High Intensity Cyclotrons for Production of Medical Radioisotopes

05 dec 2022 –

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E. van der Kraaij (speaker)

MOBO01

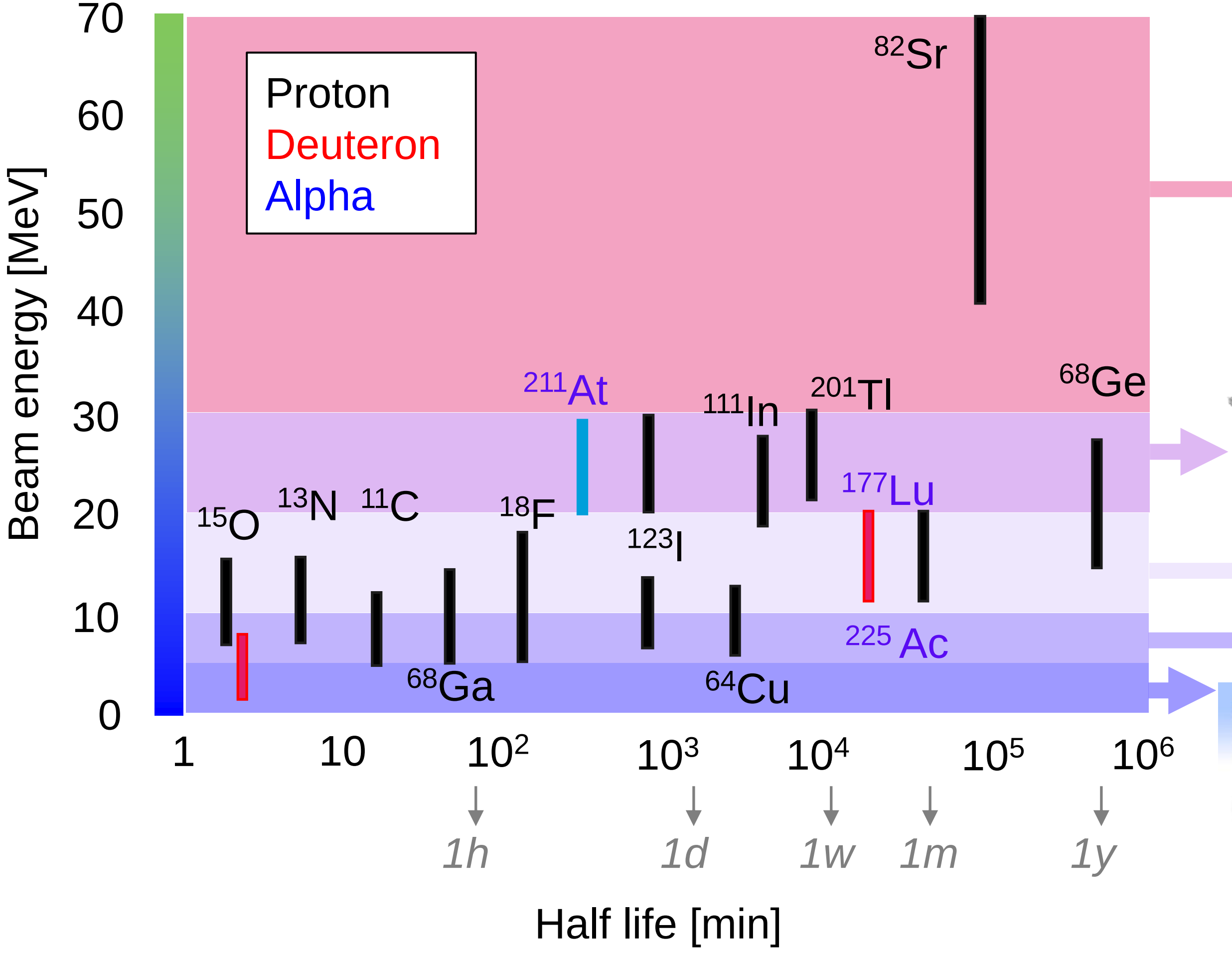
CYC2022
23rd International Conference on Cyclotrons and their Applications

Certified B Corporation

Life, Science.

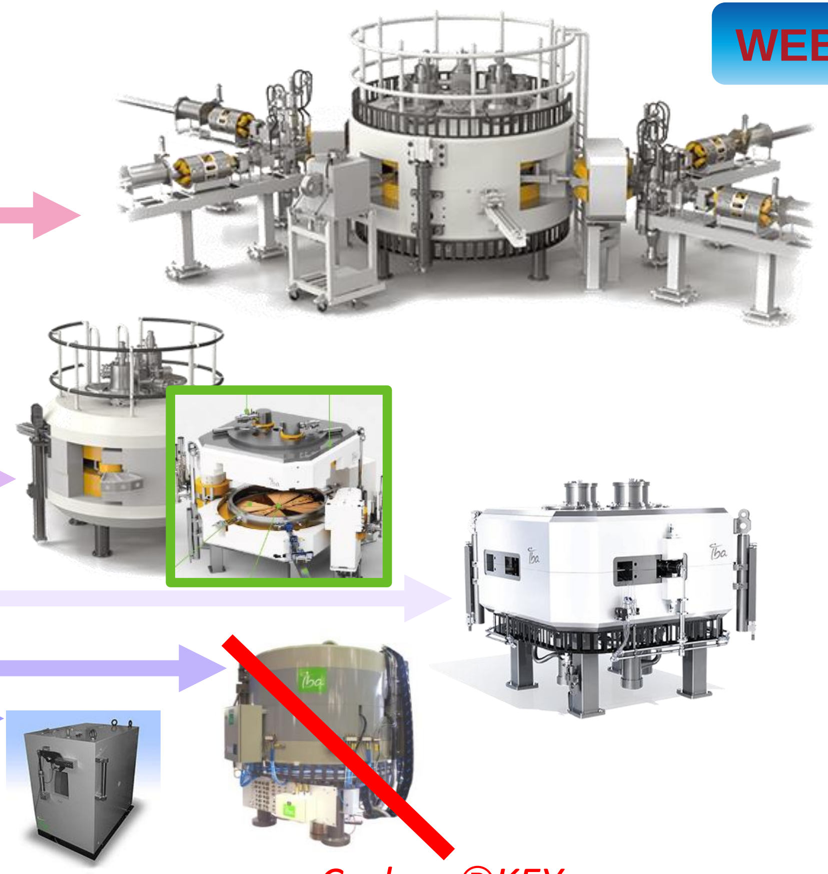
iba

Energy ranges & example of cyclotrons



See iThemba :

WEBI1



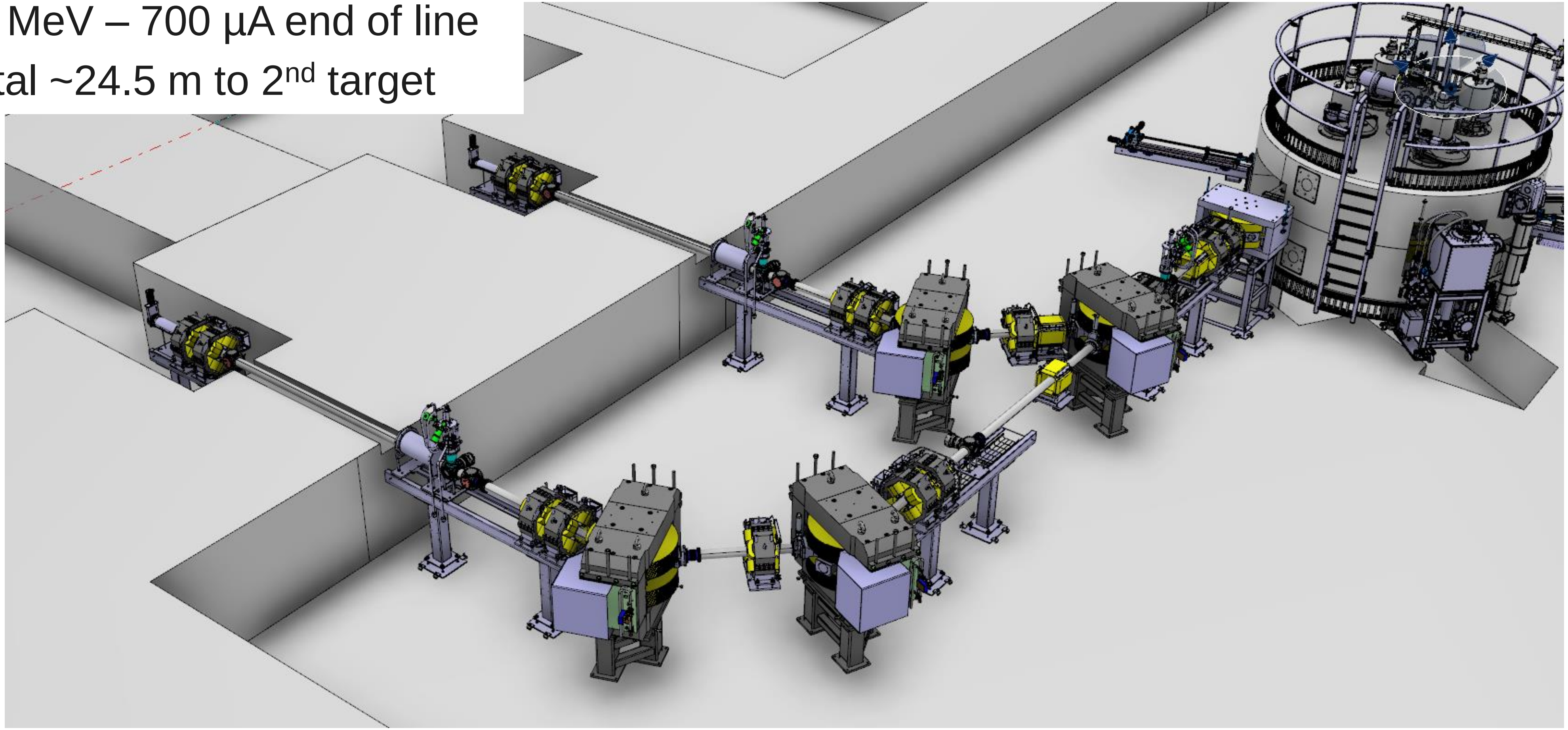
Cyclone®KEY :

WEAO3

Cyclone® 70P installed in IBS, Korea

Installed in existing bld complex:

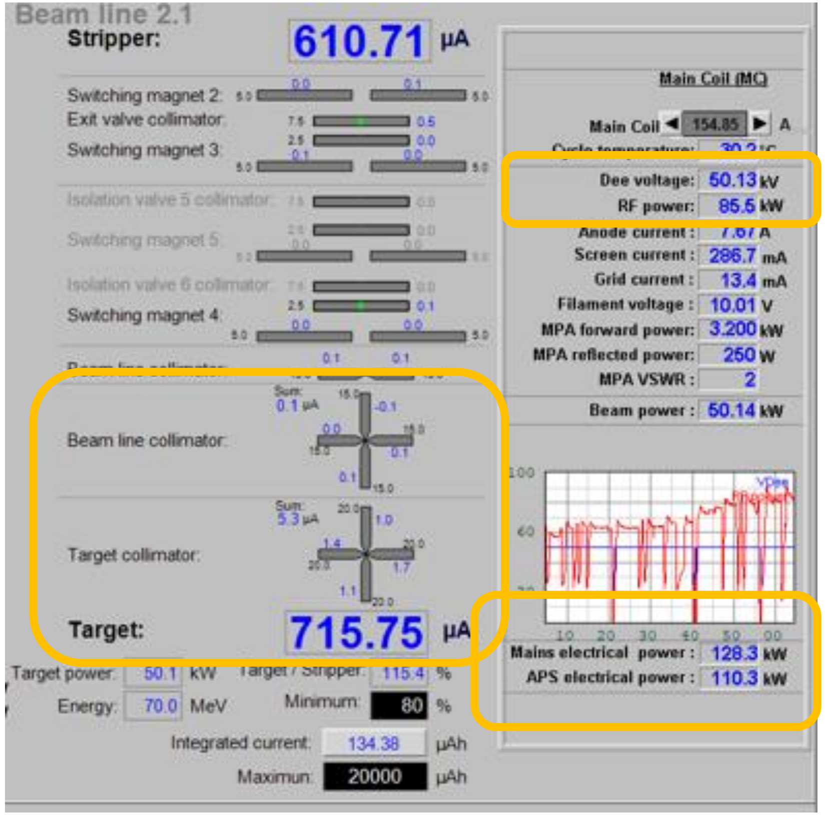
- 70 MeV – 700 µA end of line
- Total ~24.5 m to 2nd target



Nov 2022: effective completion

- 12 month after the rigging, the Cyclone 70 is now ready for operation.
- Beam power 50 kW,
  Elec load 238 kW

See IBS : **THBO5**



IBA in-house BPM ‘wire scan’

- Beam shapes measured using a film dosimeter and a wire scanner for beam profile monitoring, upstream of the beam dump.
- ISOL target will be placed at position of beam dump

➢ Possible beam tuning:
(customer needs ‘donut’-shape)

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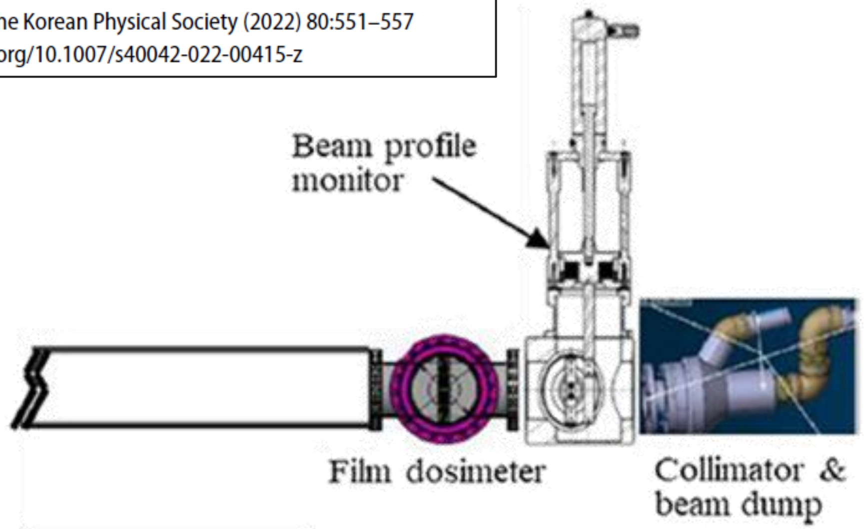
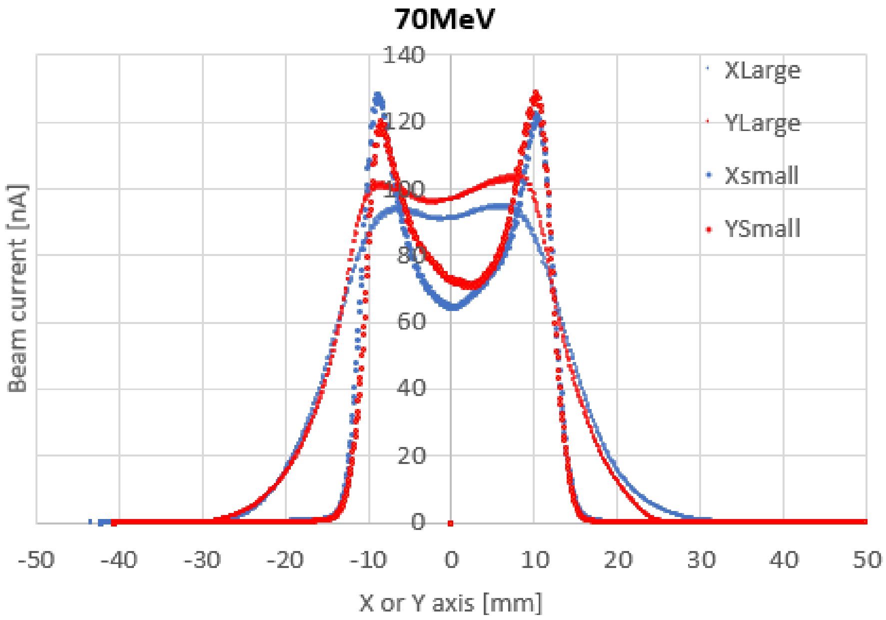
https://doi.org/10.1007/s40042-022-00415-z

