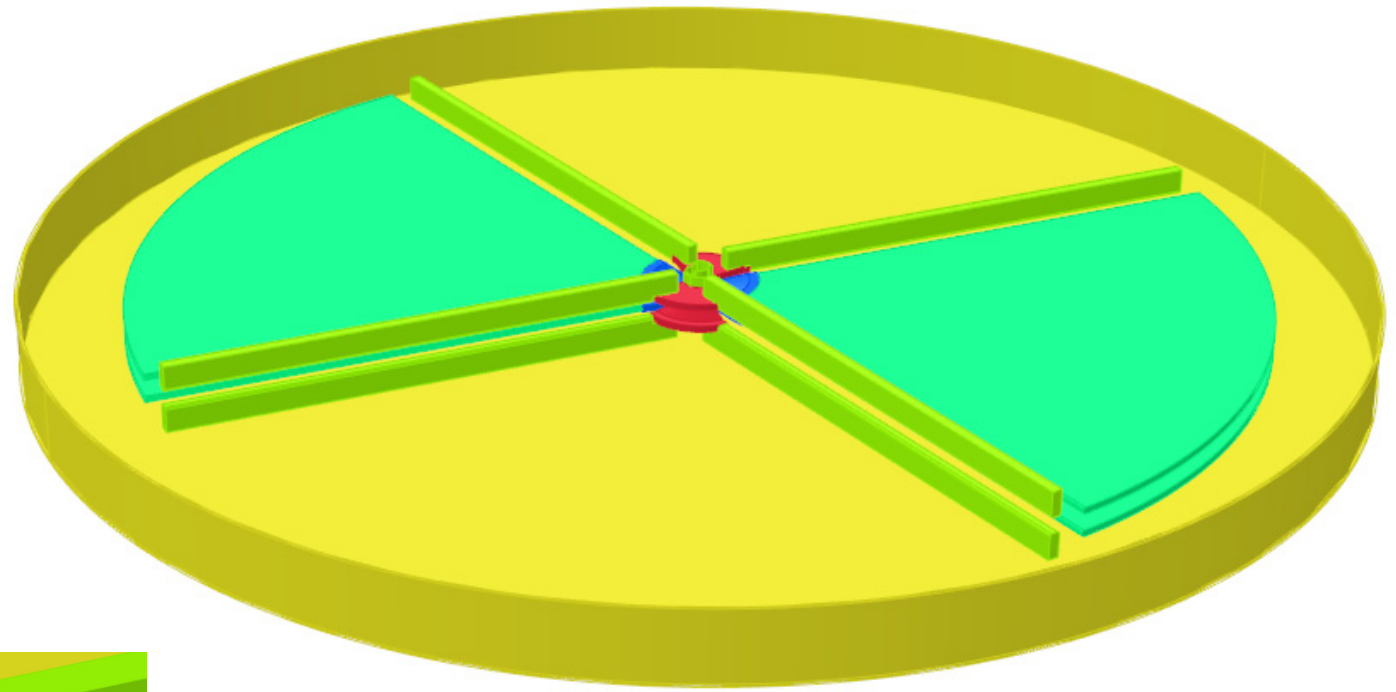
Magnetic model



Magnetic model

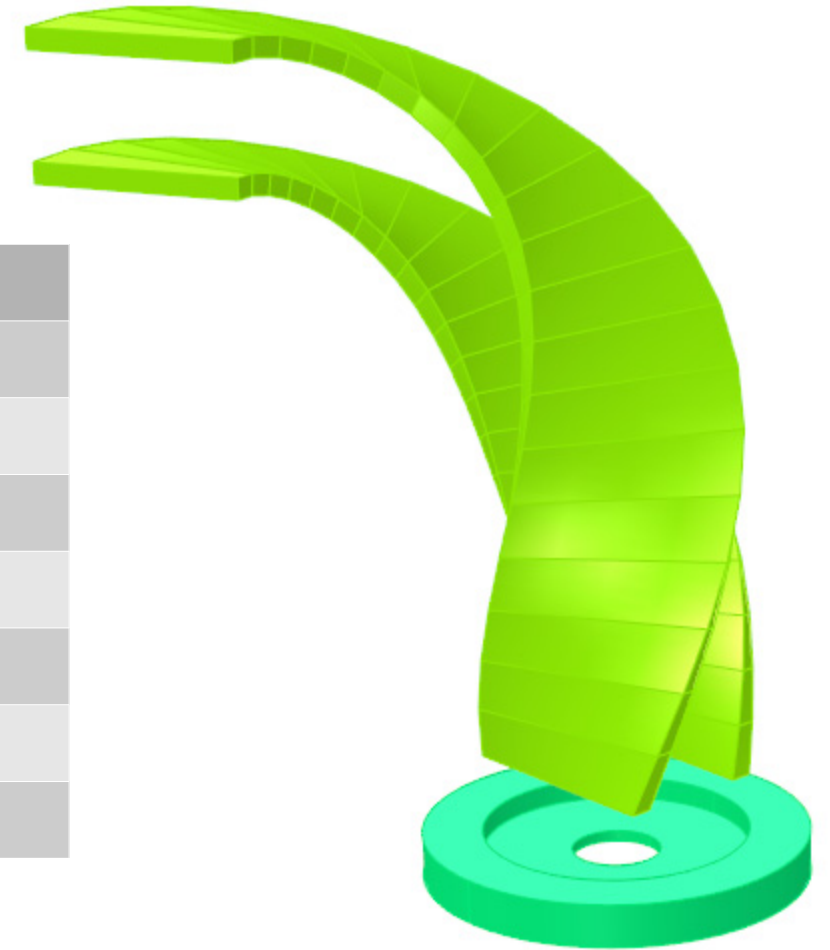


Potential calculation



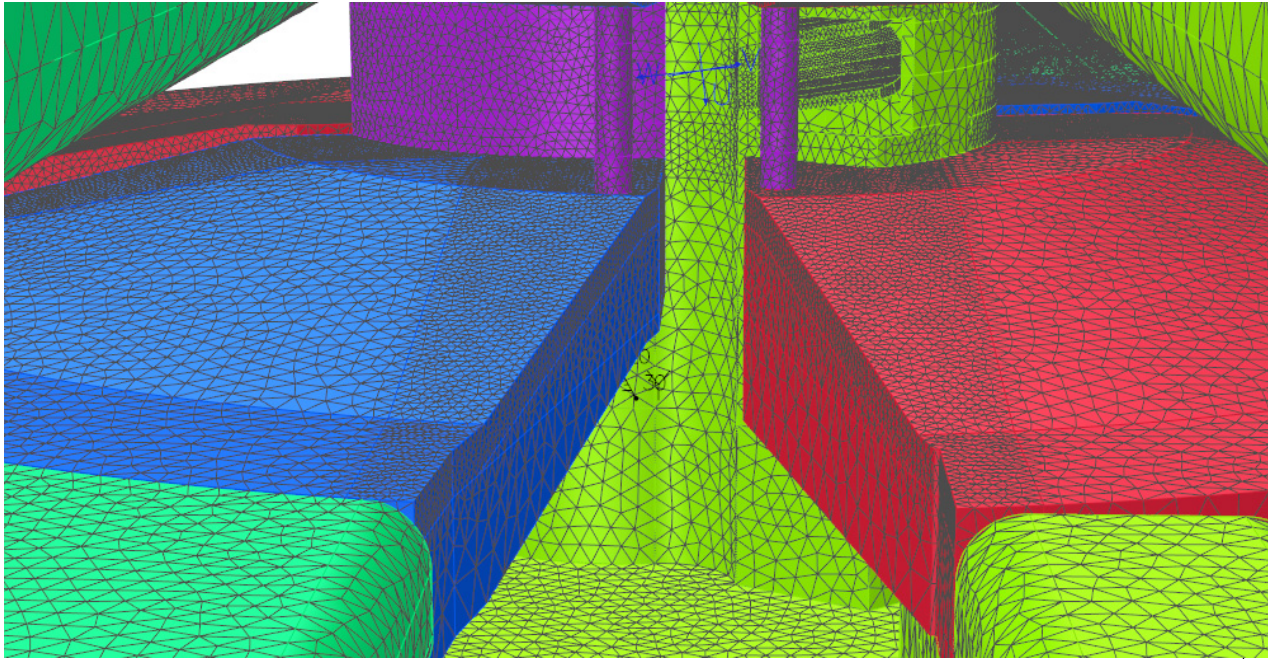
Original inflectors

Harmonic mode	1	2	3
Max injection voltage (kV)	15.0	20.0	13.3
Spiral height (mm), A	30.0	30.0	29.0
Gap height (mm), d	5.0	5.0	5.0
Gap width (mm)	10.0	10.0	10.0
Tilt parameter, k	0.00	0.19	0.00
Injection radius (mm), R	13.1	18.8	18.8
