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Production of 70-MeV proton beam in a superconducting cyclotron

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Motivation

- Production of 70-MeV proton beams with help of a cyclotron-type facility is one of highly requested tasks presently.
- A normal-conducting cyclotron is commonly used for that purpose.
- There is a set of commercial firms and institutes producing compact 70-MeV proton cyclotrons (IBA, BEST, NIIEFA, …). Weight of a normal-conducting cyclotron is 140-200 ton. Outer diameter ~4-5 m.
- Superconductivity is now a well established technology. It allows reducing of facility size, weight, and power consumption.
- Negative effect of high magnetic fields is the limitation on acceleration of H^- ions (due to Lorentz's stripping):
  - NO ~100% extraction efficiency!
  - NO beam energy variation!
- It's interesting to simulate superconducting cyclotron and compare its parameters and functionality with normal-conducting machine

Requirements (task formulation)

- Isotope production:
  - Beam current of hundreds micro-Amps, it’s better to have 1 mA
    - External injection!
  - Extraction with ESD
    - Beam power losses at extraction <1 kW
  - Energy variation in range 30-70 MeV
- Eye melanoma treatment
  - Beam current of tens nano-Amps
    - Internal ion source can be used!
  - Energy variation in range 60-70 MeV
- High power cyclotrons
  - Beam current of hundreds micro-Amps or even several milli-Amps
    - External injection!
  - Stripping extraction