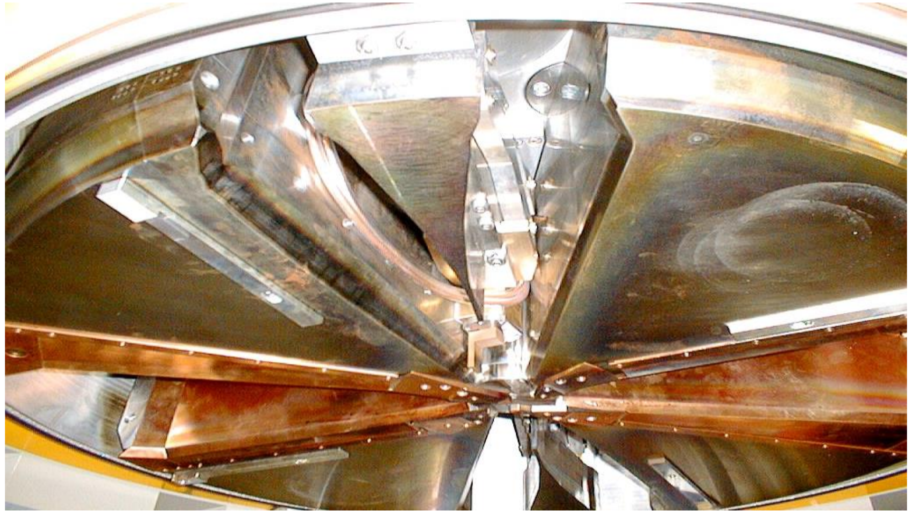




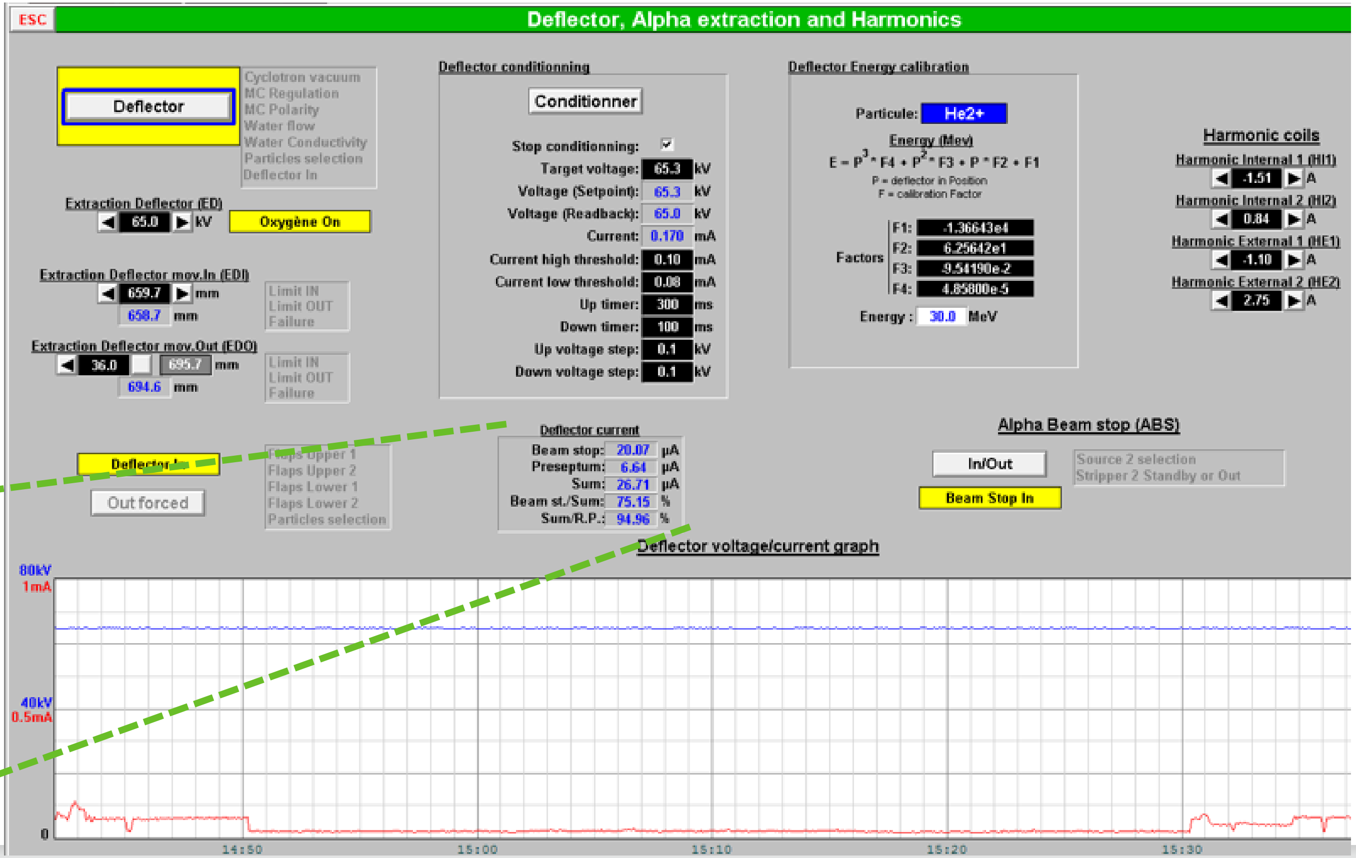
Multi particle cyclotron: Cyclone®30XP

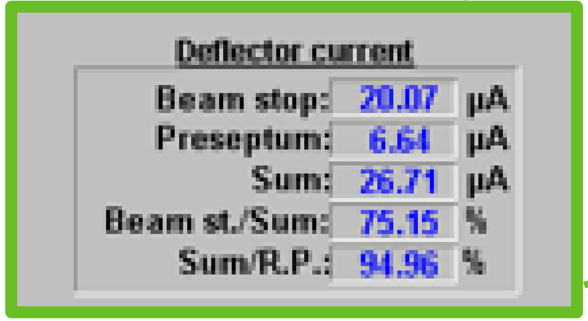
- “Flaps” to isochronize magnetic field

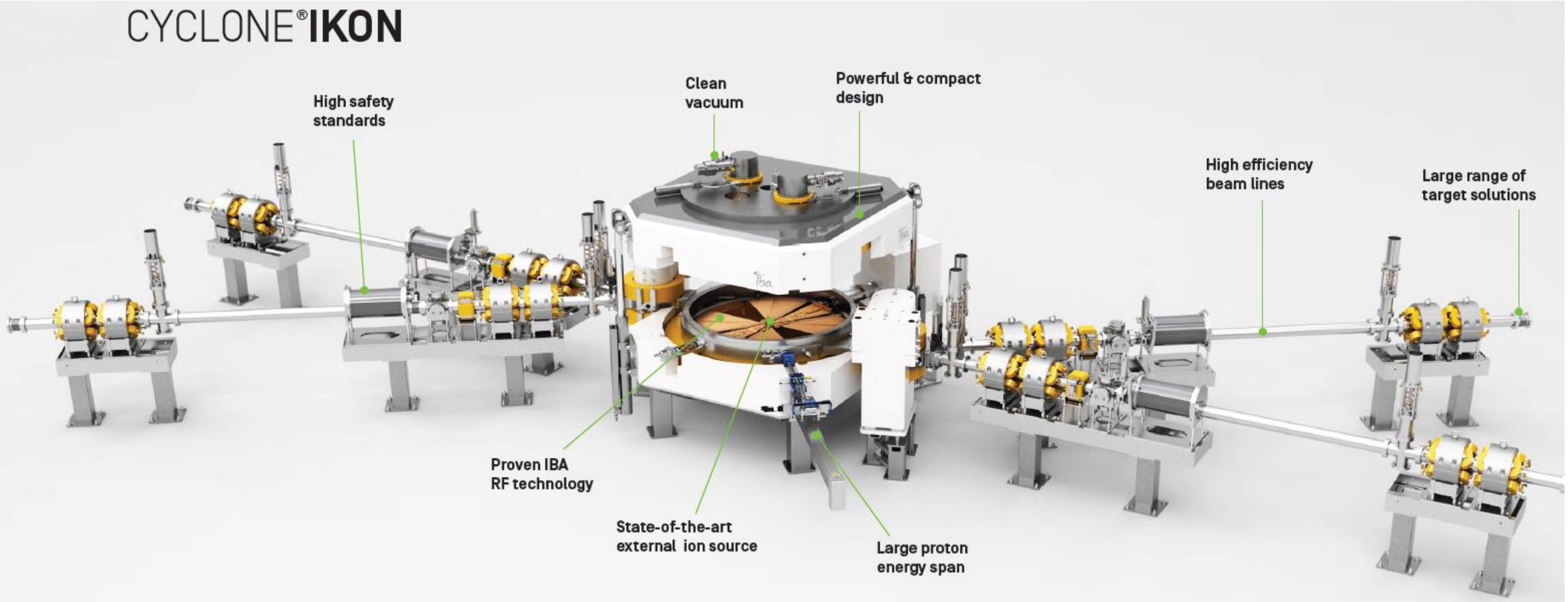
Particle	E [MeV]	Curr Spec [µAe]	Extraction
P	15-30	300	Stripping
D	8-15	50	Stripping
α	30	50	ESD



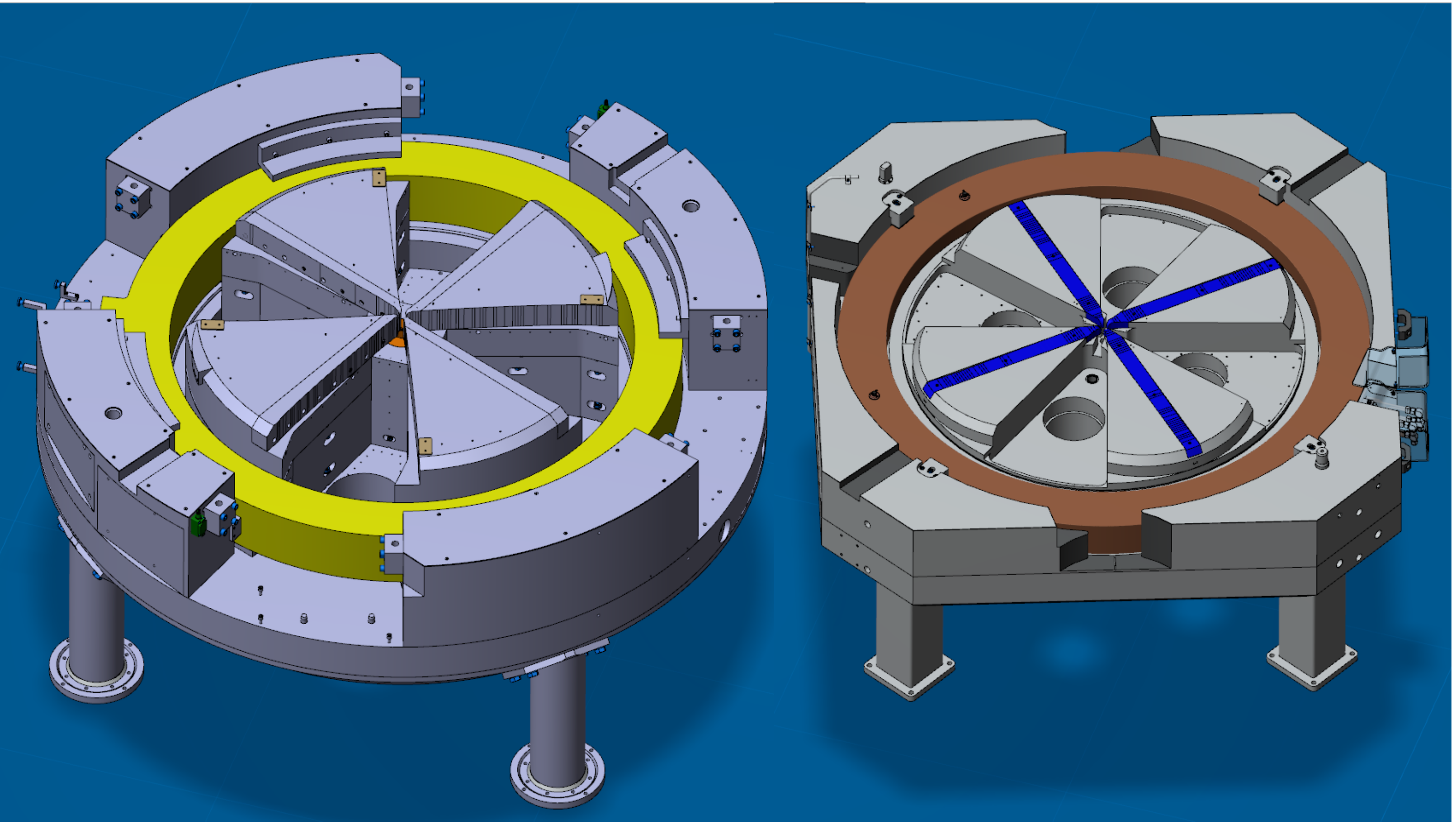
EANM 2010, # 7, session P14, Sunday Oct 10,





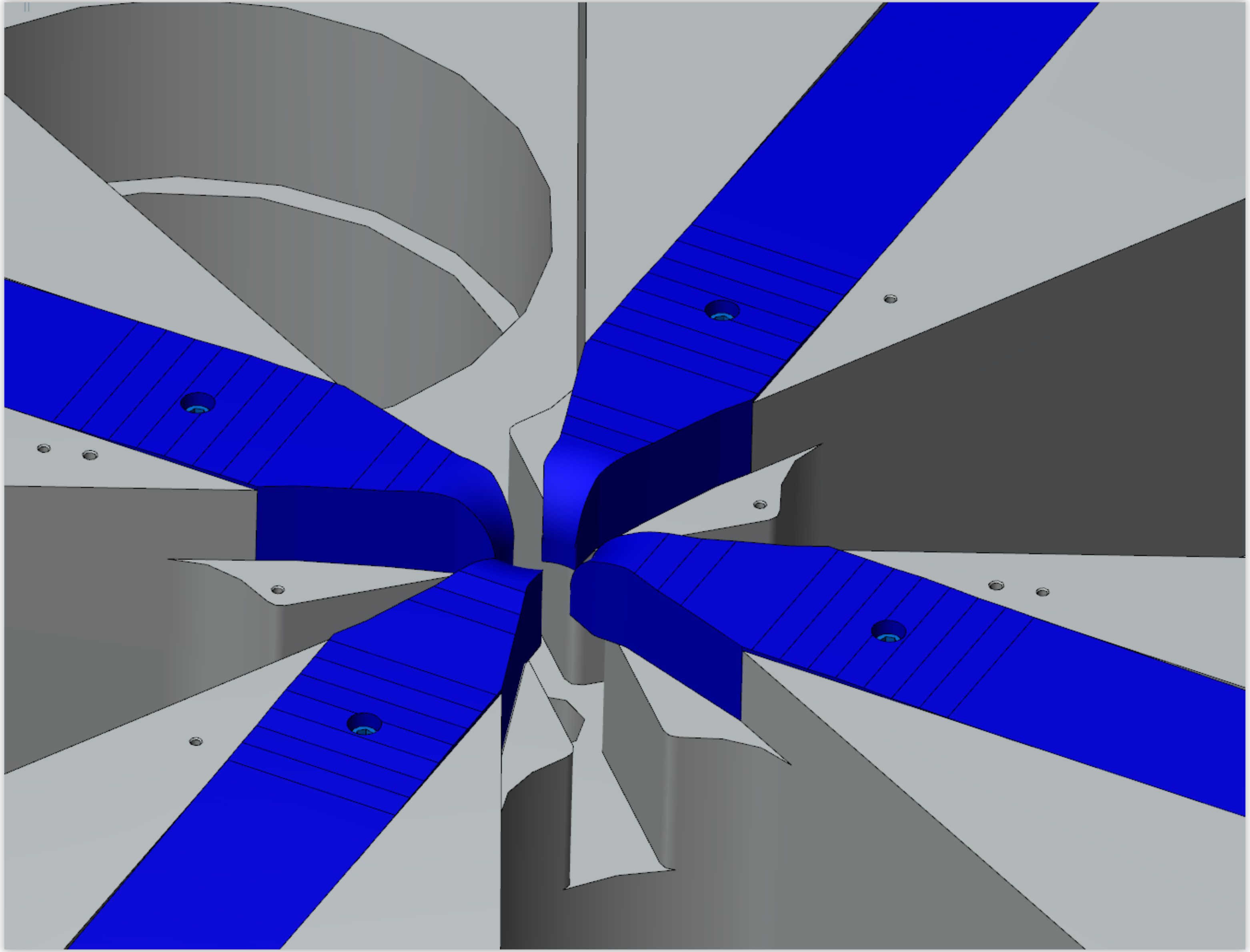

CYCLONE®IKON
High safety standards
Clean vacuum
Powerful & compact design
High efficiency beam lines
Large range of target solutions
Proven IBA RF technology
State-of-the-art external ion source
Large proton energy span

Cyclone® 30P vs IKON



		30p	IKON
Pole gap (total)	[mm]	30	30
Valley depth to MP	[mm]	550	159
Cyclo height	[mm]	1550	920
square size / diameter	[mm]	2700	2145
Amp-turns	[.10^3]	42.7	35.9
Iron Mass	[10^3 kg]	43	23
Copper mass	[kg]	1440 *2	1125 *2
RF freq	[MHz]	62	75
Harmonic mode	[-]	4	4
Beam E	[MeV]	15 – 30	13 – 30
Beam intensity	[mA]	0.5 – 1.2	0.8 – 1.2

CR



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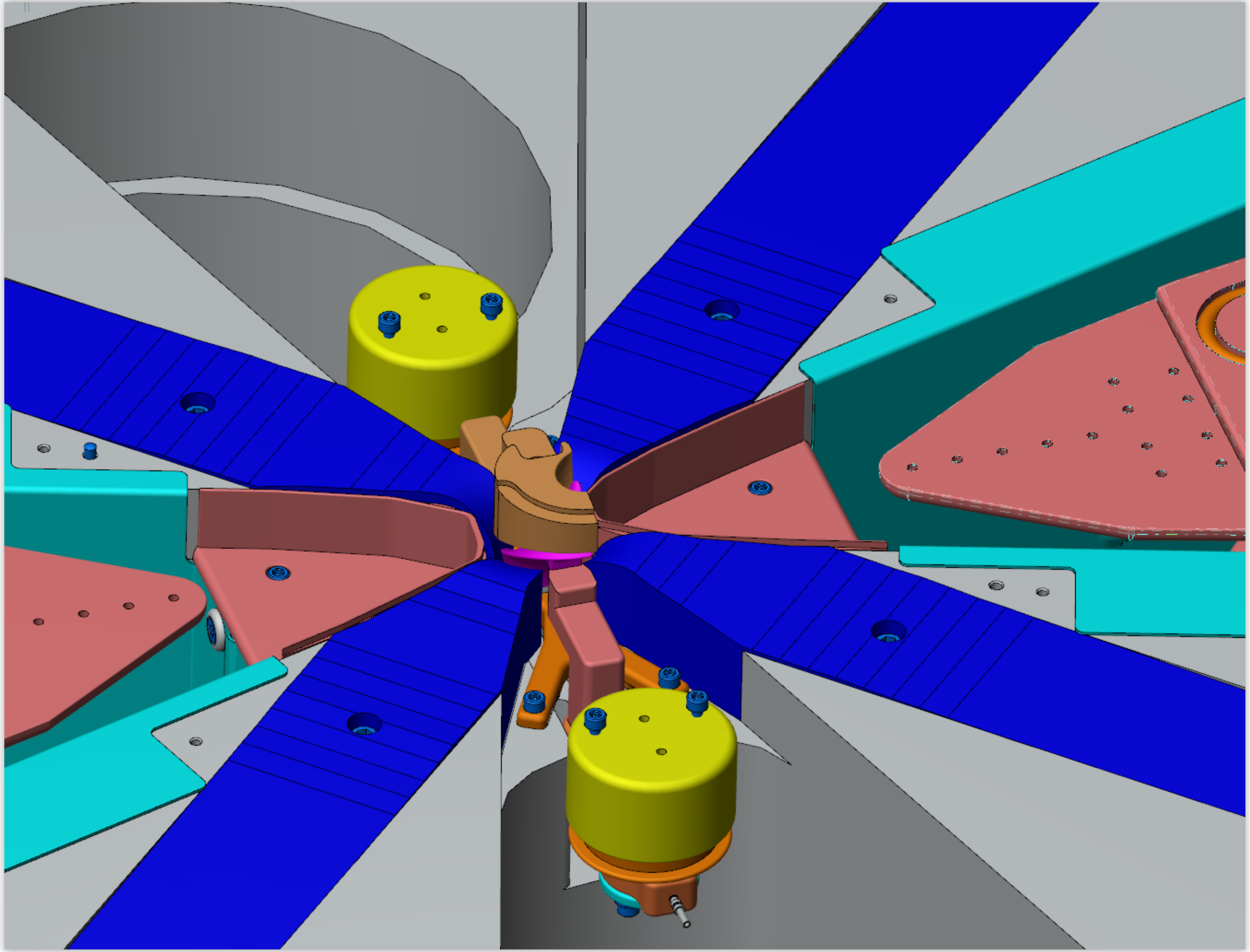