Max spiral voltage (kV)	± 2.5	± 3.3	± 2.3



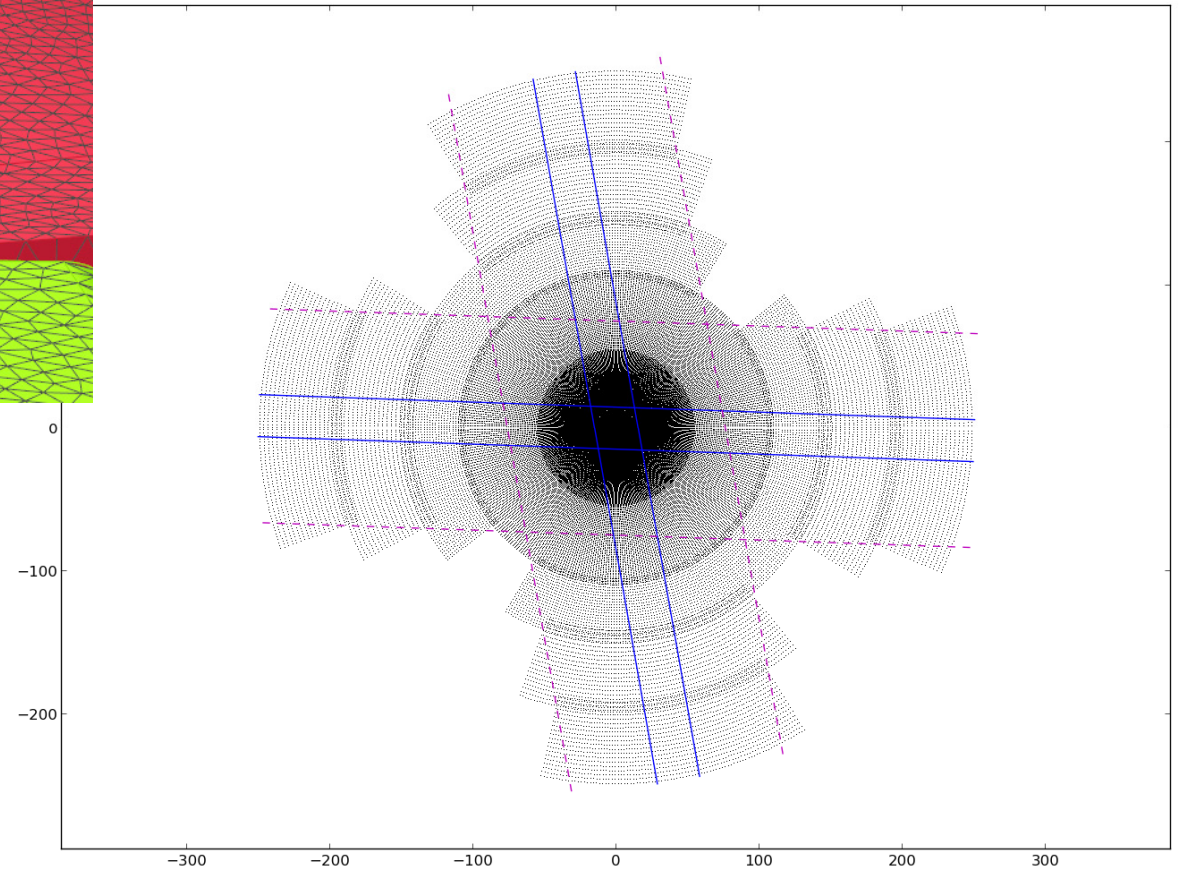
Inflector surfaces are otherwise built around Belmont-Pabot central trajectory, but length is trimmed at the exit to compensate for the stray field.

Potential calculation



Potential calculation about some hours on a desktop computer

About 4 M nodes in a set of regular grids



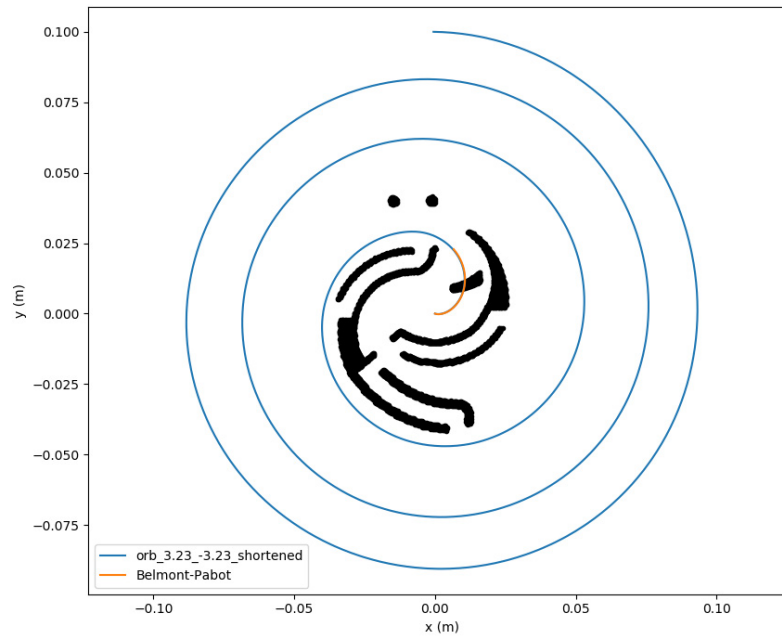
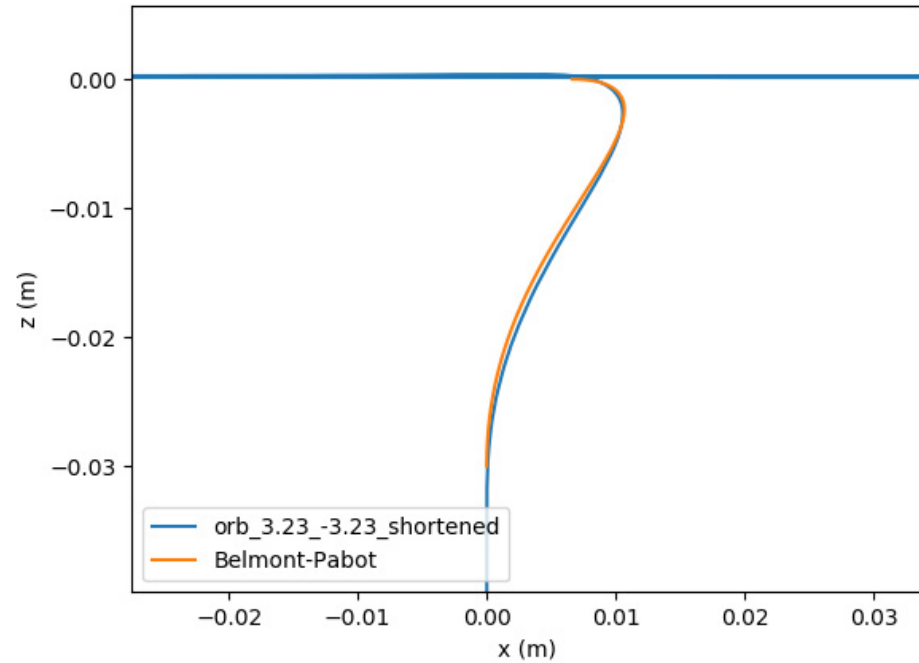
Tracking with AOC