Energy variation
+
High extraction efficiency

↓

Acceleration of H_2^+ ions

Energy variation
+
High extraction efficiency

↓

Acceleration of H_2^+ ions

Smallest cyclotron size

↓

Acceleration of protons

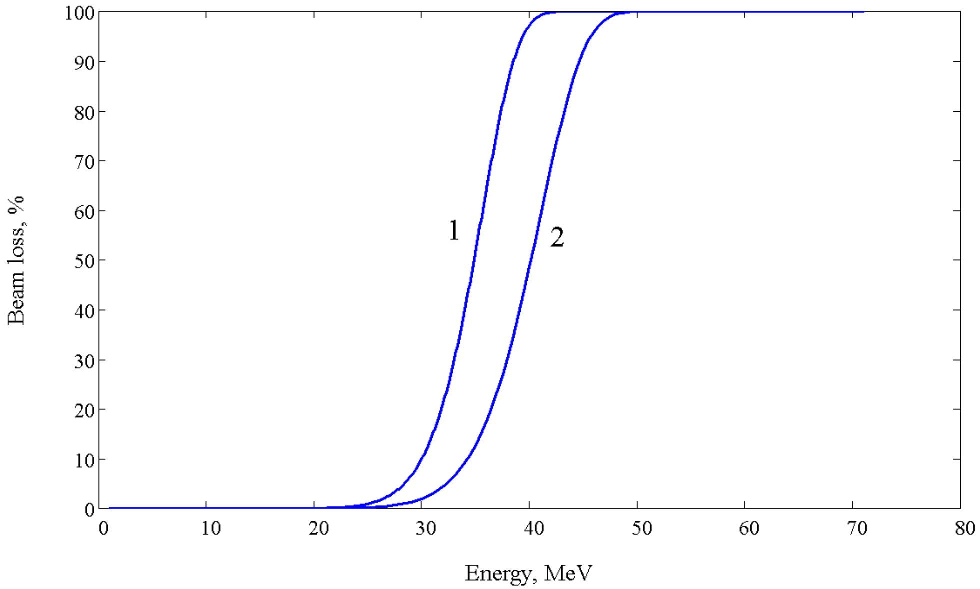
Cyclotron for acceleration of protons

K-factor is 70 MeV

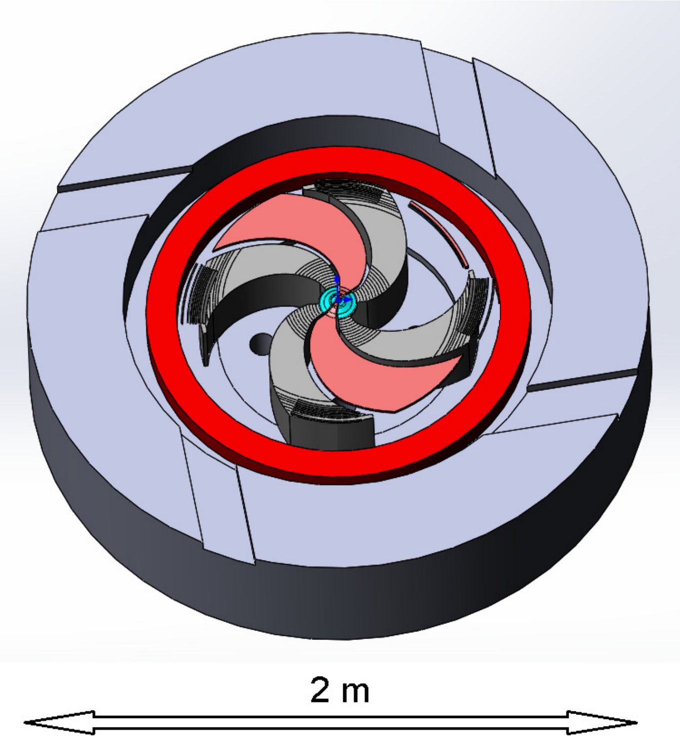
Lorentz stripping for H^- ions:

1 – B_0=2.9 T, N_{dee}=2, h=2, U_{dee}=30 kV

2 – B_0=2.9 T, N_{dee}=4, h=2, U_{dee}=90 kV

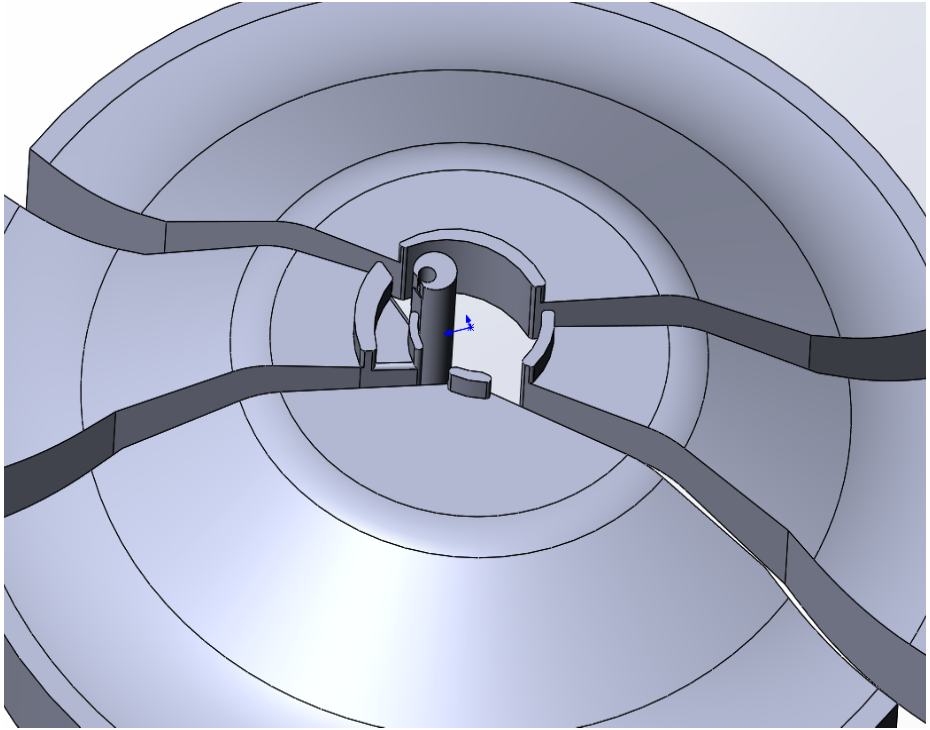


K70 cyclotron



Parameter	Value
Type of ion	Proton
Final beam energy	70 MeV
Output intensity of the beam	100 μA
Final beam emittances	~15 π·mm·mrad
Magnetic structure	4 spiral sectors
Average magnetic field: injection/extraction	2.9/3.1 T
Spirality	55 degree
Pole radius	435 mm
Hill gap	30-22 mm
Valley gap	450 mm
Acceleration system	2 spiral cavities
Peak dee voltage	30 kV
Acceleration frequency	88 MHz
Acceleration mode	2
External injector	ECRIS/PIG
Extraction type	Electrostatic deflector
Average extraction radius	400 mm
Dimensions: diameter/height	1940/940 mm
Total weight	~18 t