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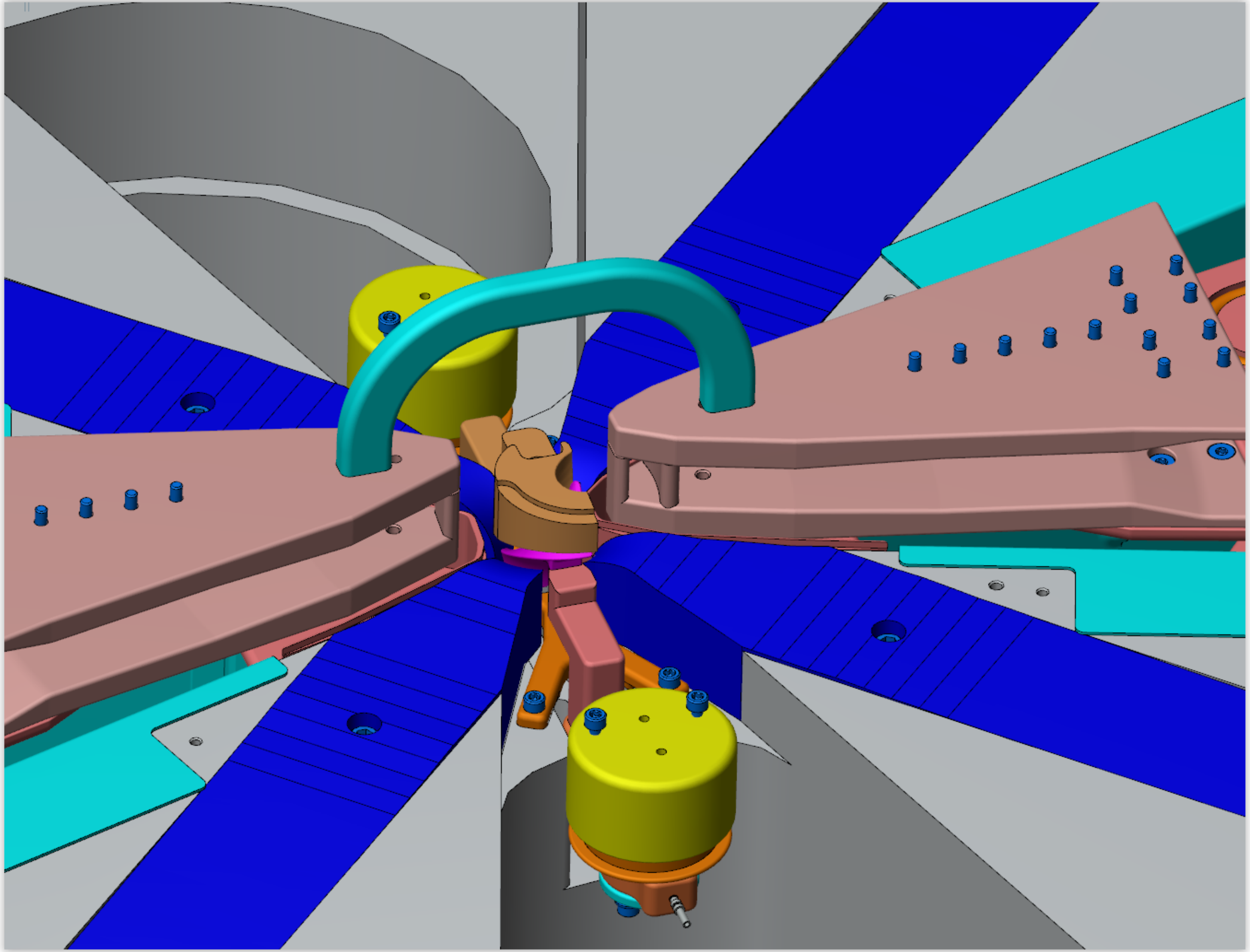

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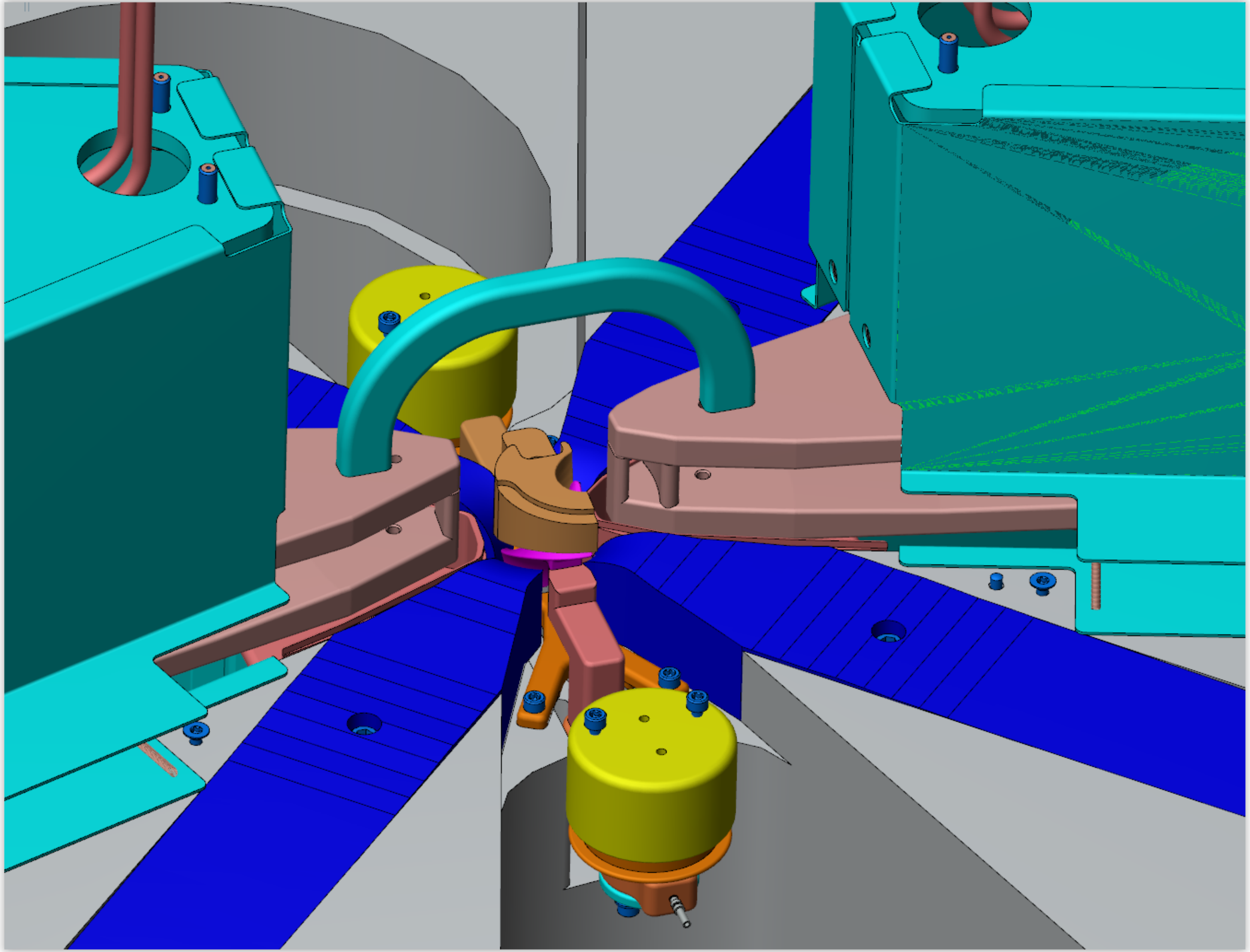

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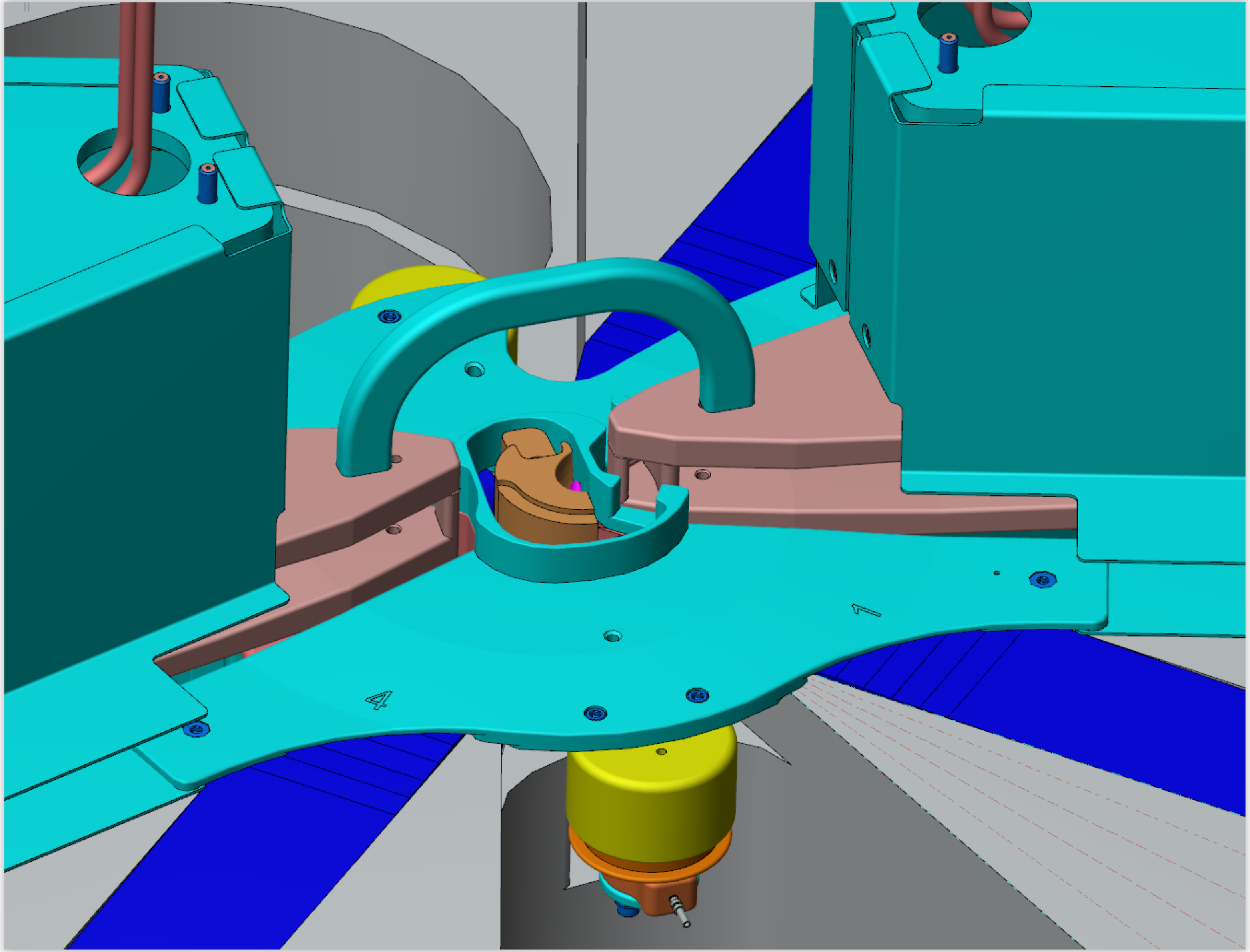

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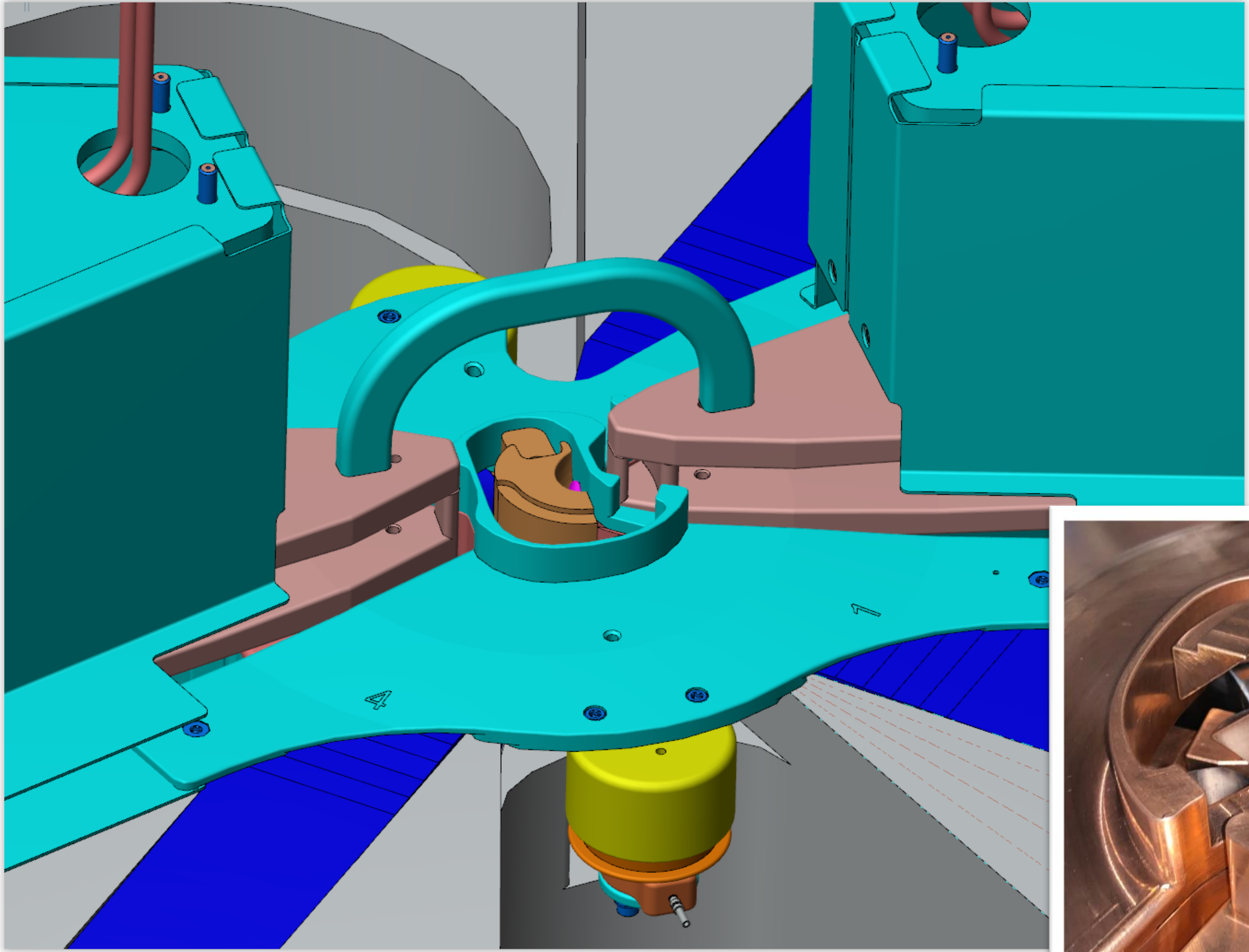
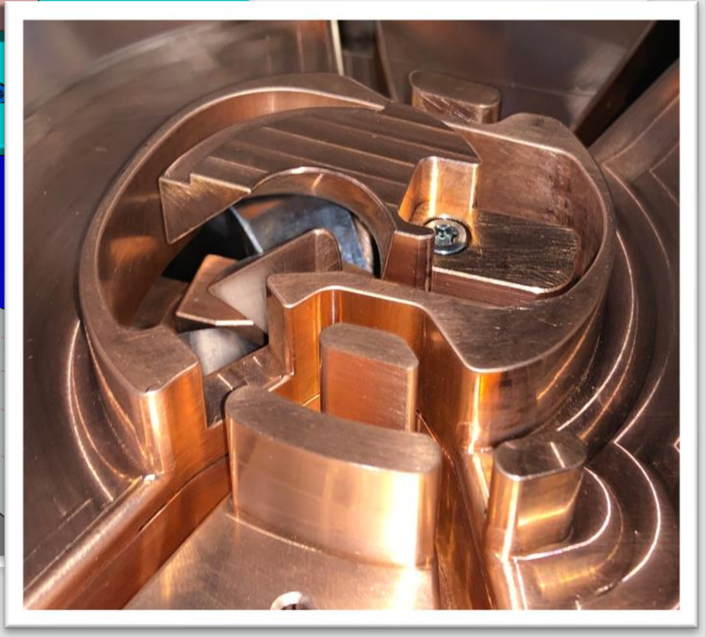
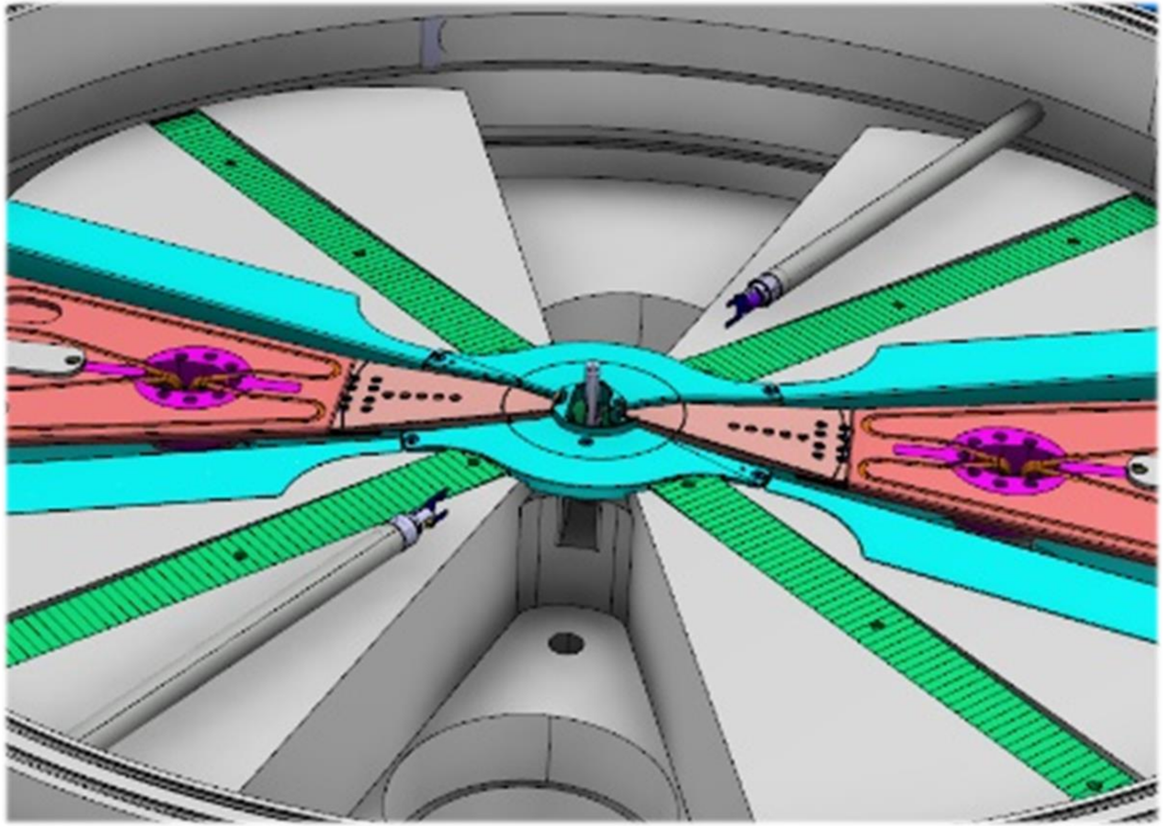
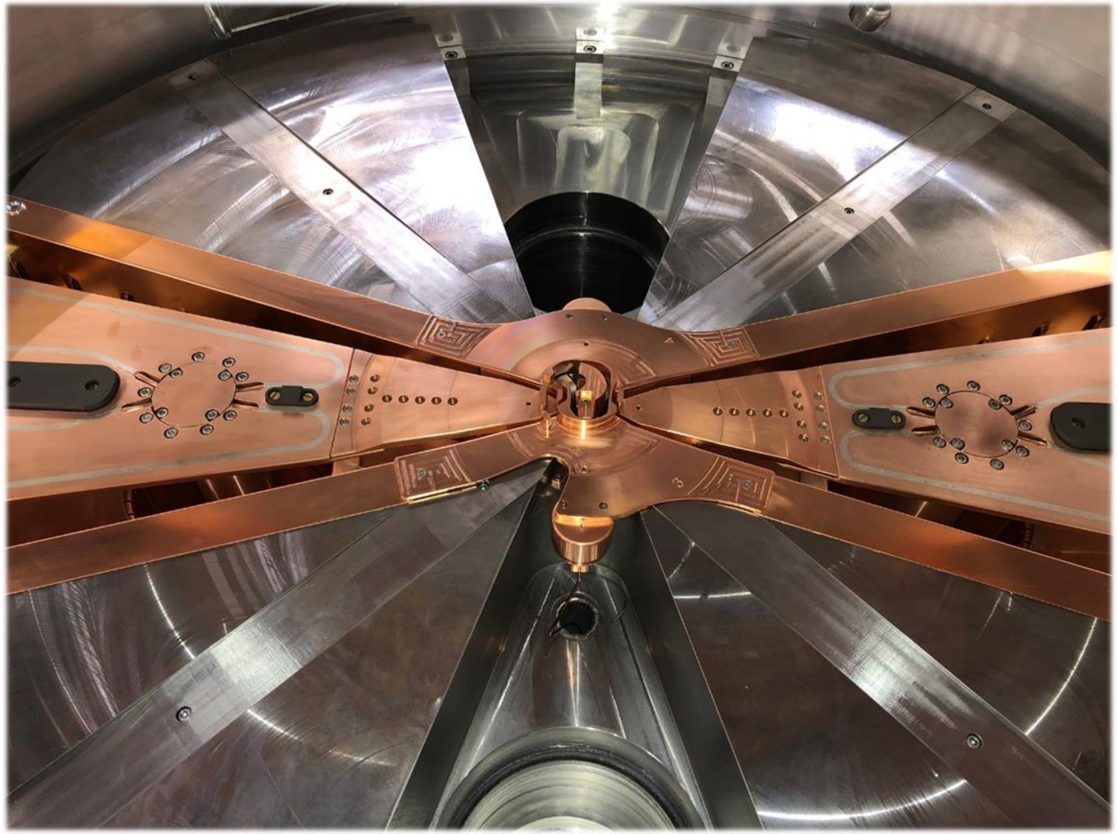