IBA "Accelerated Orbit Code"

- A C program by Will Kleeven

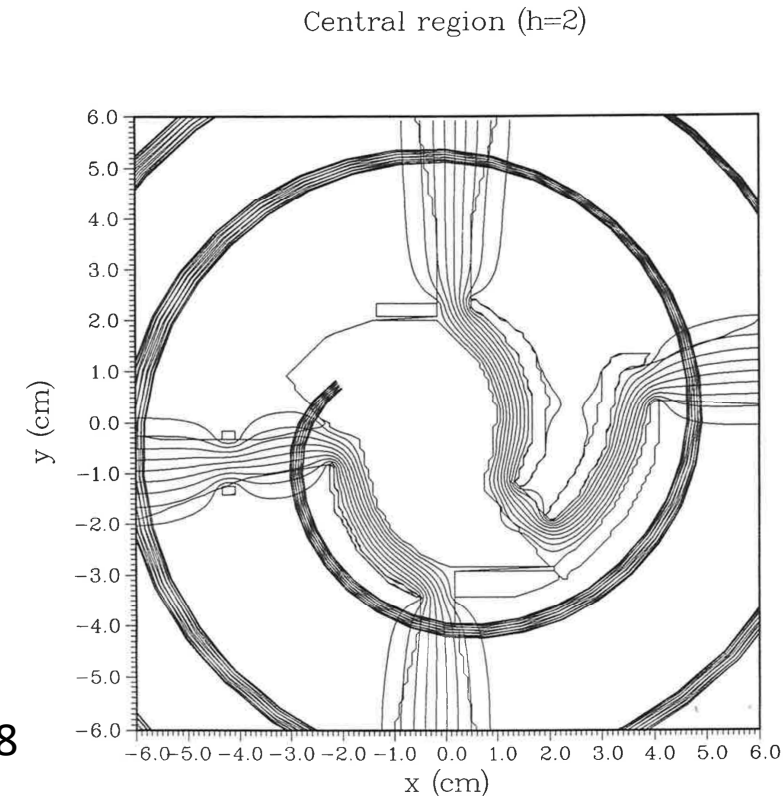
- Computes beam orbit by integrating equations of motion in $E(t)$ - and B -fields
- Modules for inflector designing, extraction, field errors, ...
- Relatively fast: a few minutes for a beam of 100s of particles, full acceleration, a few hours for a space charge calculation
- Data dumping in ascii allows easy post processing (Python scripts for plotting, etc.)

AOC modelling original h=2 injection



Ideally, inflector voltage 3.39 kV. 3.23 kV gives optimal angle in AOC with 0.4 mm offset from midplane

Matches simulations from 1988

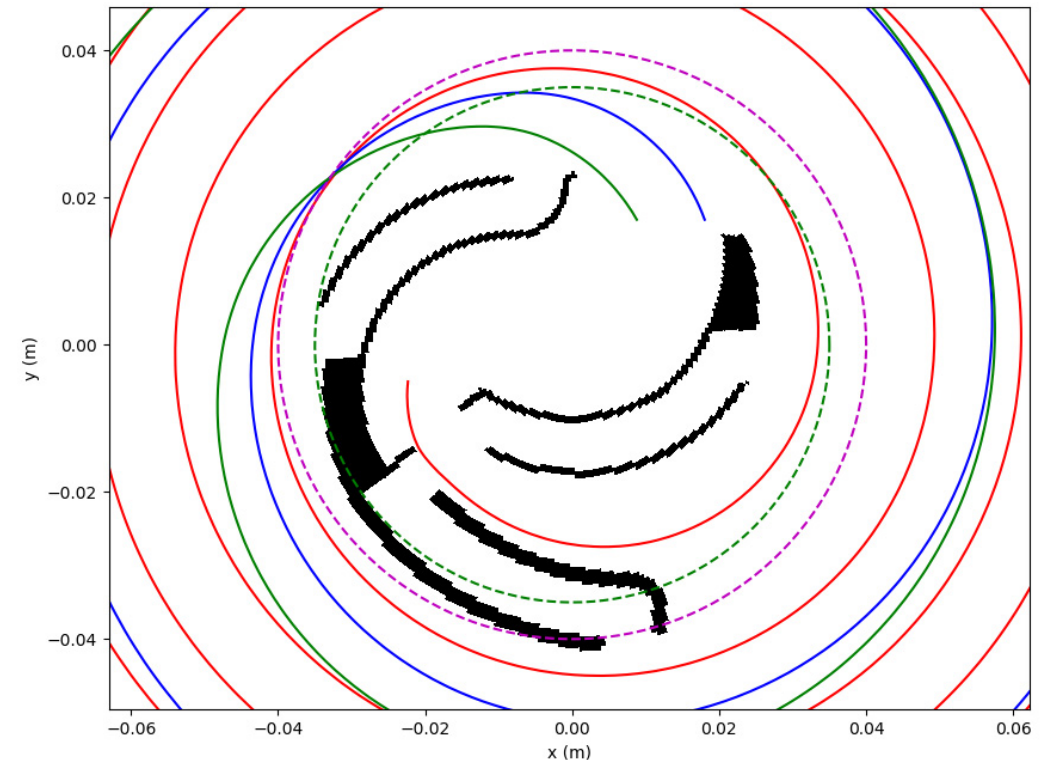
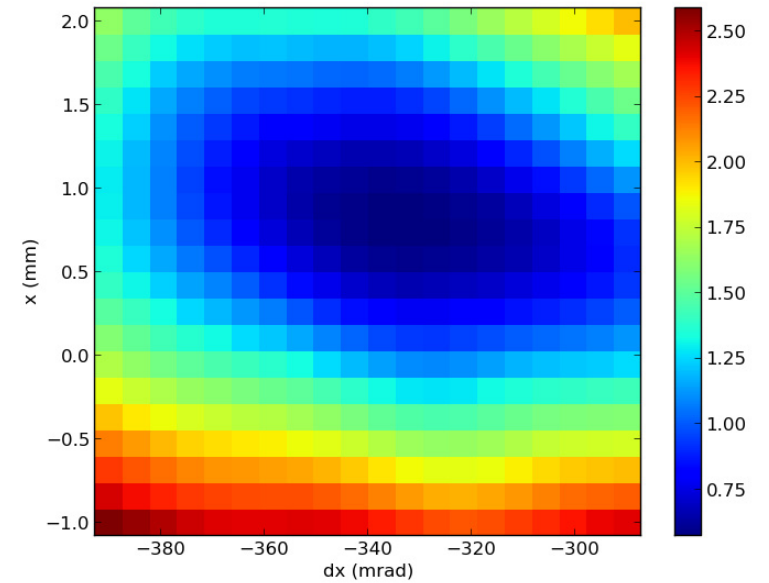