Central region structure with using internal ion source



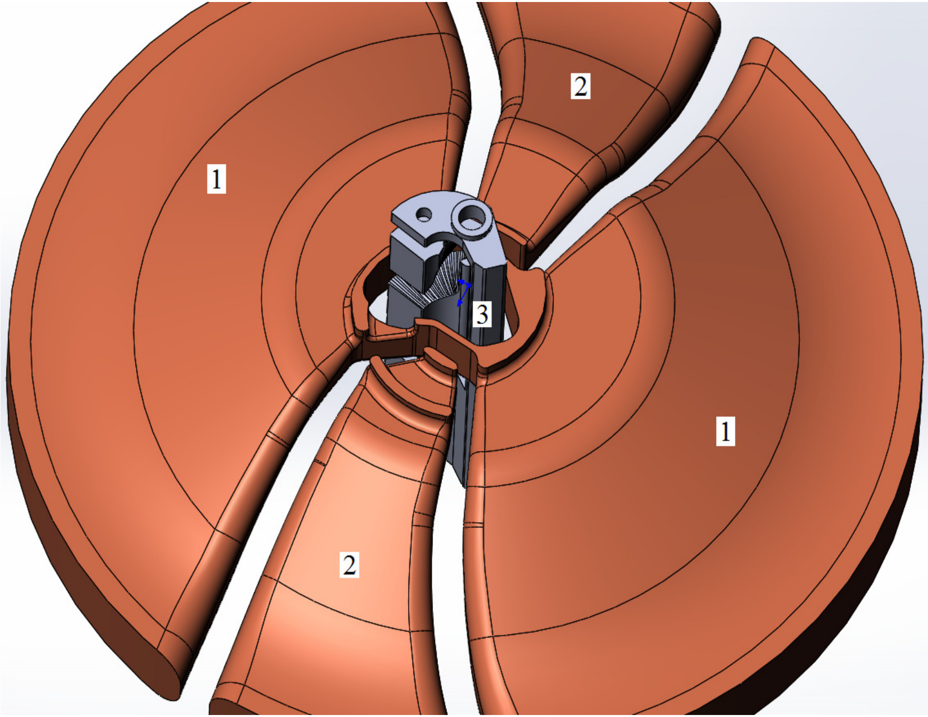
Central region configuration with using axial injection

The RF shield of the inflector is mounted on the dummy dee (1).

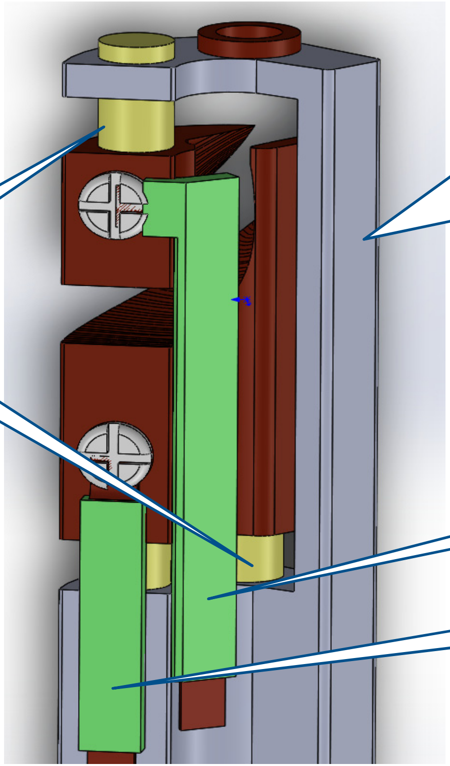
The dees (2) are not connected in the center.

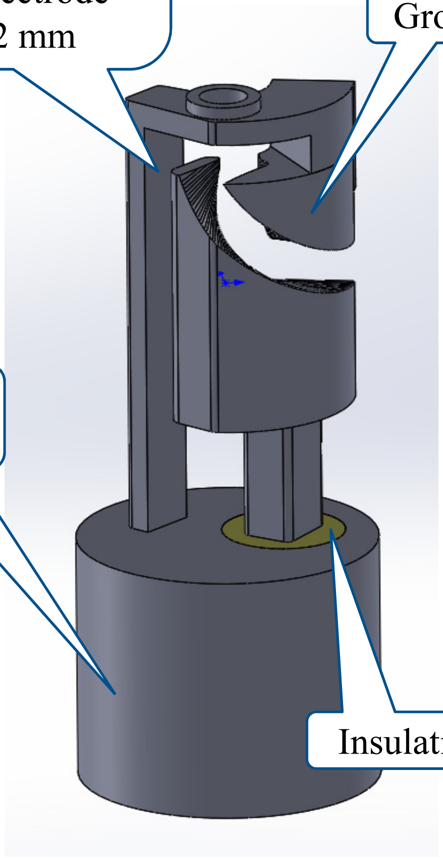
The inflector (3) is moved to its operation position from below of the cyclotron.