Construction and assembly has finished

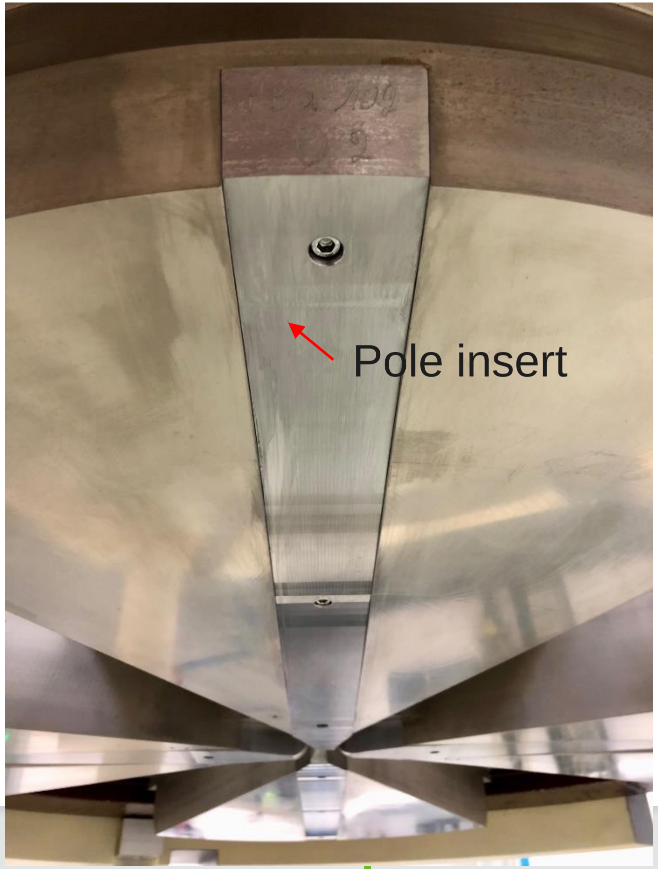
- 3D modelization versus reality…

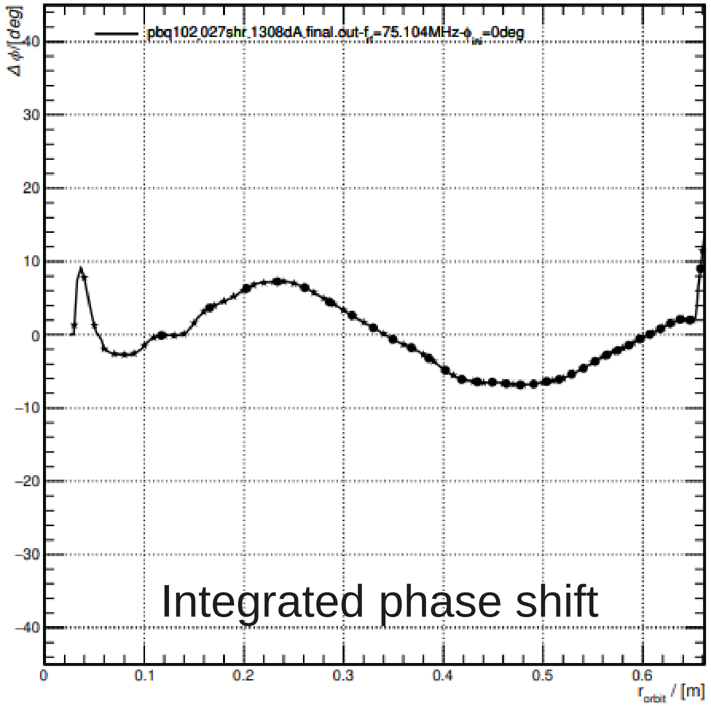


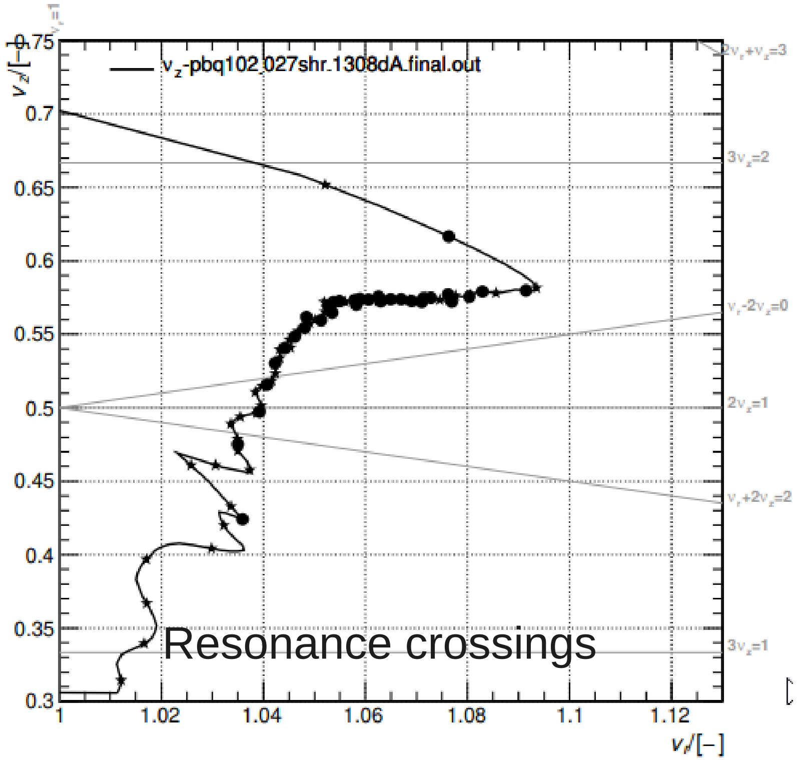


Cyclone® IKON – mapping and isochronisation

- Magnetic field shaped by machining patented pole inserts according to field map results:
  - External elements (hydraulic jacks, feet, switching magnets yoke)
  - Deformation of magnet yoke due to atmospheric pressure and magnetic force

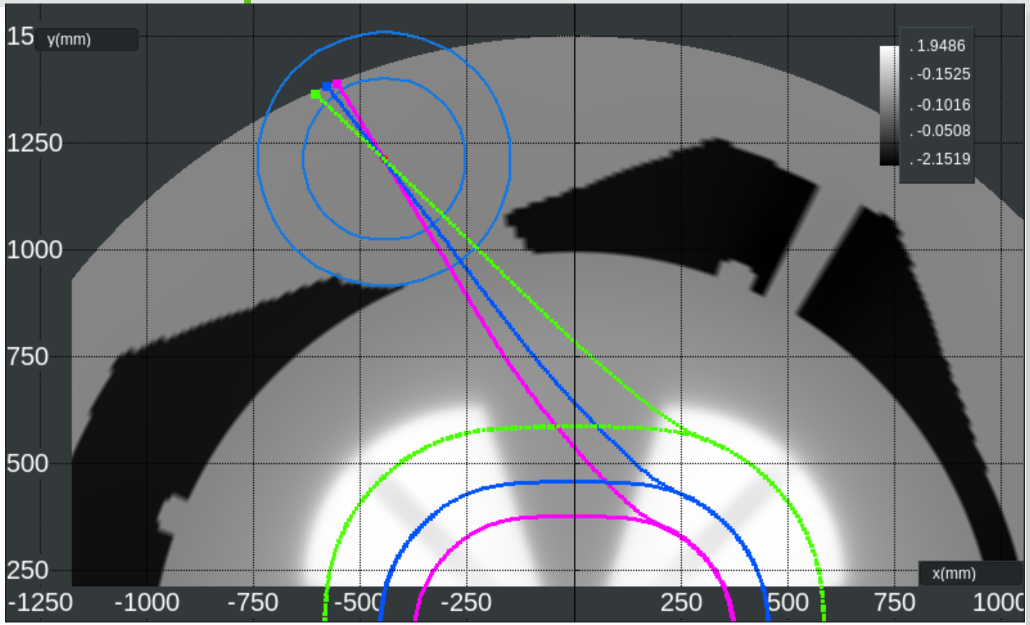


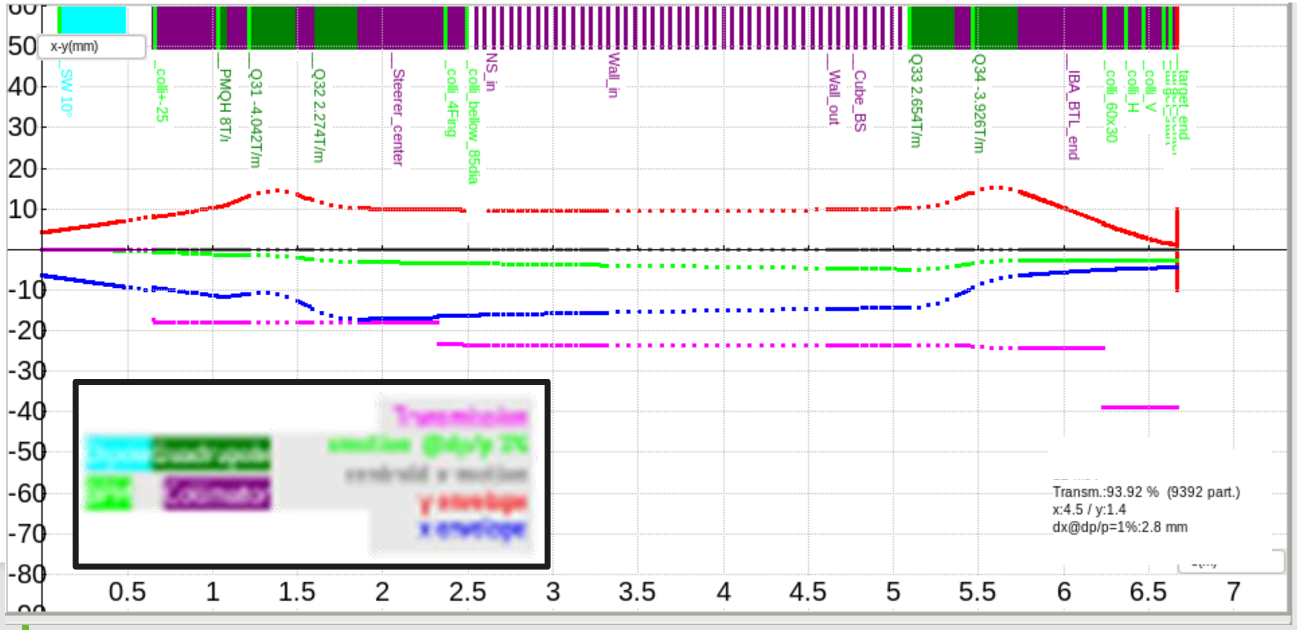


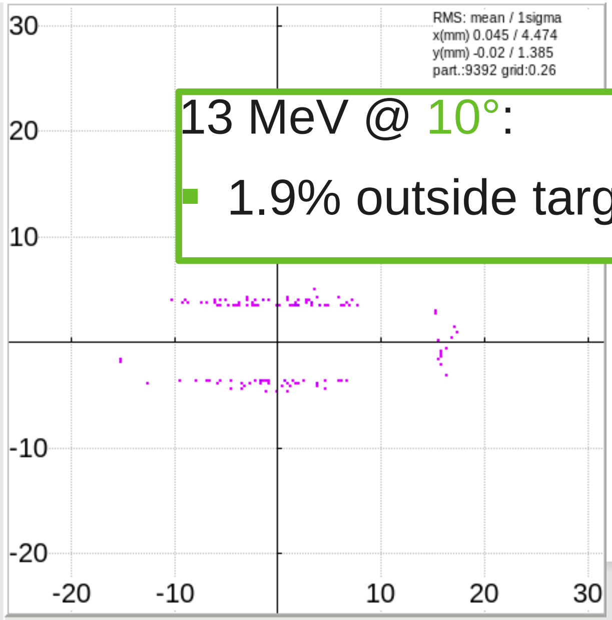


Extraction & BTLs

	vs BL1		vs BL2		vs BL3
	Orientation	Trans.	Orientation	Trans.	Orien.
13 MeV	25°	96%	-10°	94%	-35°
30 MeV	10°	99%	-25°	99%	N.A.





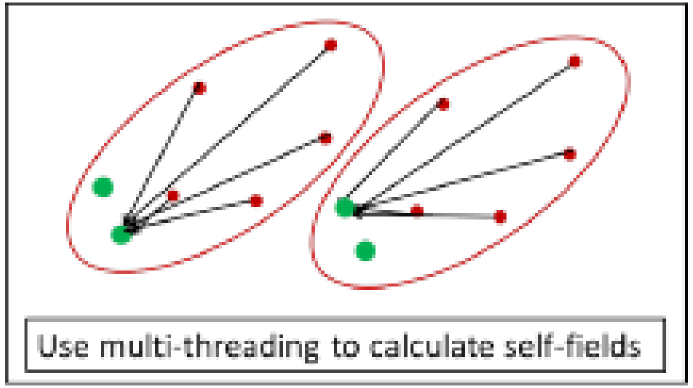


13 MeV @ 10°:

- 1.9% outside target

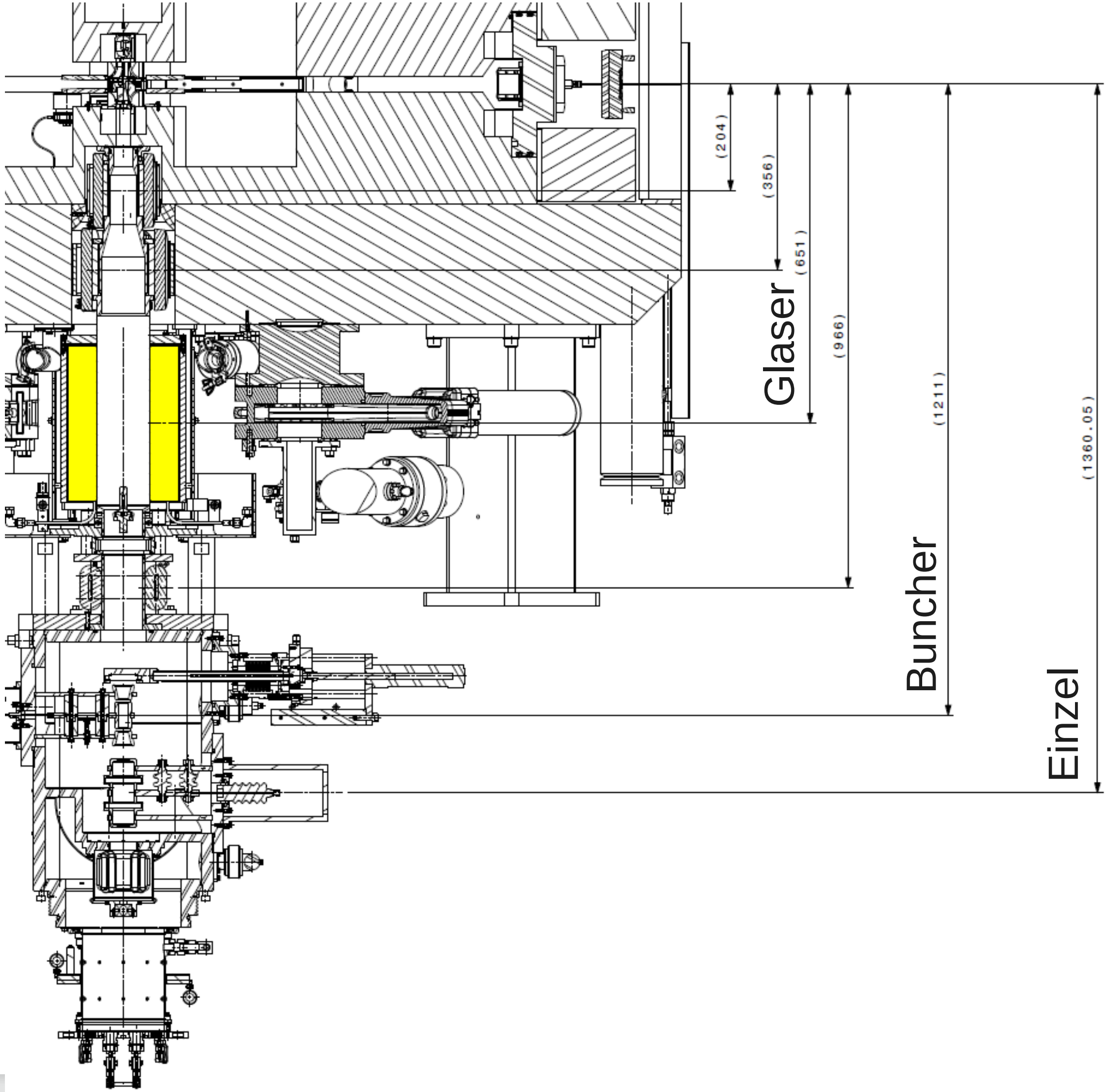
Space Charge effects in AOC

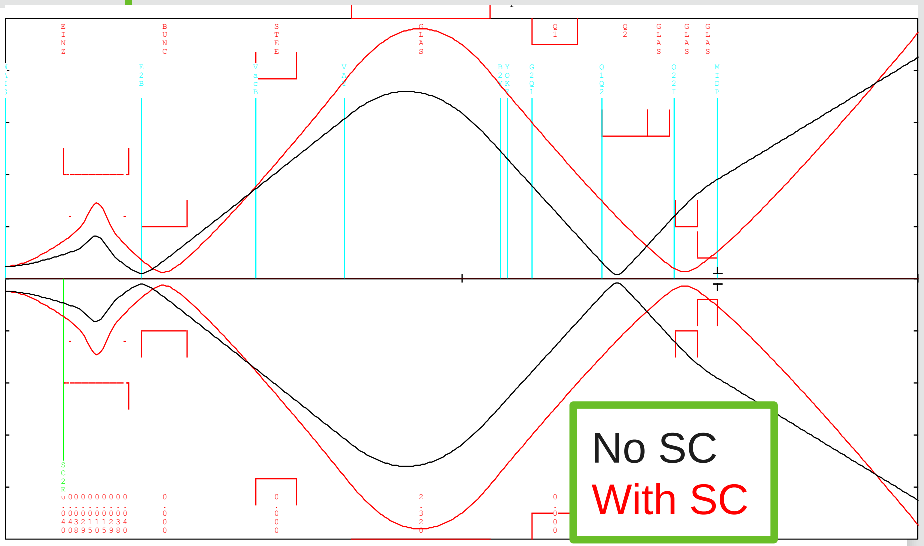
- Particle-to-particle method used for calculation of self-field of a bunch.
- Assume self-field acting on one particle is obtained as sum of contributions of all other particles in bunch.