New central region

Iterative design process for a new K130 central region with

- 30 MeV proton beam with $h=1$ ($V_{inj} = 11.5$ kV)
- 200 MeV Ar40 8+ with $h=2$ and $h=3$ ($V_{inj} = 20.6$ kV)

1. Started with existing geometry and original V_{dee}
2. Searched for well centered orbits at the phase with maximum energy gain per turn
3. Modified geometry according to orbits or to intentionally change the orbits.
4. Repeat



Inflector design

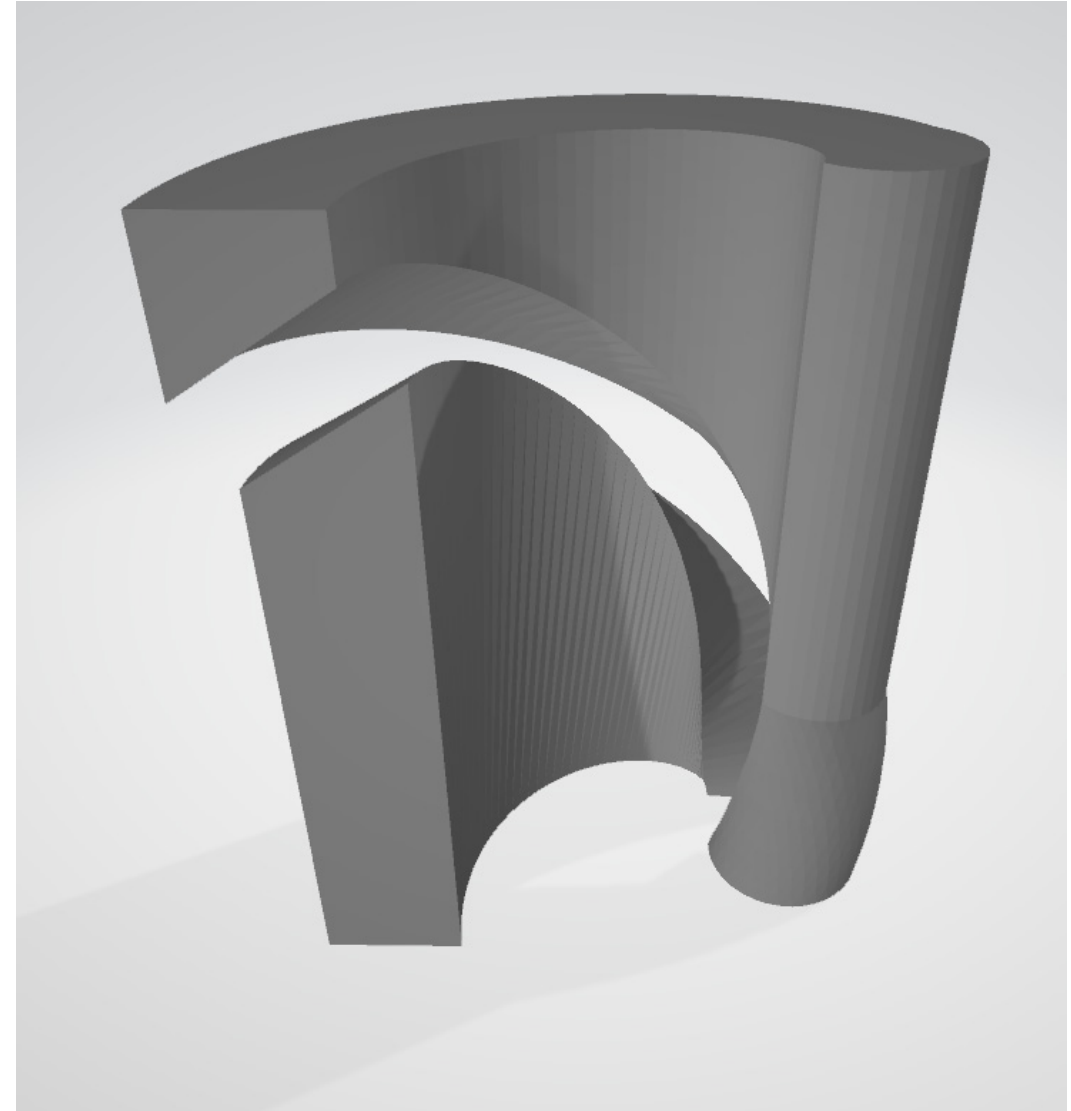
After finding well centered orbits design an inflector to deflect particle propagating along the axis to the orbit.

- Choose width (10 mm) and height (5 mm) of gap.
- Select electrostatic turning radius (A) to maximize physical size/minimize E-field.
- Find tilt (k) and rotation (θ) to meet the centered orbit.

Originally analytic Belmont-Pabot formula was used with K130 inflectors:

Gap decreases as tilt increases to maintain cosine shape deflection.

New solution with AOC: Maintain fixed gap and lengthen the inflector as deflecting field is lost to tilt.



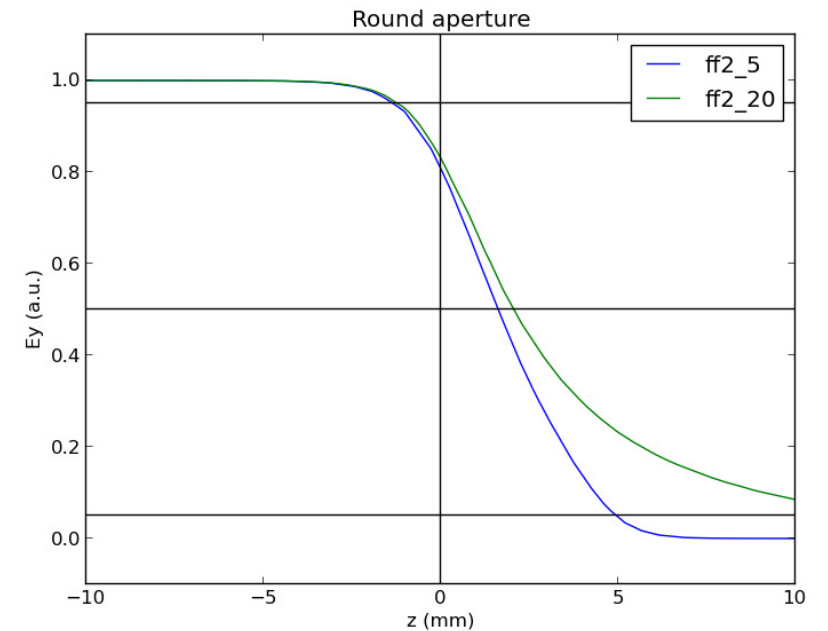
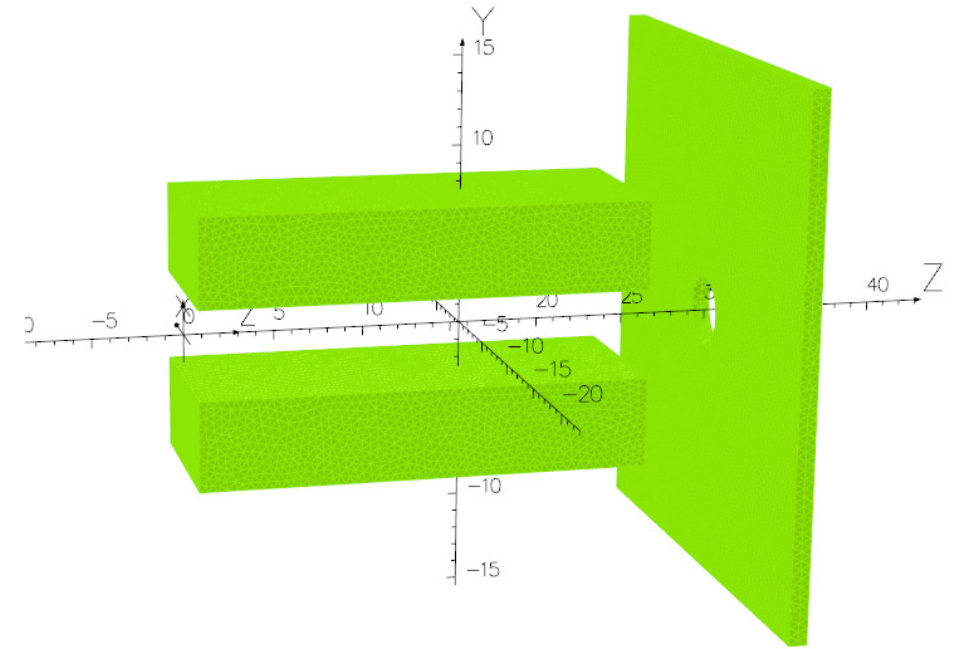
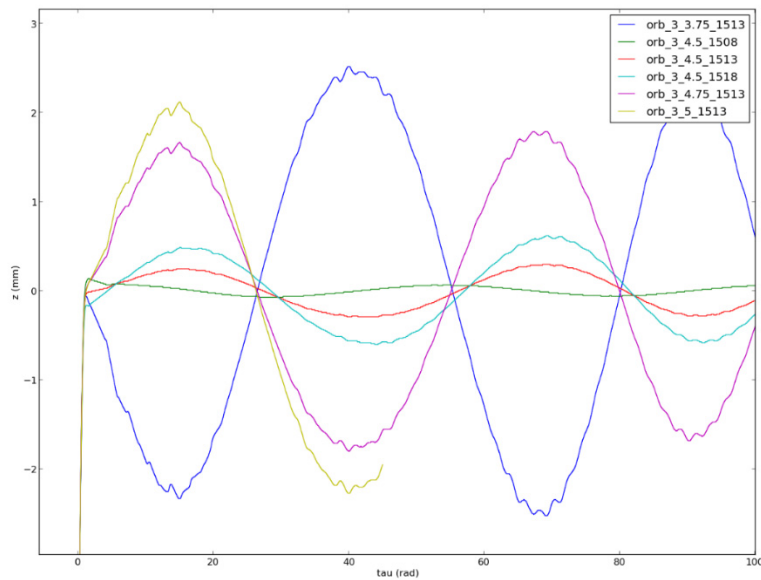
Inflectors