The air gap between the inflector and the RF shield is 2 mm.

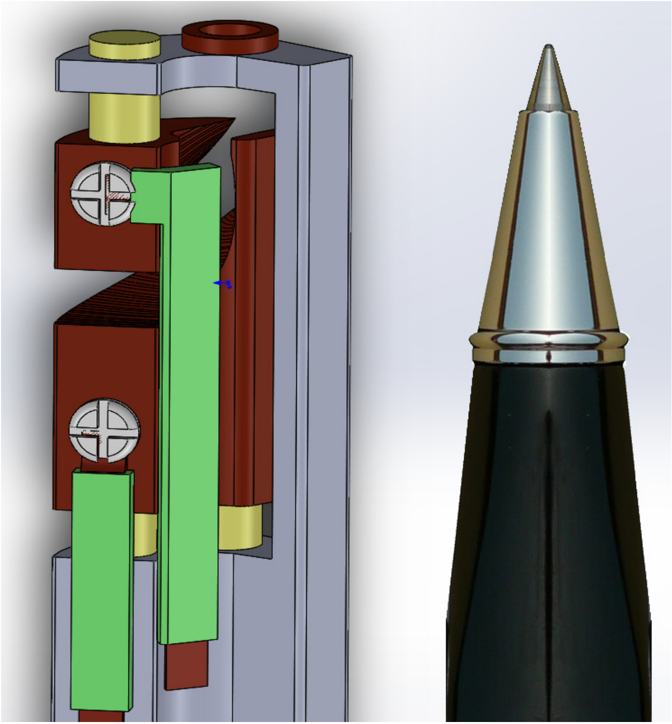


Proposed inflector infrastructure. Two possible schemes.

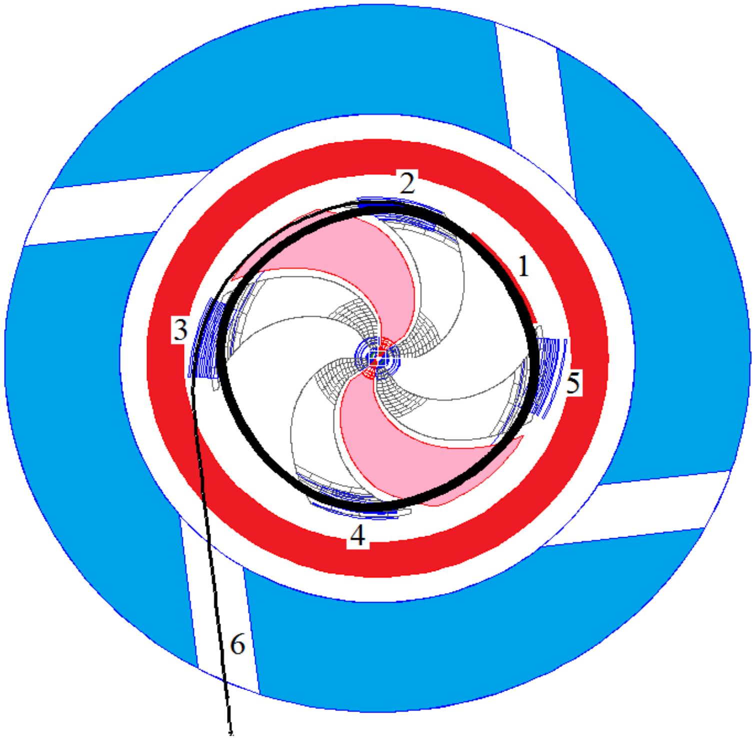




Comparison the inflector dimensions to a pen tip



Layout of K70 extraction system:
1 – ESD (110 kV/cm), 2 – MC1, 2 – MC2, 4 – C_MC1, 5 – C_MC2, 6 – outlet window.