- Advantage is that one can immediately include SC option together with existing 3D features of the E- and B-fields and with a complex 3D shape, such as for the spiral inflector.

Cyclone® IKON – Axial Injection





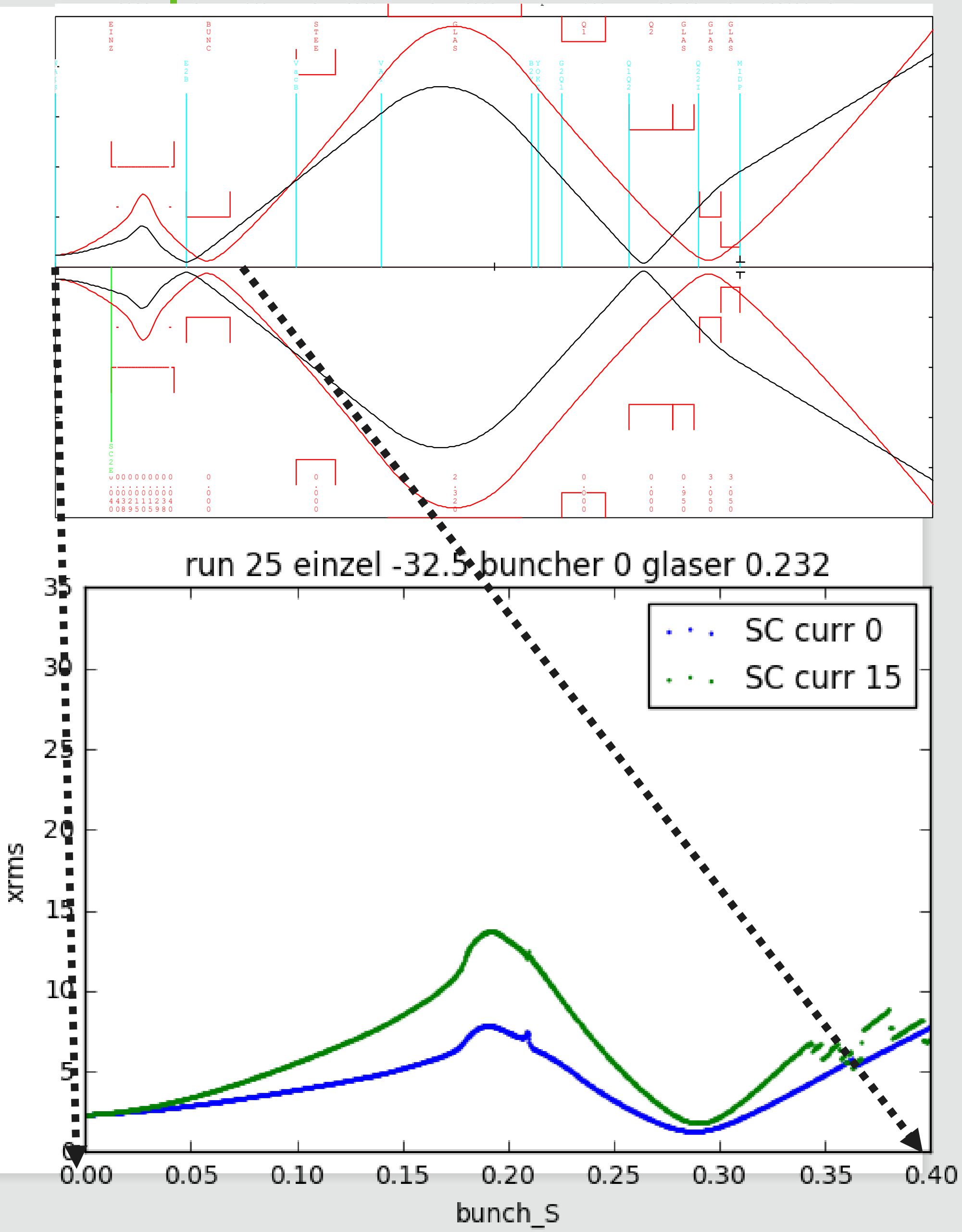
- Similar to injection line used in upgraded Cyclone® 30HC
- D-pace DC volume cusp source for 15 mA of H^- beam with 89 pi.mm.mrad at 30 keV for injection
- Machine tuned for 40 keV to reduce SC effects

Injection : AOC calculations VS transport

- Measured in mm from source, the focal point is at :

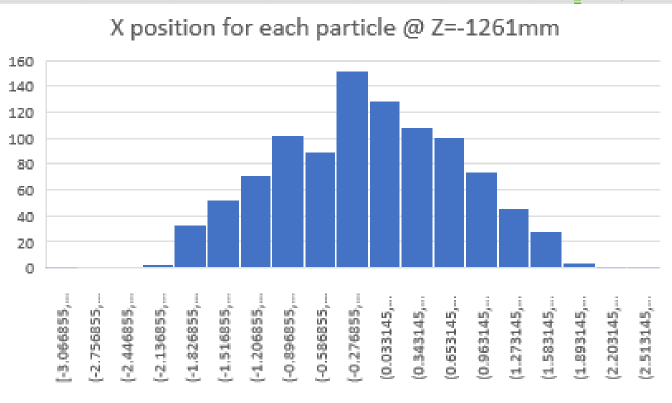
	SC 0 mA	SC 15 mA
Transport	300 mm	350 mm
AOC	285 mm	290 mm

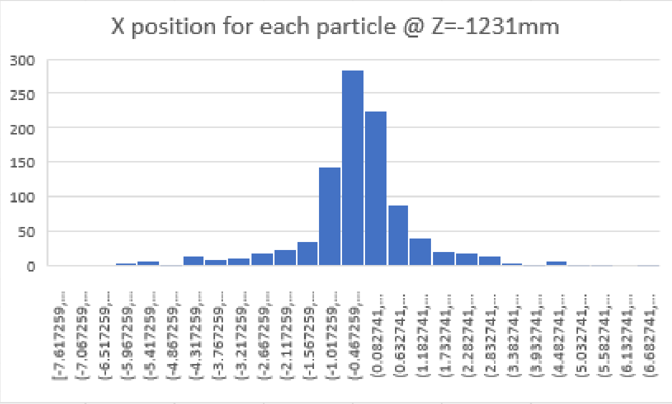
- No matter the distribution used in AOC, the position of the focal point hardly changes, and never gets near the 350 mm of Transport.

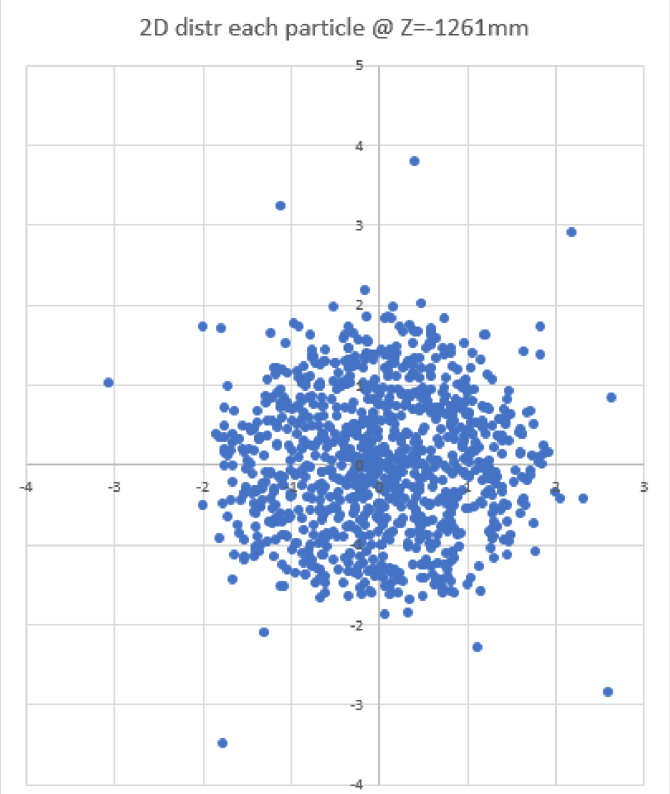


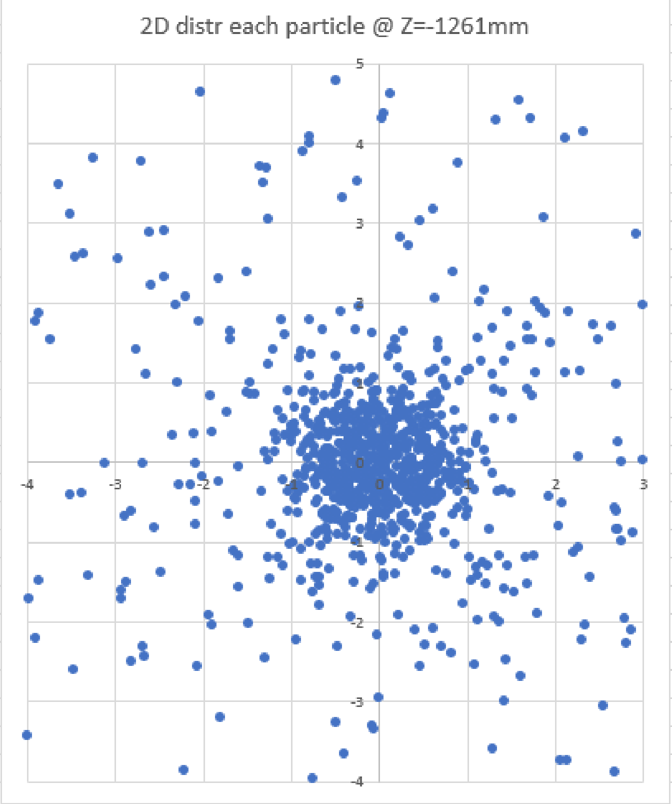
SC effect on trans. distr.

- Transport assumes a gaussian distribution everywhere. In AOC however, the distribution changes.
- In this example, beam starts out gaussian in 2D, and is still such just before the waist, see left distributions. Just after the waist, see right distributions, this has changed.
- Comparing the rms(X) values of transport with the rms of the patches in AOC is thus not equivalent.







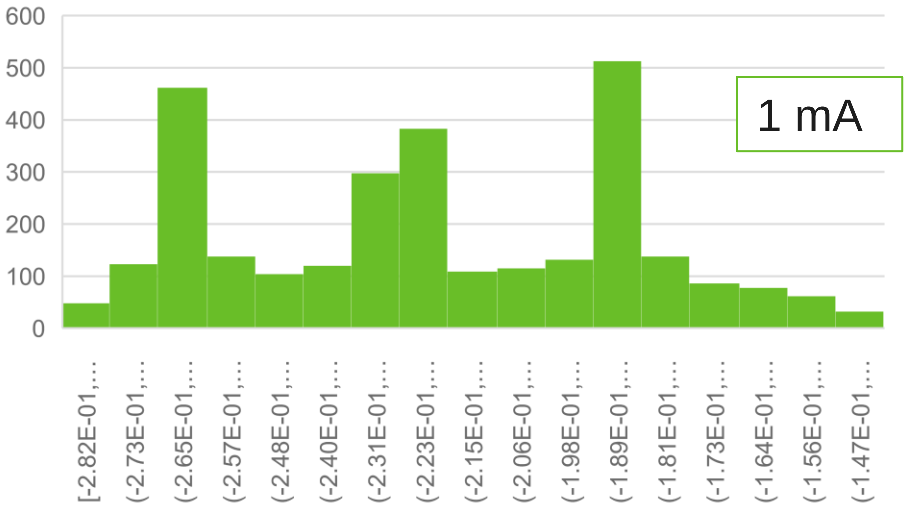


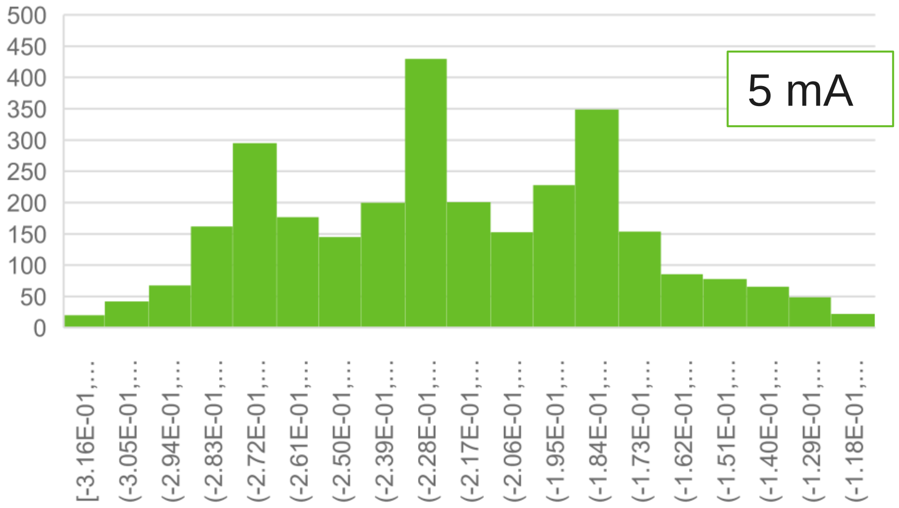
Approximate DC by 3 bunches

Starting longitudinally with flat uniform distribution, 3 RF periods long, with buncher at 563 V:

- with 1 mA, at inflector :
  - Three sub bunches visible.
  - Distance between the two is ~36 mm,
  - As expected from beta*lambda (=37mm)
- With 5 mA, at inflector:
  - Distance between the two bunches increase to 45 mm

➢ “injecting” 1-by-1 the particles in AOC creates an artificial longitudinal force, non-existent in real DC bunches





Summary

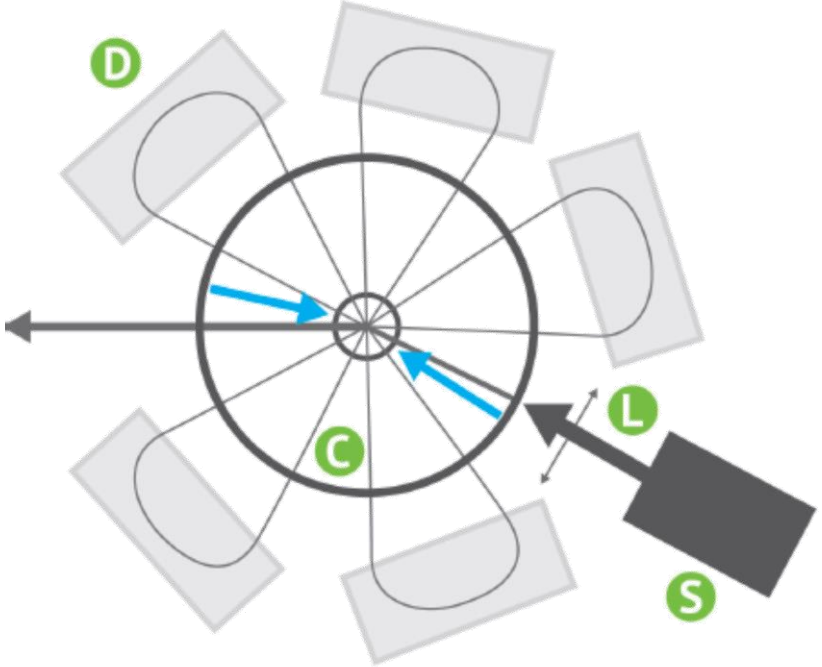
- High intensity cyclotrons for medical radioisotopes continue to develop
- At IBA, the new generation of cyclotrons, which started with the 18 MeV Cyclone® KIUBE, has expanded with the 30 MeV Cyclone® IKON and 9 MeV Key
- For the IKON, the construction phase has finished, and it is currently being installed
- Started study on the Space Charge effects in the high intensity beam along the injection line

40 MeV Rhodotron

Electron accelerator

This is not a cyclotron

Rhodotron® TT300-HE
High Energy Electron Generator



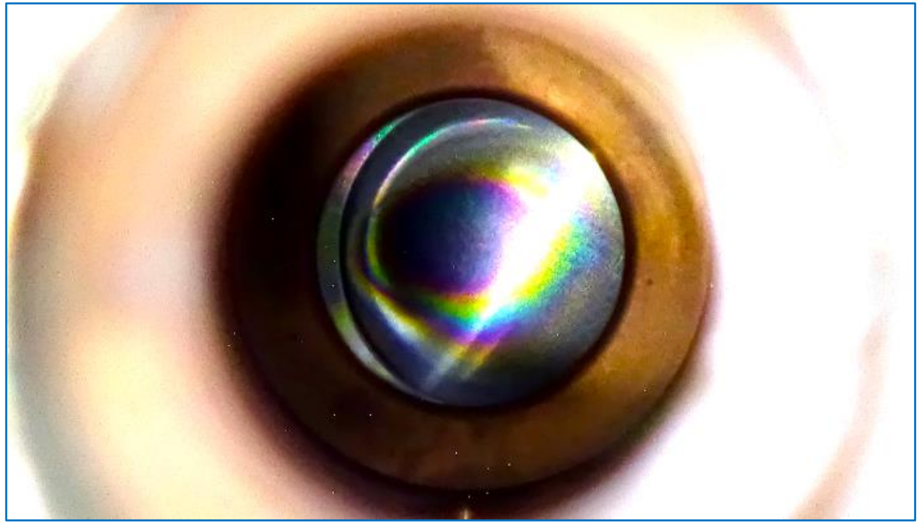
New development RadioPharma – IBA Industrial (electrons)