An automated tool in AOC generates virtual fields inside an ideal inflector while searching for the parameters (A, k, θ)

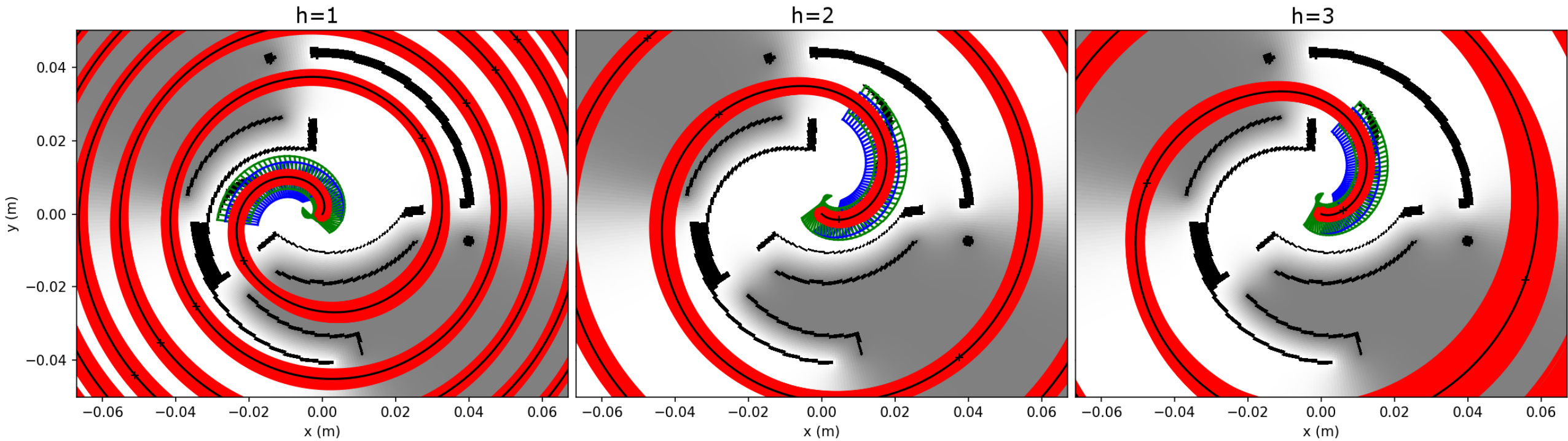
The fringe field was assumed to have length of $L_{\text{eff}}-L=1.71$ mm at entrance and $L_{\text{eff}}-L=3.29$ at exit by the model.

The final length of the inflector was adjusted to have

- Beam at the center of the inflector
- Perfect vertical centering of beam at midplane ($z=0$)
- Zero vertical oscillation ($v_z=0$)