Summary table of the beam parameters
(Limitation for beam power losses at extraction is 1 kW)

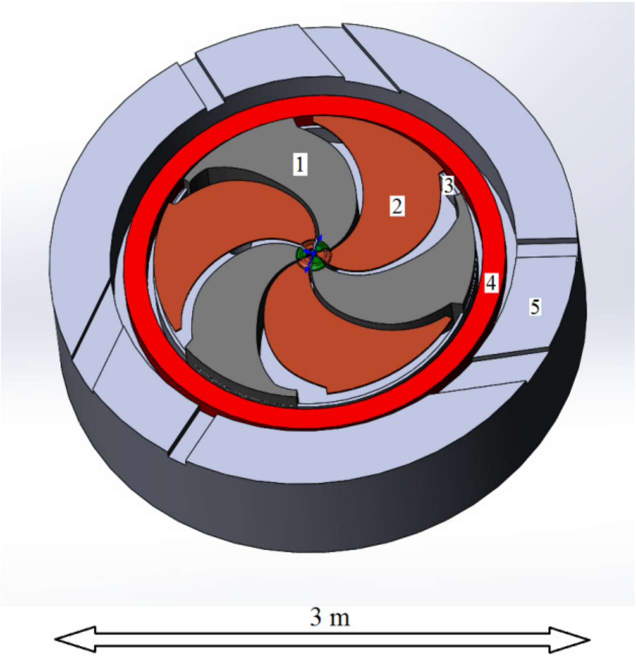
Ion	Injection type	Beam current from ion source, µA	Beam transmission through the central region, %	Beam extraction method	Beam extraction efficiency, %	Output beam current, µA	Output beam emittances hor./axial, π·mm·mrad	Output beam energy spread, %	Beam power loss at extraction, kW
Proton	External	400	30	Deflector	87	100	15/1	±0.4	1
	Internal	60	34		70	14	12/1	±0.3	0.4

K70:
weight ~18 t, proton current ~100 µA, NO energy variation

Cyclotron for acceleration of H_2^+ ions

K-factor is 280 MeV

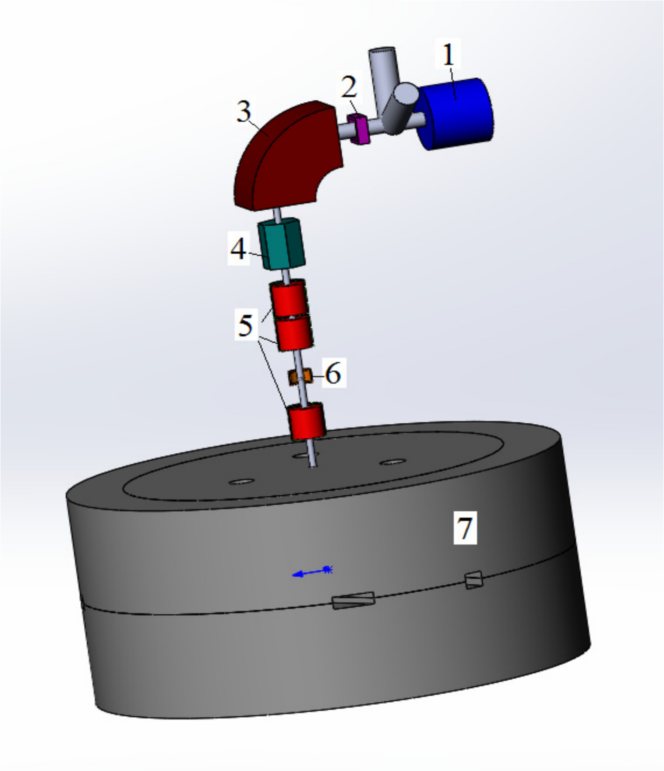
K280 superconducting compact cyclotron*



Parameter	Value
Type of accelerated ion	$^{12}C^{6+}$, H_2^+
Final beam energy	70 MeV/u
Output intensity of the beams: $^{12}C^{6+}$/H_2^+/proton	0.9/15/800 μA
Final beam emittances: radial/axial	~20 π·mm·mrad
Magnetic structure	3 spiral sectors
Average magnetic field: injection/extraction	2.6/2.9 T
Spirality	55 degree
Pole radius	920 mm
Hill gap	52 mm
Valley gap	540 mm
Acceleration system	3 spiral cavities
Peak dee voltage	90 kV
Acceleration frequency	60.8 MHz
Acceleration mode	3
External injector	ECRIS
Extraction type: carbon, H_2^+ /proton	Electrostatic deflector /stripping foil
Average extraction radius	870 mm
Dimensions: diameter/height	3000/1400 mm
Total weight	~70 t

* V. Smirnov, S. Vorozhtsov, F. Taft, T. Matlocha, Superconducting 70 AMeV cyclotron-injector for a hadron therapy complex, Nuclear Inst. and Methods in Physics Research, A 934 (2019) 1–9.

Injection system of the K280: 1 – ECRIS, 2 – steerer, 3 – bending magnet, 4 – Faraday cup, 5 – solenoids, 6 – buncher, 7 – cyclotron.