Rhodotron® TT300-HE
High Energy Electron Generator

- Photo nuclear reaction with 40 MeV electrons
- (with Northstar, USA) - 125 kW beam
- **^{99m}Tc**: ^{100}Mo (γ,n) ^{99}Mo -> ^{99m}Tc

Rhodotron - TT300HE – Commissioning first units

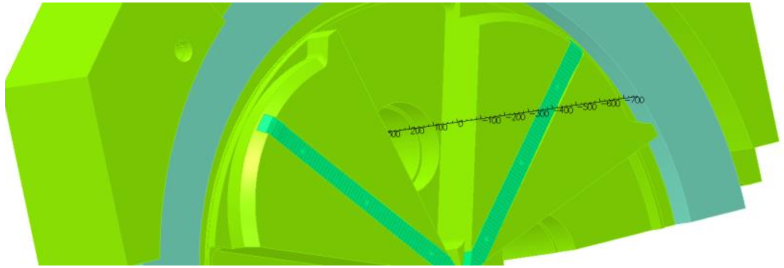
- Currently shooting on beam stop at the end of the beam line, after a 270° magnet
- Spot diameter of about 25-30mm
- 40 MeV at 3.125 mA (average of a 25 mA pulsed beam) ➔ 125 kW achieved



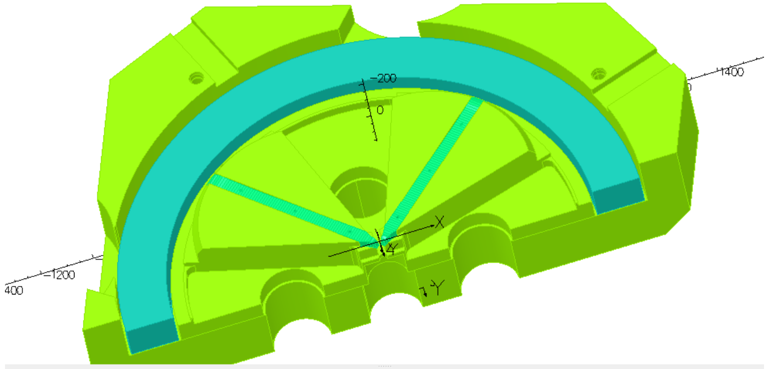
BACKUP

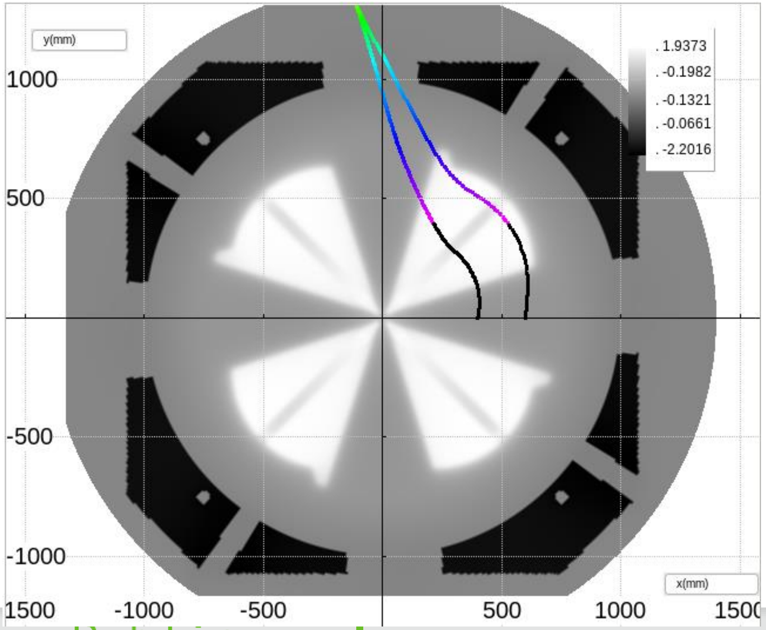
Exit port and Switch positions

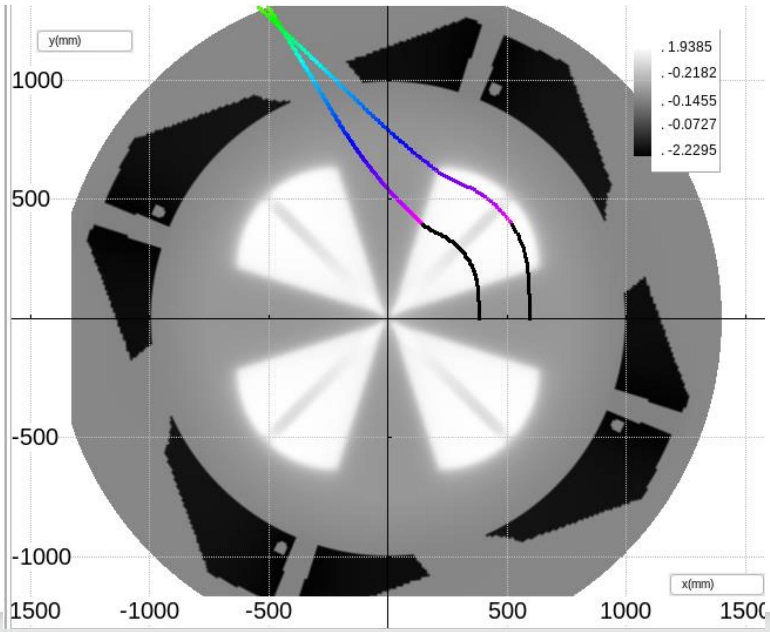
Long Pole edge

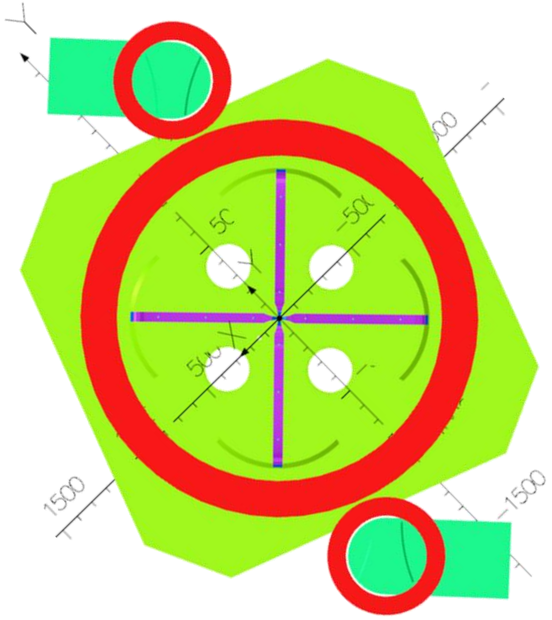


20° tilt w/o spiaral





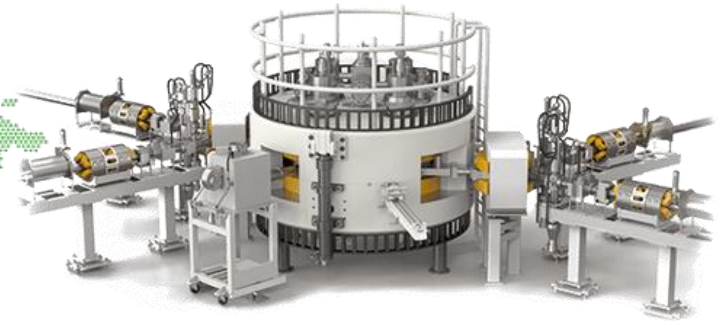




Switch rotated away from cyclotron:

- Remaining dB is ~0.1 G ➔ Integrated phase slip ~1°
- H1 ~ .4 G ➔ Orbit decentering about ~0.3 mm.

Cyclotron High Energy segment 70 MeV



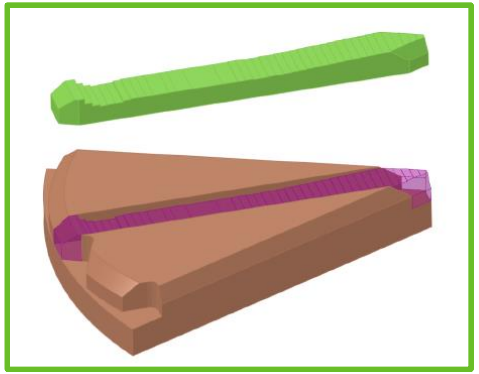
^{68}Ge **^{82}Sr**

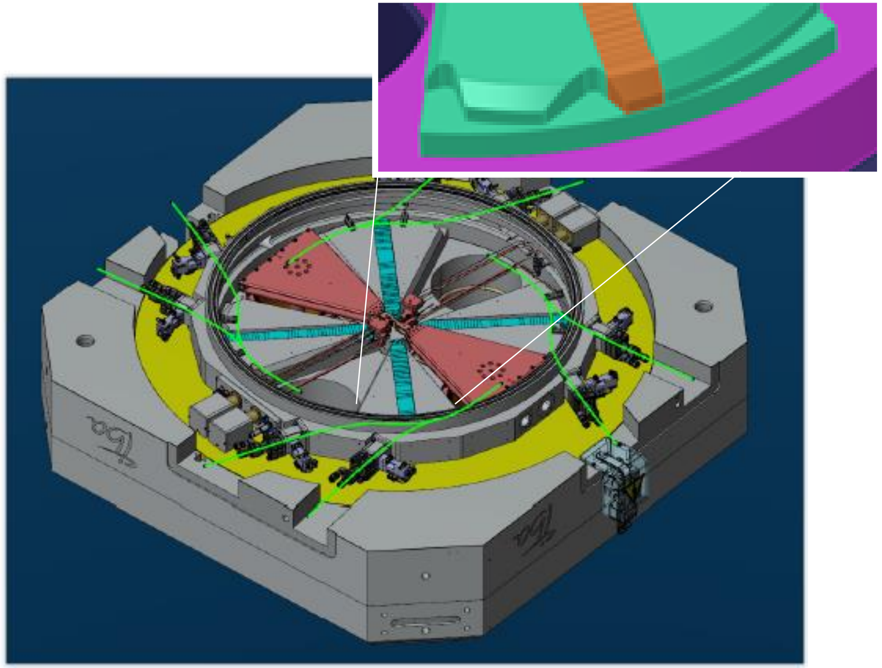
High intensity 30 MeV cyclotrons

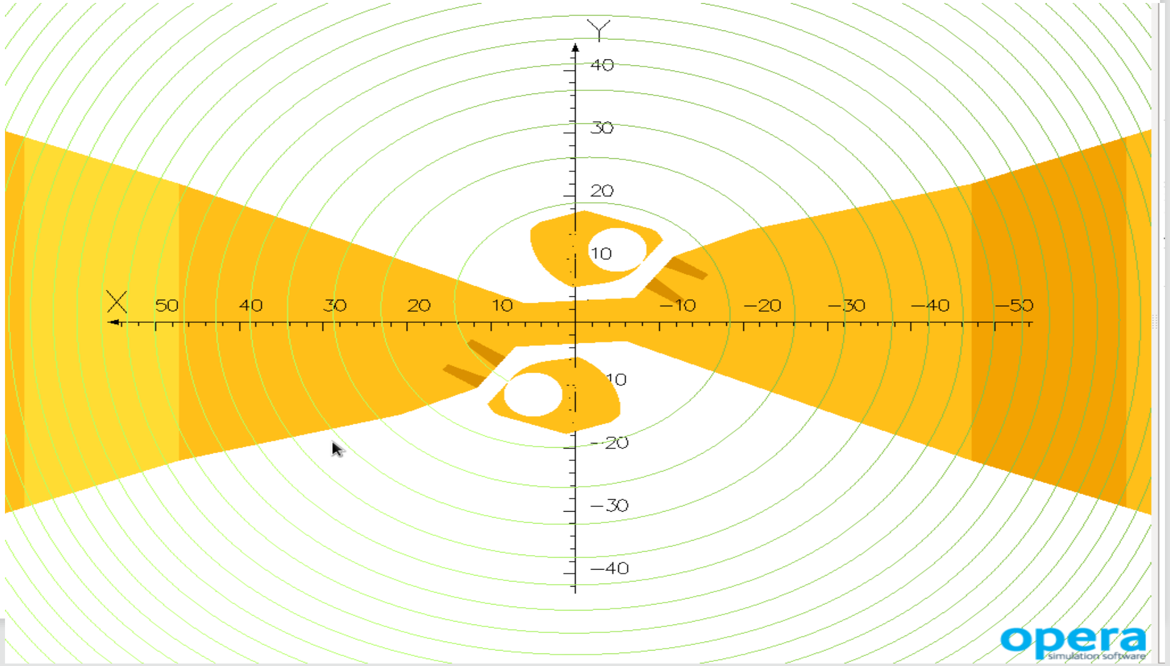
Name	country	30 MeV beam	Year of Op.
IBA Cyclone® 30	Belgium	400 - 800 - 1200 µA	1986 / 2010
ACS TR-30	Canada (Triumf lab)	500 – 1200 µA	1990 / 2000
SHI HM-30	Japan	1 mA (BNCT)	2009

Cyclone® KIUBE

- 90’s → 21st century tools
- Improved magnet design (OPERA3D)
- Improved vacuum design (Comsol) : **H-** (transmission 55% -> 80%)
- Optimized central region
- Optimized extraction optics







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Rhodotron® TT300-HE
High Energy Electron Generator

Photo nuclear reaction with 40 MeV electrons
(with Northstar, USA)

^{99m}Tc: ^{100}Mo (γ,n) ^{99}Mo -> ^{99m}Tc

Future development in Nuc Med Therapy :

^{225}Ac: ^{226}Ra (γ,n) ^{225}Ra → ^{225}Ac

^{67}Cu: ^{68}Zn (γ, p) ^{67}Cu

Ayzatskiy *et al.*, Cyclotrons conference 2007

Particle	Reaction	Cross-section σ,mb
p	^{68}Zn(p,2p)^{67}Cu	**6** (E_p=30…85,MeV) **24.8** (E_p=130…425,MeV)
	^{70}Zn(p,α)^{67}Cu	**15** (E_p=16MeV)
α	^{64}Ni(α,p)^{67}Cu	**34** (E_α=22MeV)
n	^{67}Zn(n,p)^{67}Cu	**1.07**
e→γ	^{68}Zn(γ,p)^{67}Cu	**11** (E_γ=22MeV)

ACSI TR24

System Specifications – TR24 Cyclotron

TECHNICAL SPECIFICATIONS SY

Type		
Type of cyclotron	negative ion	Fl
Ion Source	external	Ir
Type of magnet	four sector, strong focus	Er
Energy	24 MeV	Er
Beam Current	300 microamps	
		Io
Size		Yi
Size of Cyclotron	1.7 m x 1.7 m x 1.0 m	
Size of Frame	1.7 m x 4.1 m	
Shielding		Ta
Type	bunker & partial	Nu
Weight of cyclotron	22,000 kg	Ty
Weight of partial shield	2000 kg each	
		Ex

ACSI TR-FLEX

TR-FLEX at a glance

Accelerated Ions	H^-
Extracted Ions	H^+
Extraction Method	Carbon foils
Max Extracted Energy	24 MeV to 30 MeV, depending on configuration
Max Extracted Beam Current	750 μA
Acceleration Plane	Horizontal
Operating Vacuum	~ 5×10^{-7} Torr
Extraction Ports	2
Extraction Probes	Single carbon foil per side (Standard) Carousel type - 4 foils per carsouel (Optional)
Cyclotron Vault Dimensions (internal)	Without beamlines: 5.0 m x 4.5 m x 3.0 m (H) With one external beamline: 6.0 m x 8.5 m x 3.0 m (H) With two external beamlines: 6.0 m x 12 m x 3.0 m (H)

ACSI TR30

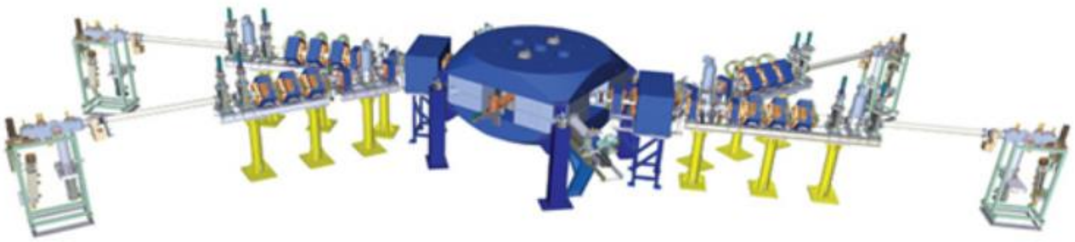
Features of the TR-30

>1000 microamps Total Beam Current
TR-30 is the first commercial cyclotron to exceeds >1000 microamps in the field.

Variable Energy Extraction
TR-30 offers variable energy extraction between 15 MeV to 30 MeV.

Simultaneous Dual Target Irradiation
Allows for maximum production of one radioisotope or concurrent production of two different radioisotopes.

External Beam Lines
Up to 9 external beam lines can be configured on the TR-30 cyclotron.



Dual Particle Acceleration
TR-30 can be configured to a TR-30/15 dual particle cyclotron to accelerate both protons and deuterons. This provides a powerful research tool in addition to cost effective production.

Proven Reliability
TR-30 cyclotrons have the lowest downtime of any commercial cyclotrons in the world. MDS Nordion's TR-30 has been operating for 10 years, 7 days per week, 24 hours per day and only requires downtime for routine maintenance.

Windows OS
TR-30 uses the familiar Windows operating system with graphical representations of the entire radiochemical process.

Safety Systems
Extensive safety features have been incorporated into the TR-30. Internal and external safety interlock systems are built into the Computer Control System using visual and audible warning signals.