New central region



A=36 mm, $k=0.497$
Max V_{inj} = 31.8 kV
Max V_{sprl} = ± 4.41 kV

A=45 mm, $k=0.560$
Max V_{inj} = 42.0 kV
Max V_{sprl} = ± 4.67 kV

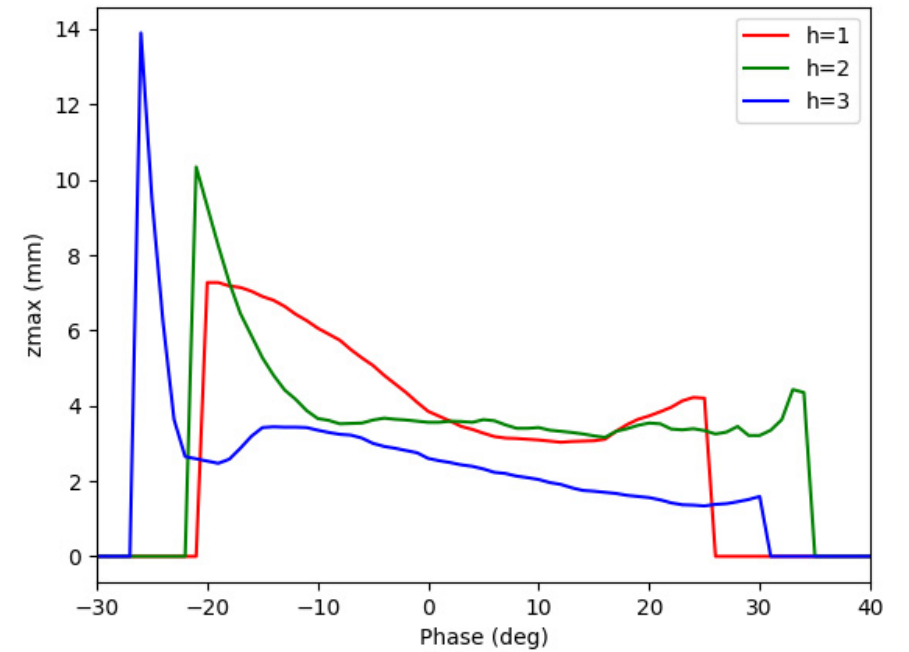
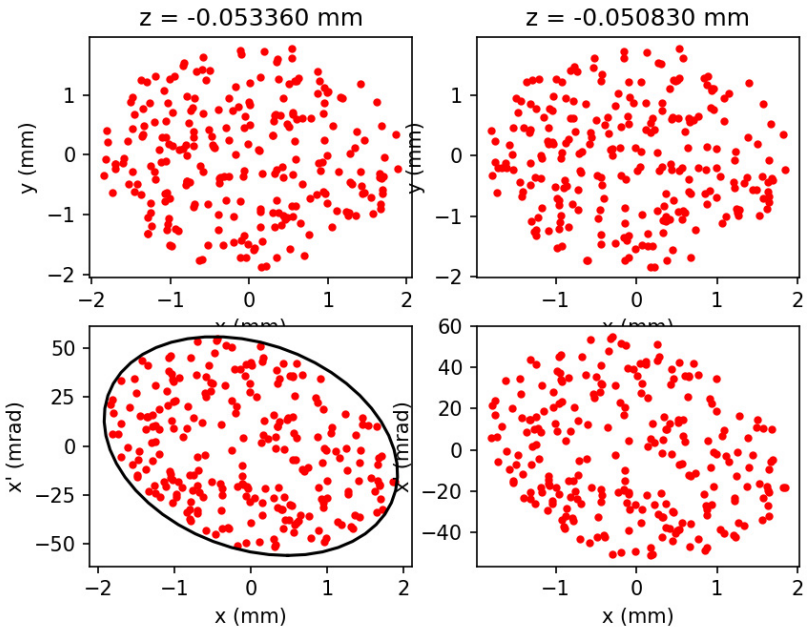
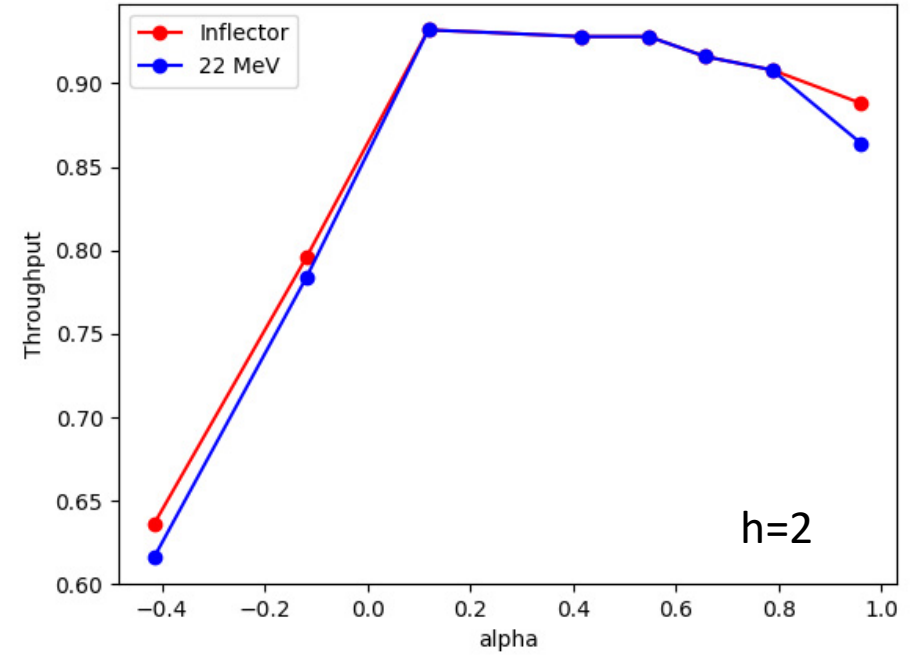
A=34 mm, $k=0.604$
Max V_{inj} = 28.6 kV
Max V_{sprl} = ± 4.21 kV

Throughput

Ar 8+ beam from ECRIS: KV-dist. 200 π mm mrad at 10 kV

Acceptance is and will be 100 π mm mrad.

Harmonic	1	2	3
Throughput at 0°	99 %	93 %	98 %
Throughput DC (0°-360°)	10 %	14 %	12 %
Phase acceptance	46°	56°	56°
Throughput due to phase	12.7 %	15.6 %	15.6 %



Throughput

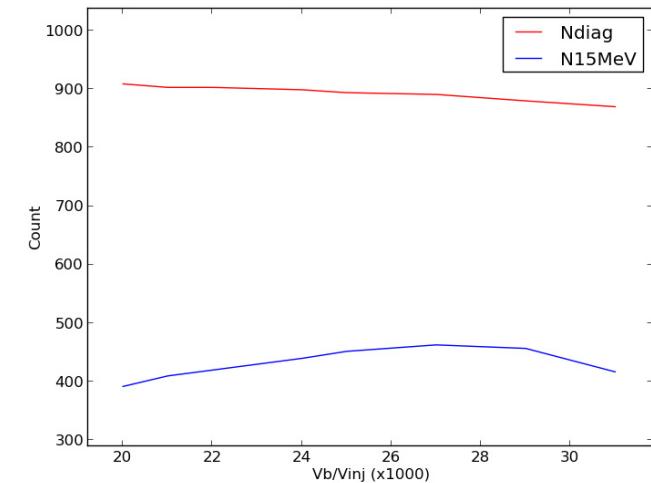
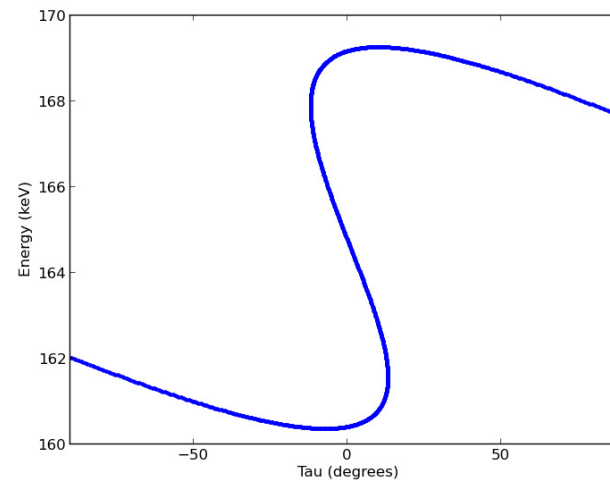
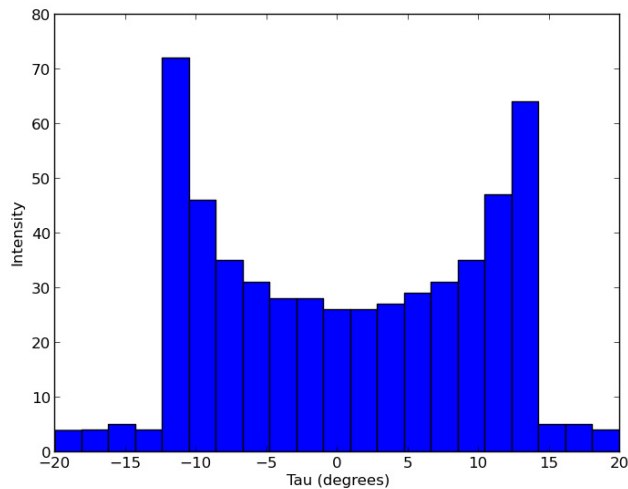
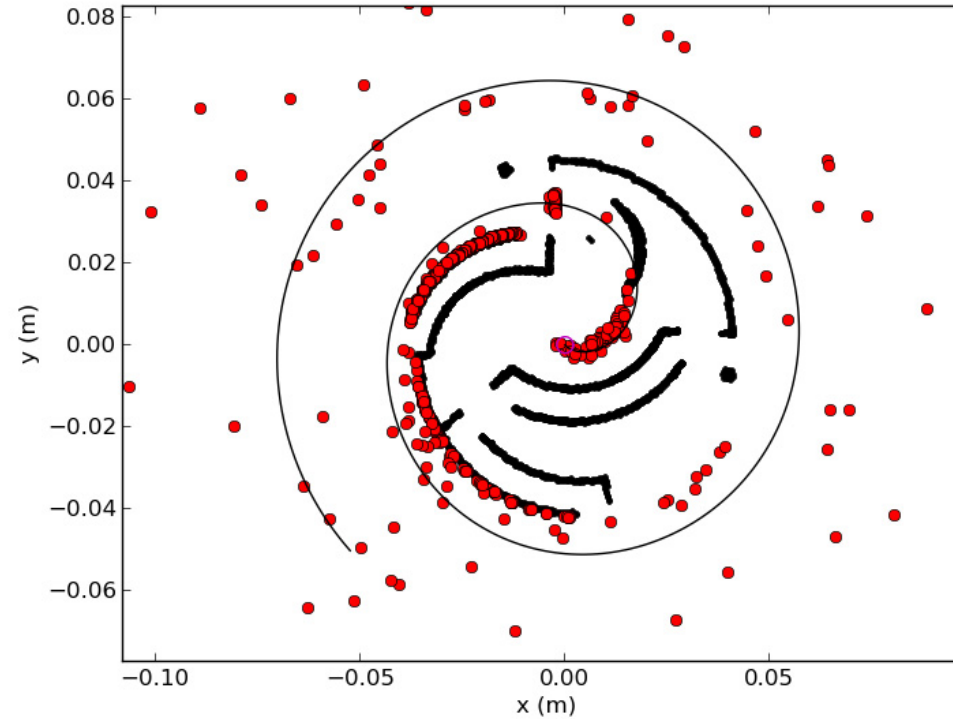
Sine wave bunching

Optimum at $V_b/V_{inj} = 27/1000 \rightarrow V_b = 556 \text{ V}$

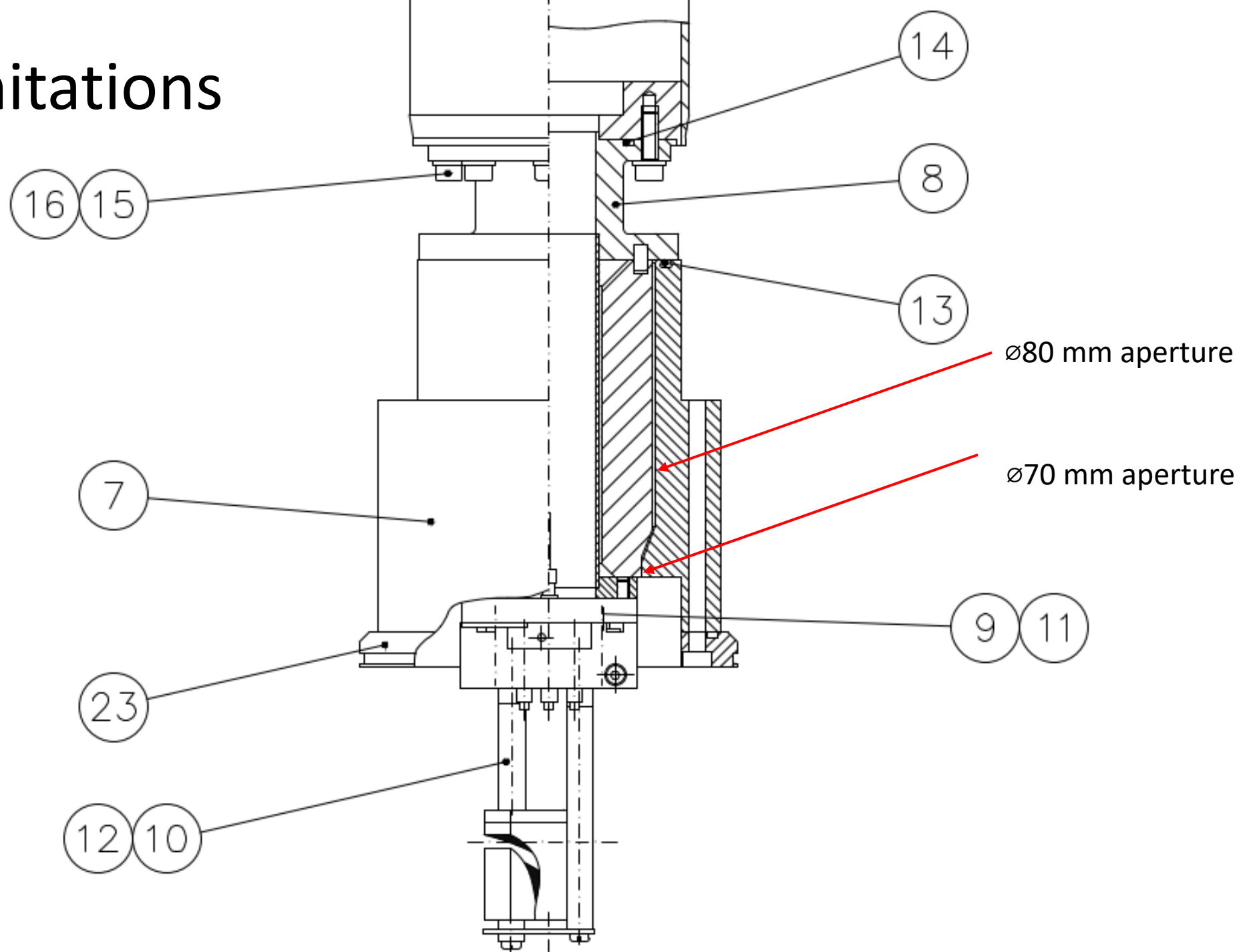
Max throughput 46 %, gain factor of 3.5

With space charge? Study to be done.