Sumitomo HM30

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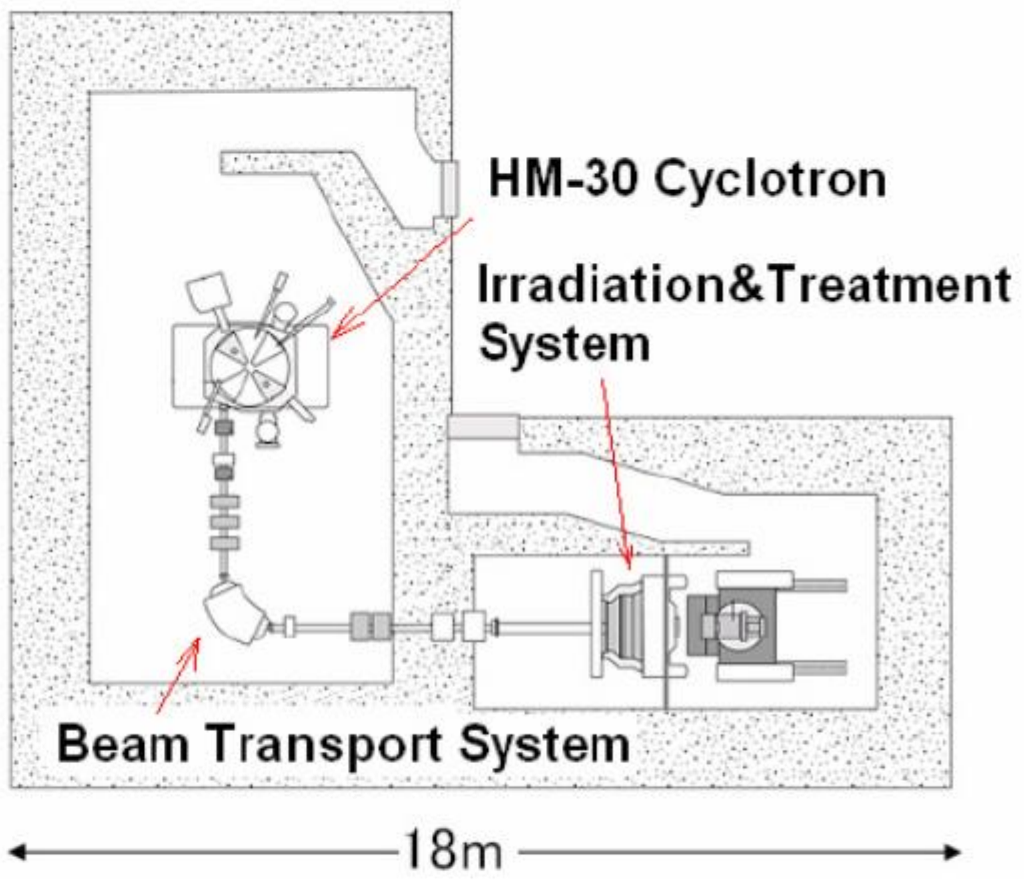

Layout of the cyclotron BNCT system at KURRI

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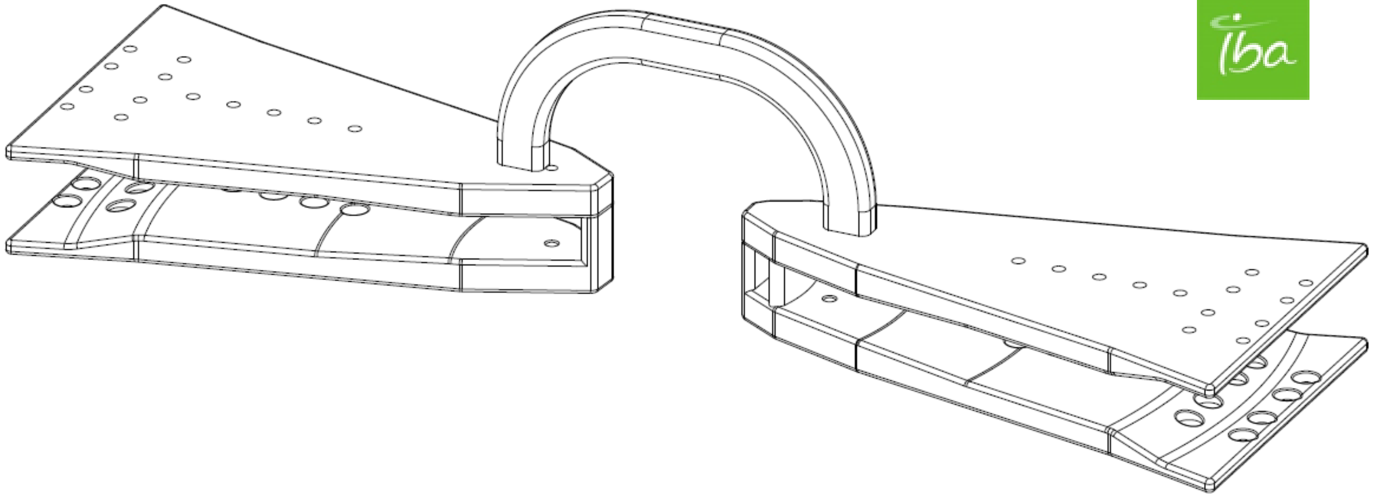
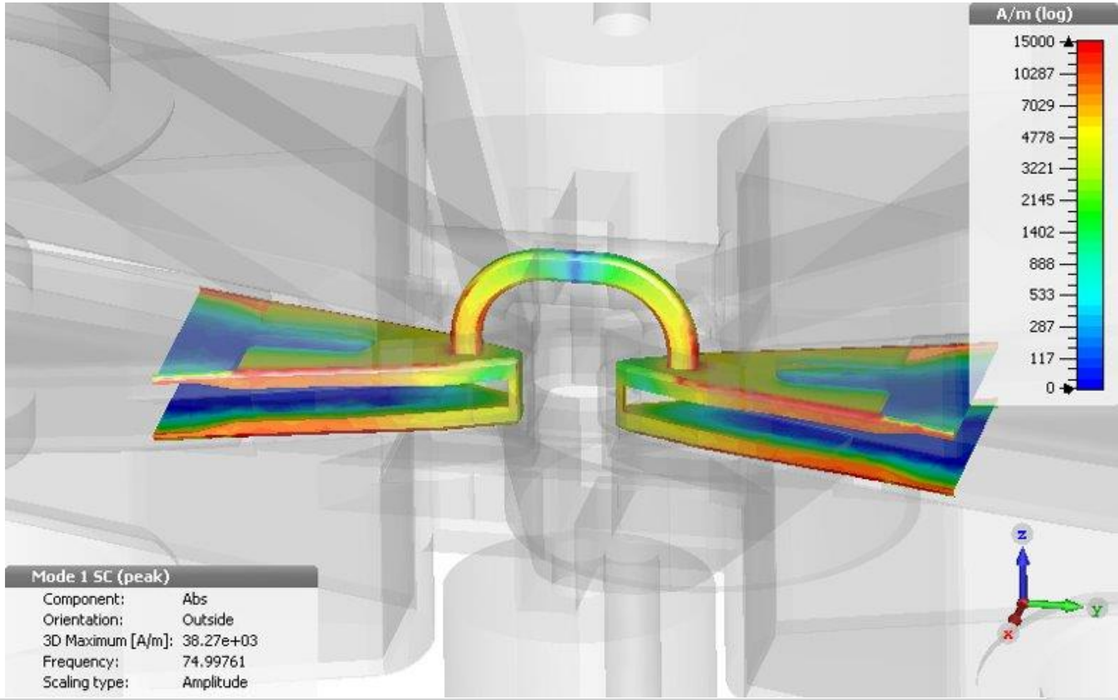
Particle	Negative hydrogen ion
Injection Energy	30 keV
Injection method	Axial injection
RF frequency	73.1 MHz
RF accelerating voltage	200 kV/turn
Harmonic number	4
Extraction method	Foil stripping
Extraction energy	30 MeV
Extracted beam current	1 mA (2 mA is possible)
Size	W 3.0m × D 1.6m × H1.7m
Weight	60 tons

Cyclone® IKON – RF System



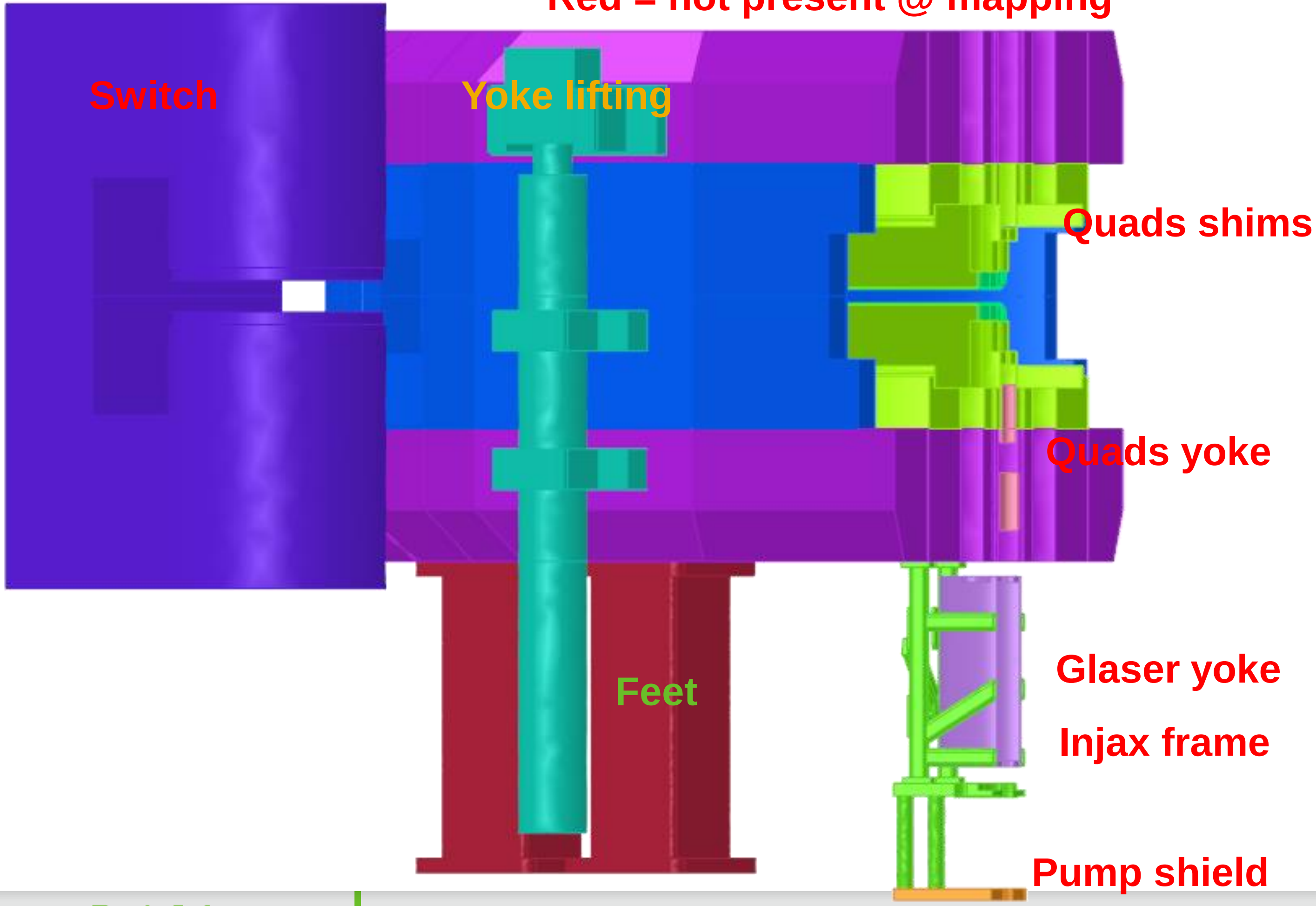
- RF bridge between cavities going through a copper tunnel above the spiral inflector.



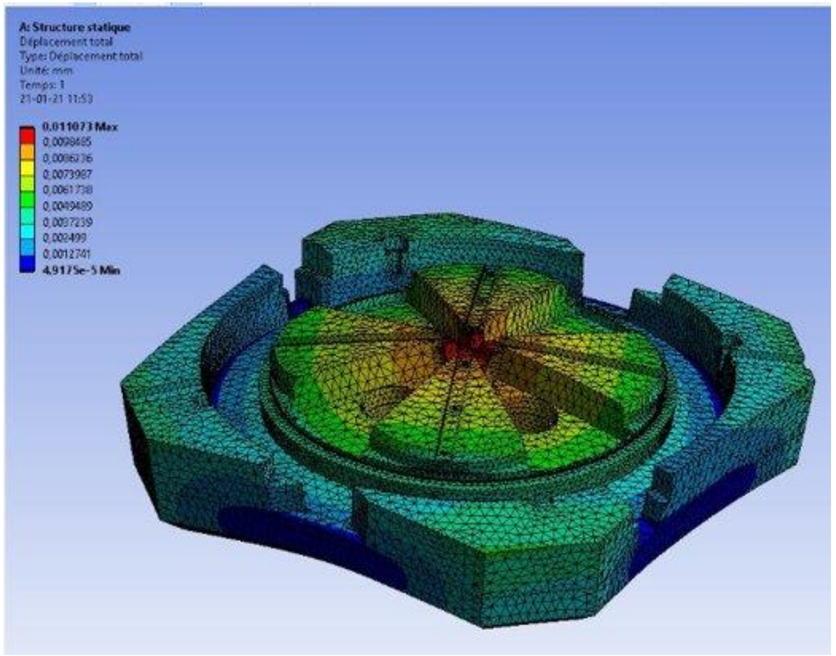
- RF bridge and Dee tips dissipate about 500W
- Ensure proper tightening !

Cyclone® IKON – mapping and isochronisation

Green = present @ mapping
Orange = present but different geometry
Red = not present @ mapping

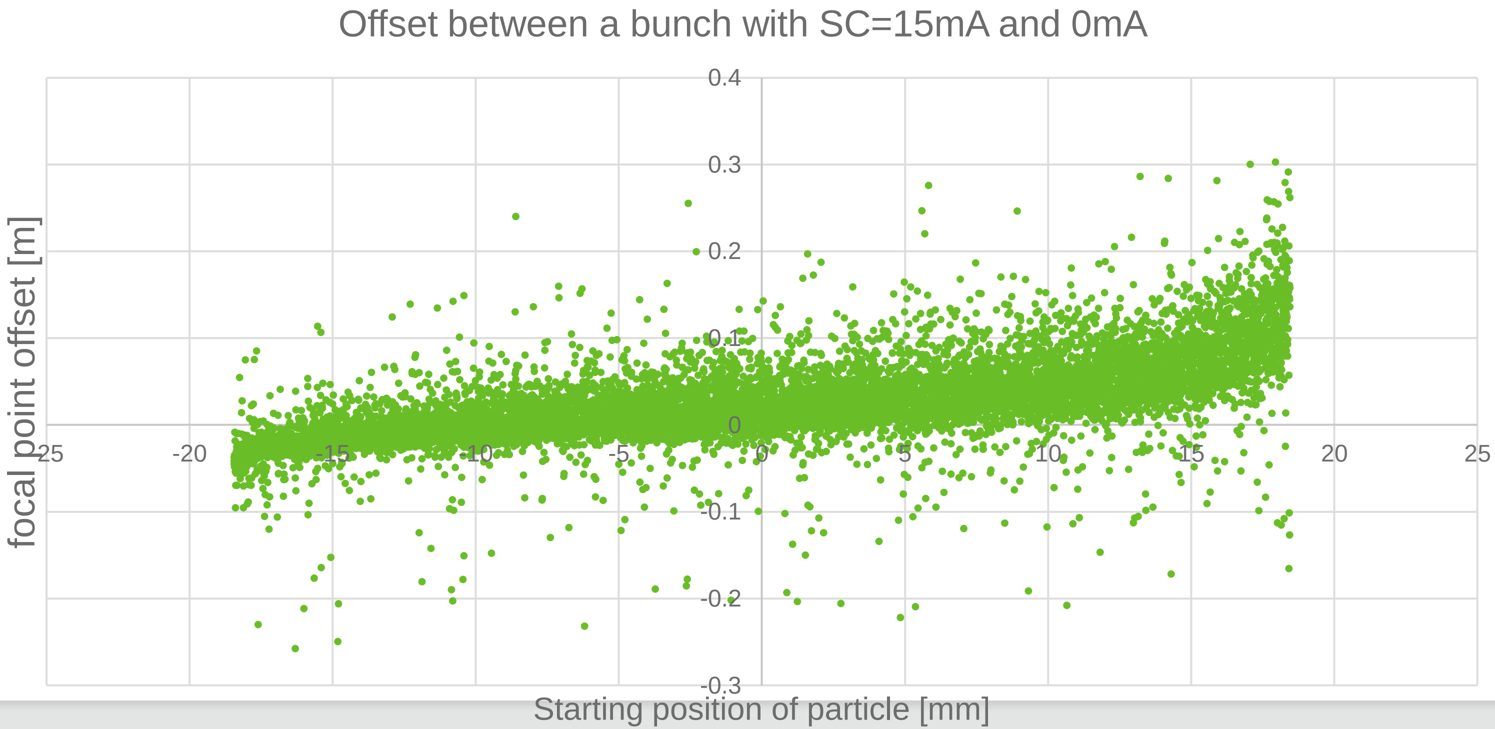


- Deformation by atmospheric pressure included → Minimize shimming during SG analysis with beam



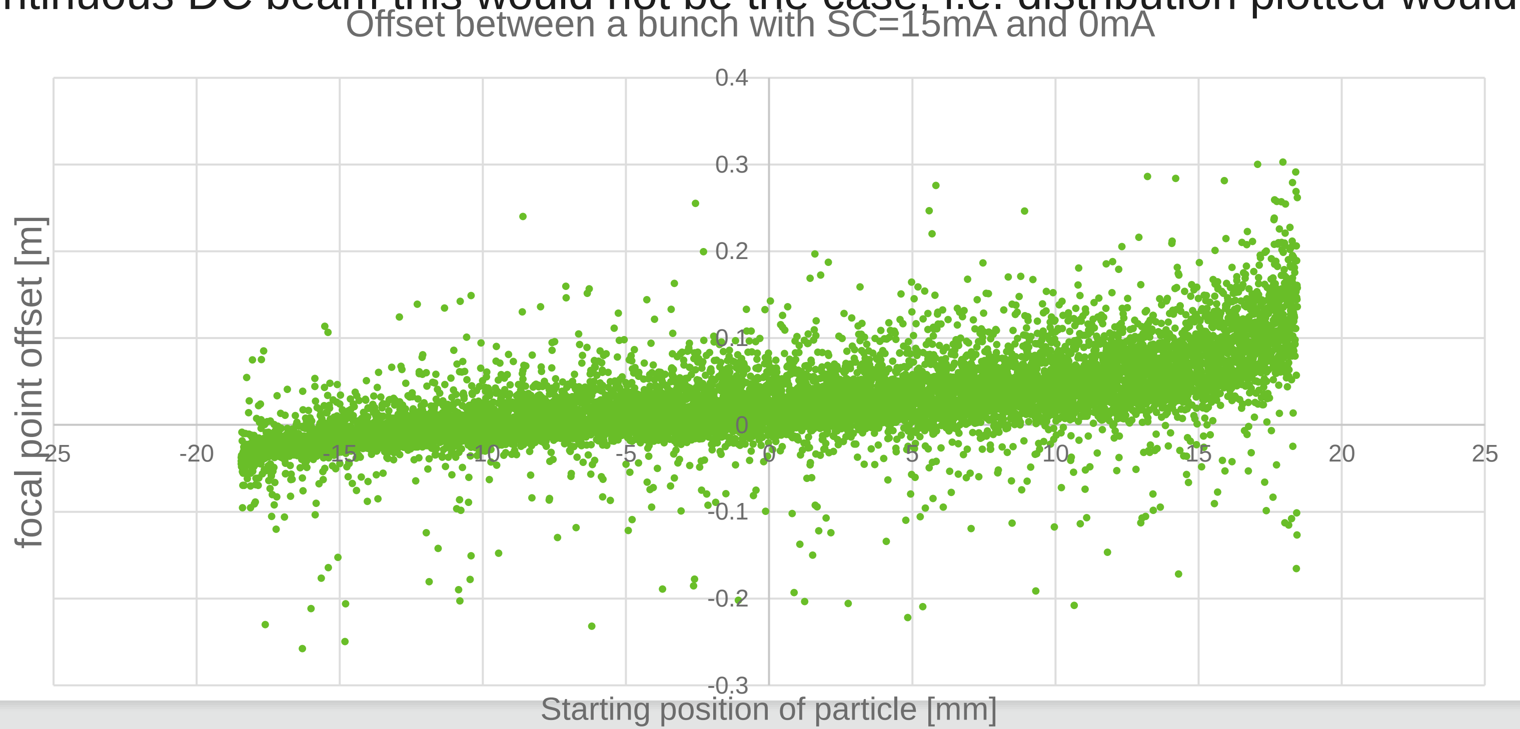
SC effect in AOC on longitudinal distribution