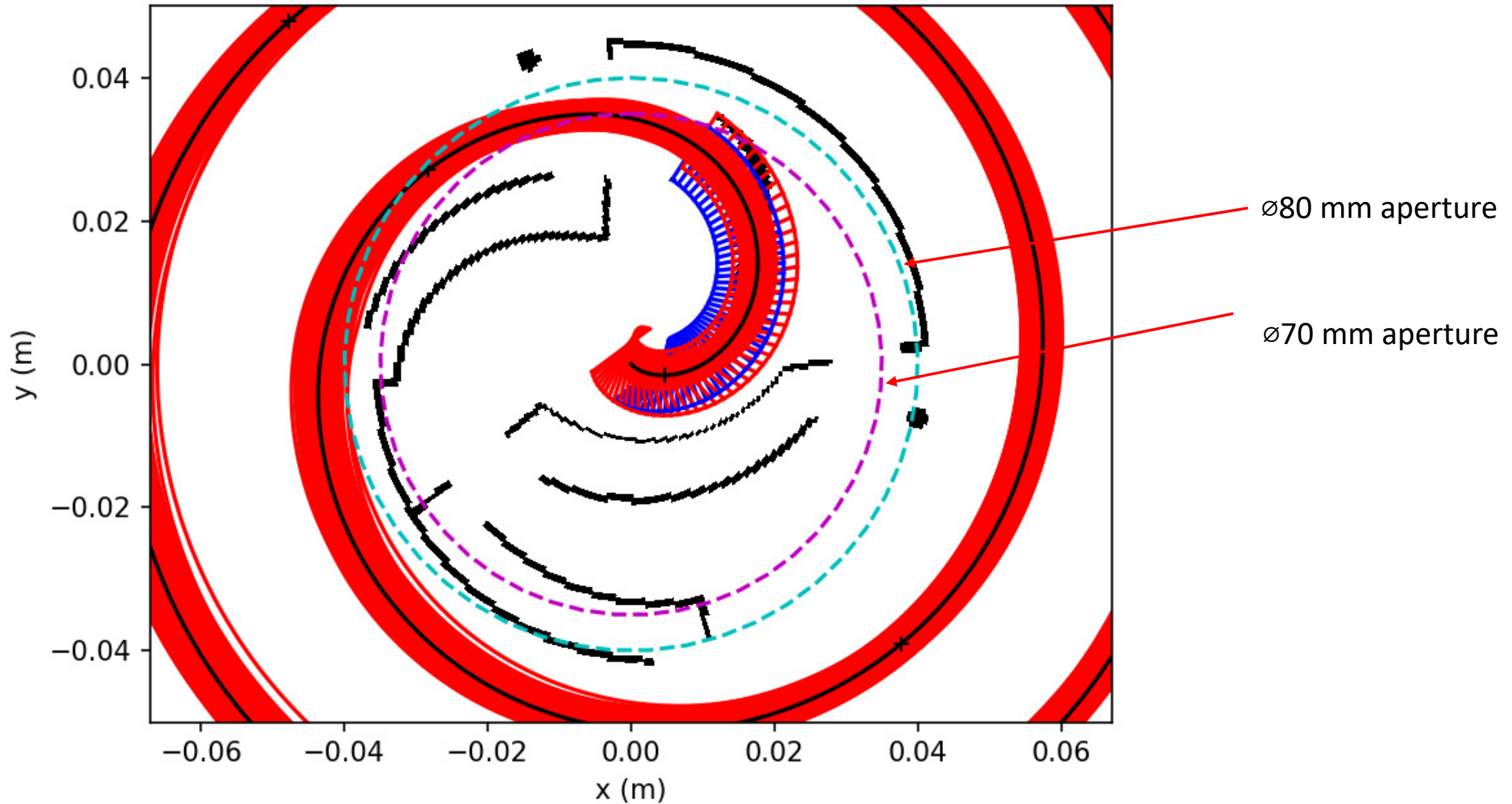
Collision positions (h=2)



Size limitations



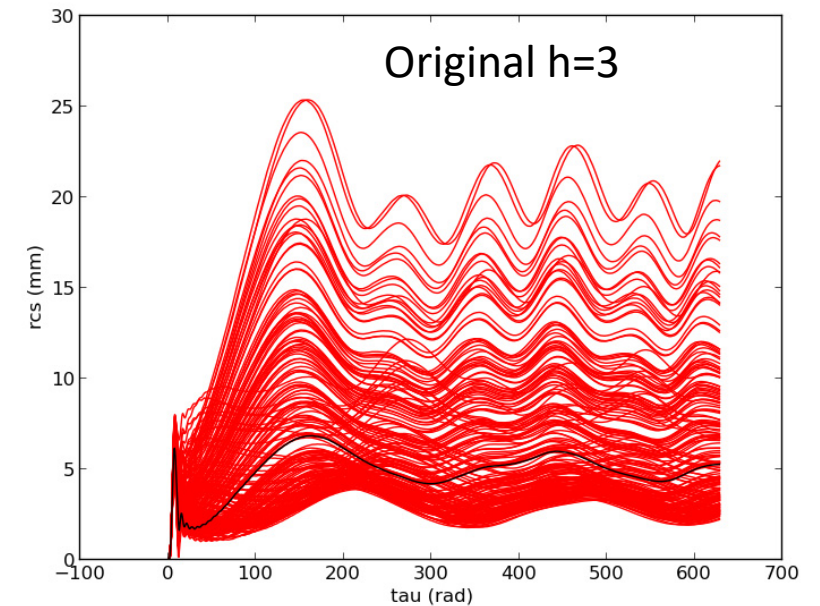
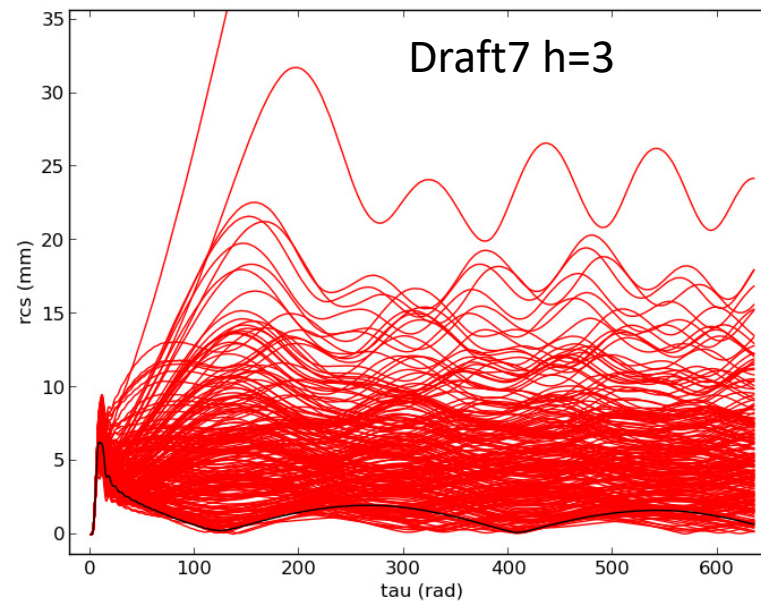
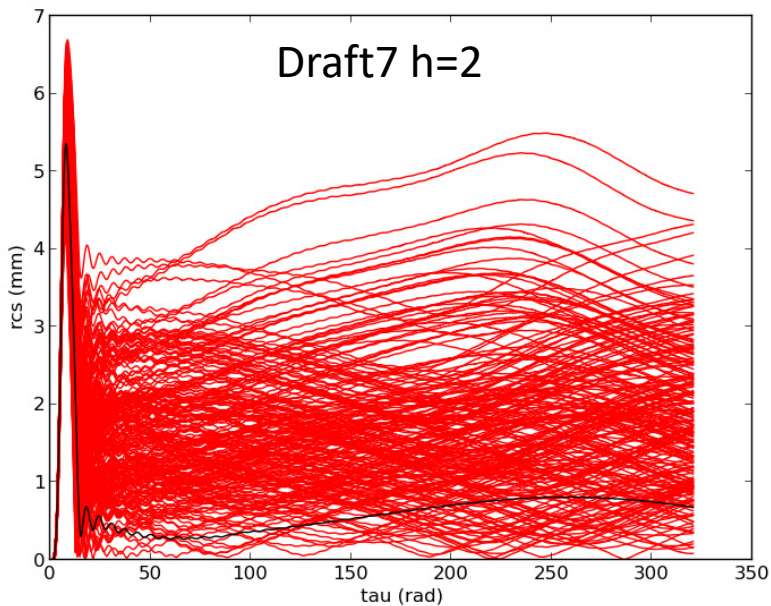
Size limitations, second harmonic larger than existing bore



Problem with harmonic 3

Centering problem with harmonic three

- Phase advance in dee $3 \times 78^\circ = 234^\circ > 180^\circ$
- Causes amplification of small centering errors
- Less than 60° dee angle would be optimal for $h=3$, but would decrease energy gain per turn for $h=1$, which is already the most critical of the three harmonics



Status now

- Physically realizable simulation models exist in CAD (no thanks to AutoCAD Inventor)
- Discussions with machine shop started (4-axis machining from outside)
- Renewed parts:
 - Inflectors
 - Central region case
 - Dee and dummy-dee tips
 - Top-side magnetic steel plug
- Next: engineering design and machining partners