- Up to now all AOC simulations are done with bunches that are 1 RF period long.
  - beta*lambda =36.9mm at 40 keV. So half a bunch length is 18.45mm.
- The beam is 2D gaussian transversally. Longitudinally the particle distribution is flat.
- Taking for each particle its point of closest approach to the axis after the Einzel, and comparing this for tracking with and without SC, we see:



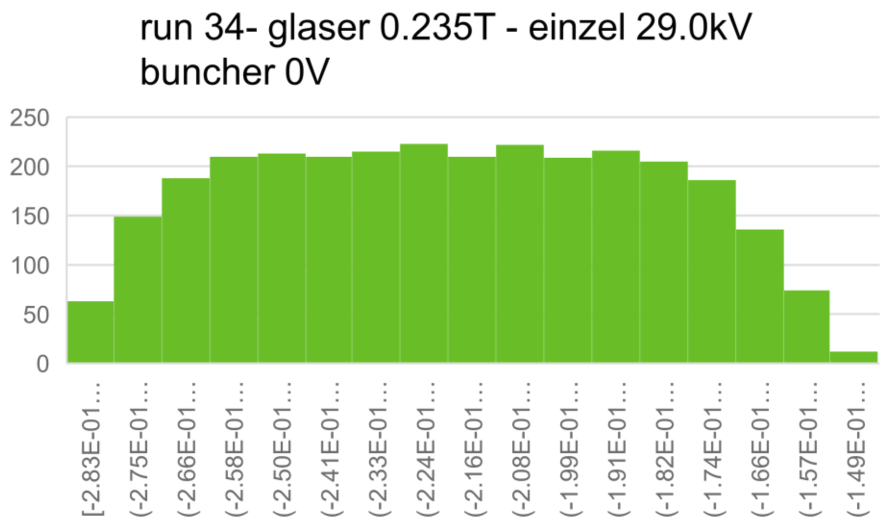
SC effect in AOC on longitudinal distribution

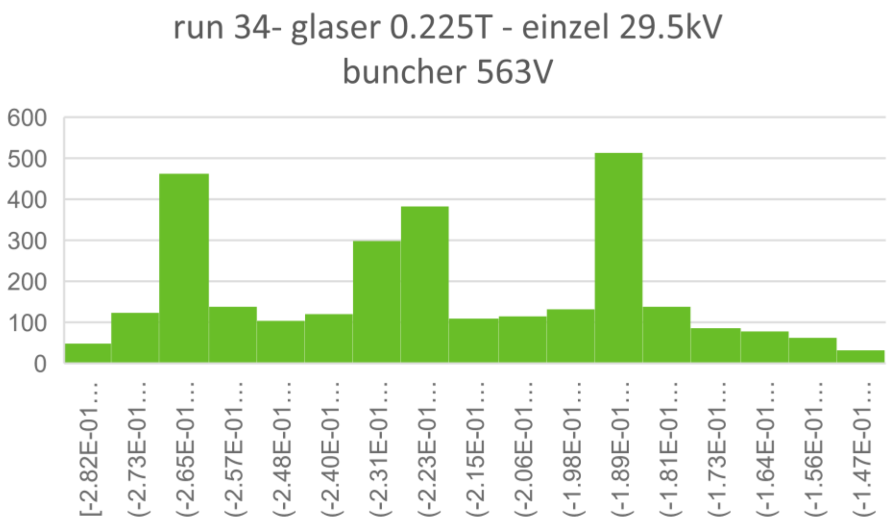
1. Average shift of the focal point per particle is ~26 mm:
   - More than ~5mm as measured from rms focal point
   - Smaller than 50 mm expected from Transport.
2. Particles that started at the front of the beam have higher offset, particles that started at the back of the beam have lower offset
   - In a continuous DC beam this would not be the case, i.e. distribution plotted would be horizontal



3 bunches of 01 mA each

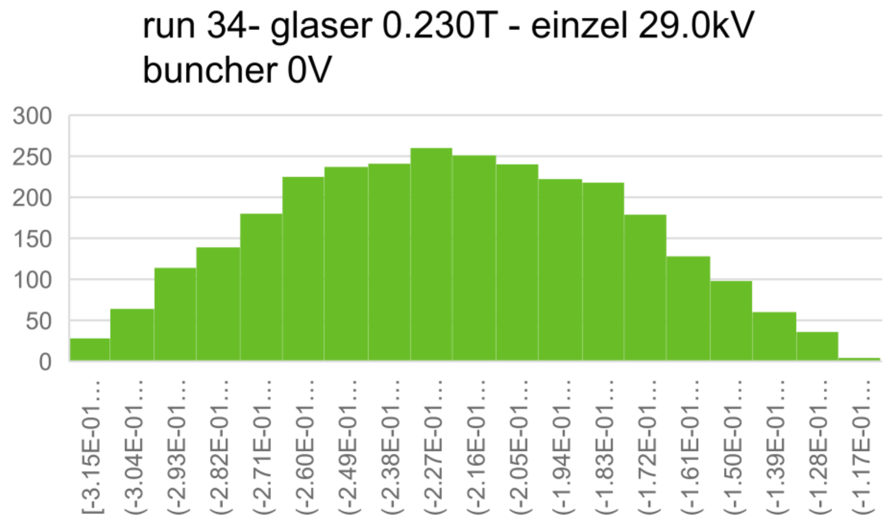
- With flat uniform distribution longitudinally, we see at inflector:
  - Left: the distribution in Z has gotten tails in both direction
  - Right: with buncher at 563 V, three sub bunches appear. Distance between the two is ~36 mm, as expected from beta*lambda (=37mm)

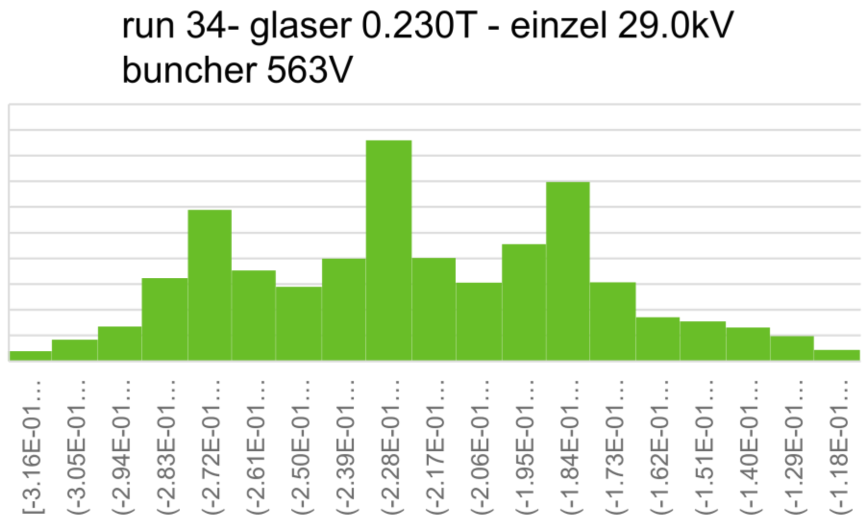




3 bunches of 05 mA each

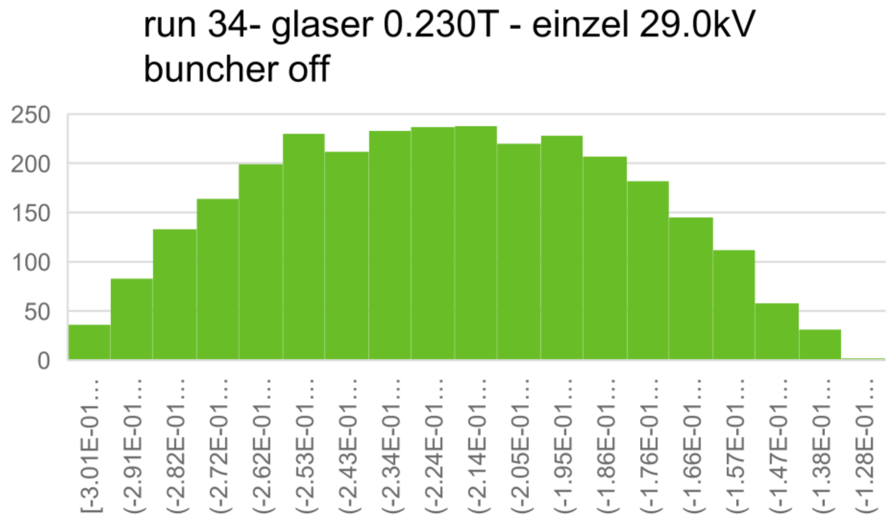
- With flat uniform distribution longitudinally, we see at inflector:
  - Left: the distribution in Z has gotten tails in both direction
  - Right: with buncher at 563 V, three sub bunches appear. Distance between the two is ~45 mm, i.e. significantly more than expected from beta*lambda (=37mm)

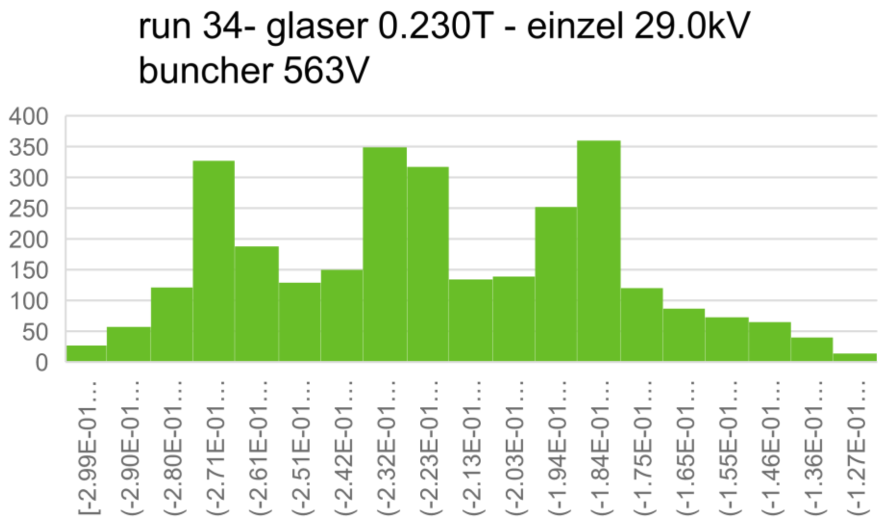




3 bunches of 03 mA each

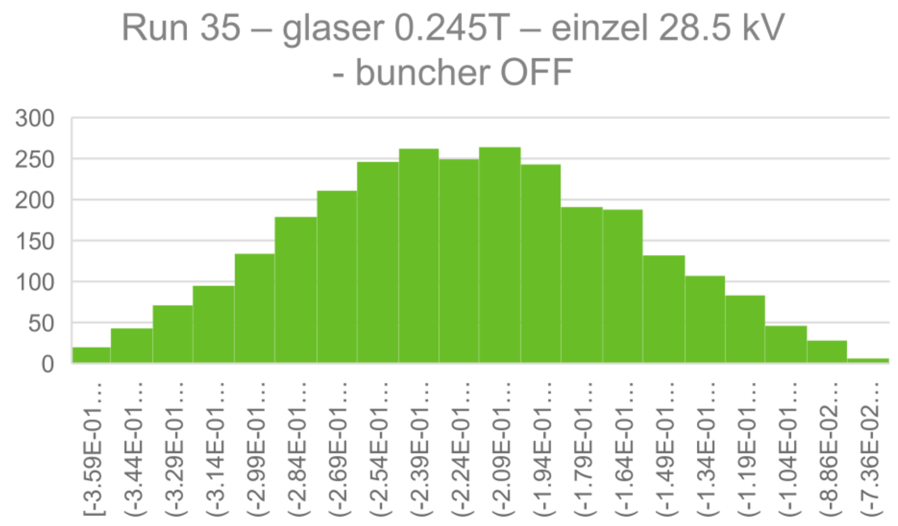
- with flat uniform distribution longitudinally, we see at inflector:
  - Left: the distribution in Z has gotten tails in both direction
  - Right: with buncher at 563 V, three sub bunches appear. Distance between the two is ~41 mm

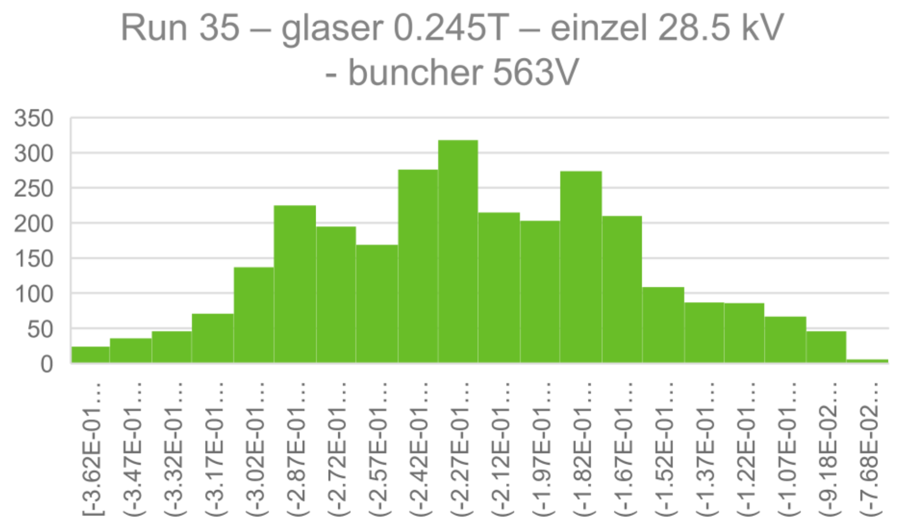




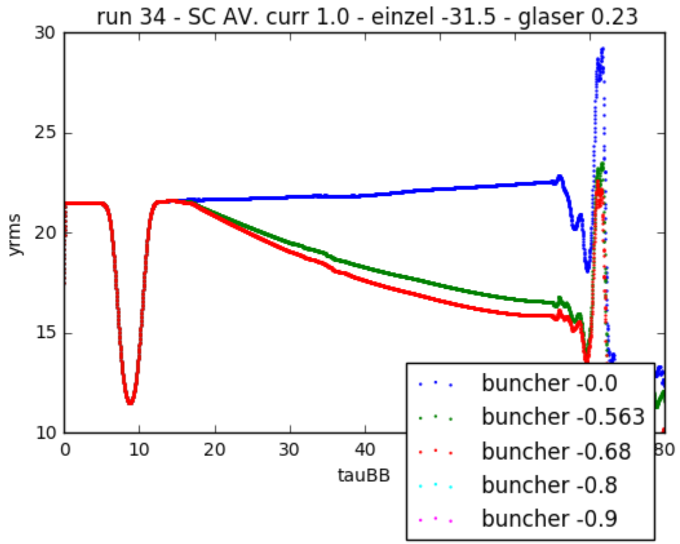
3 bunches of 15 mA each

- with flat uniform distribution longitudinally, we see at inflector:
  - Left: the distribution in Z has gotten tails in both direction
  - Right: with buncher at 563 V, three sub bunches appear. Distance between the two is ~50 mm

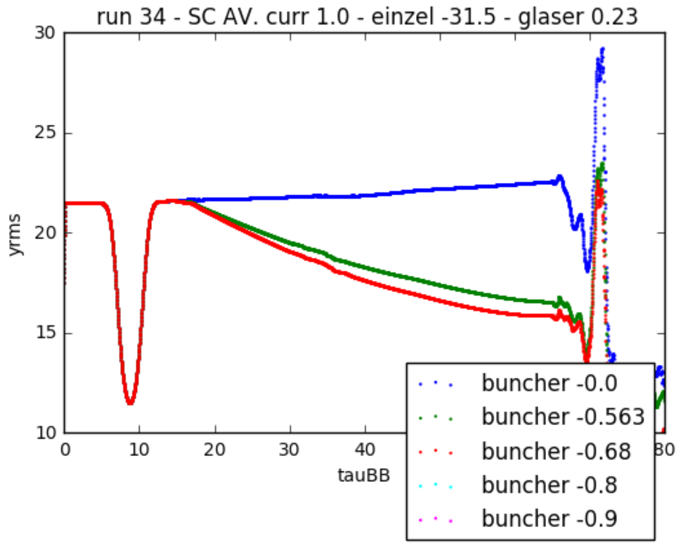


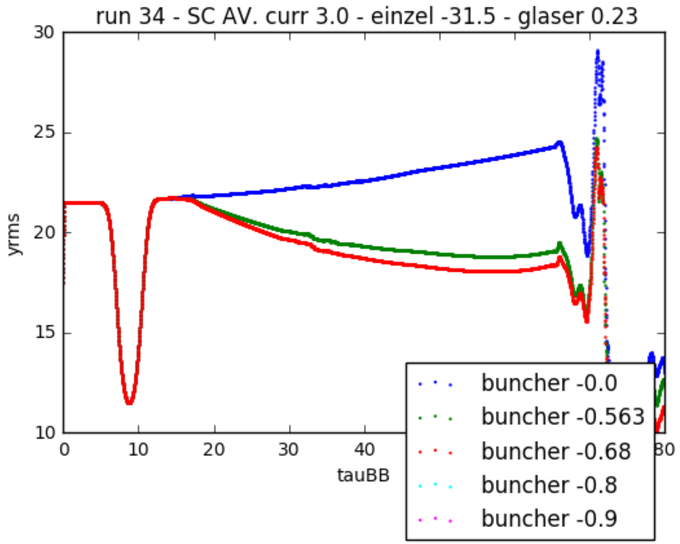


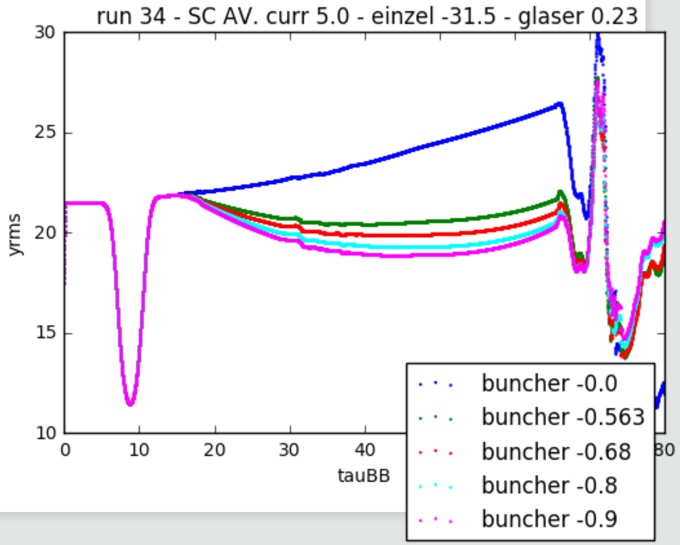
Longitudinal effects



Longitudinal effects







Longitudinal effects

- Goi