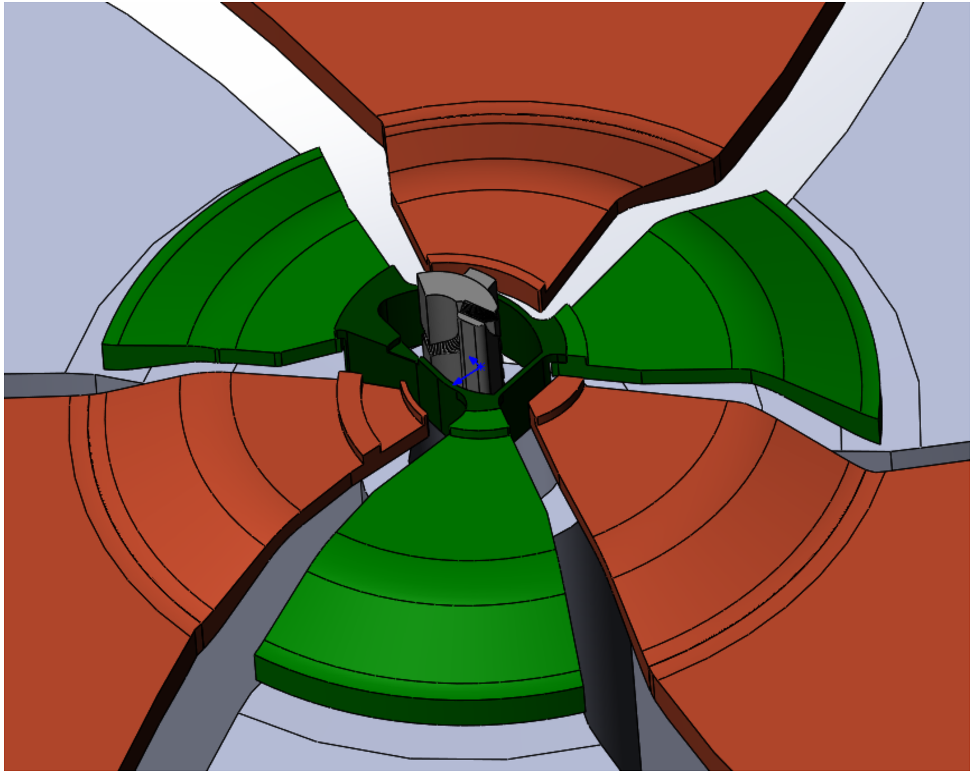


$^{12}C^{6+}$ and H_2^+ ions can be produced with single ECRIS SUPERNANOGAN* (Pantecnnik) with current 3 μA and 1000 μA correspondingly. As an alternative using of two sources: ECR for producing of carbon and multi-cusp for H_2^+ ions

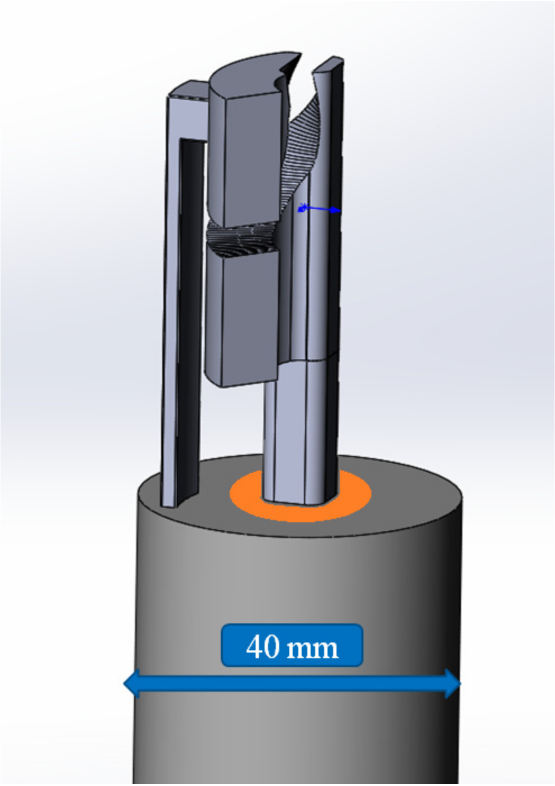
*http://www.pantechnik.com/#!sources/vstc2=supernanogan.

Central region structure of the K280

There is a possibility of the inflector and the RF shield rotation by several degrees

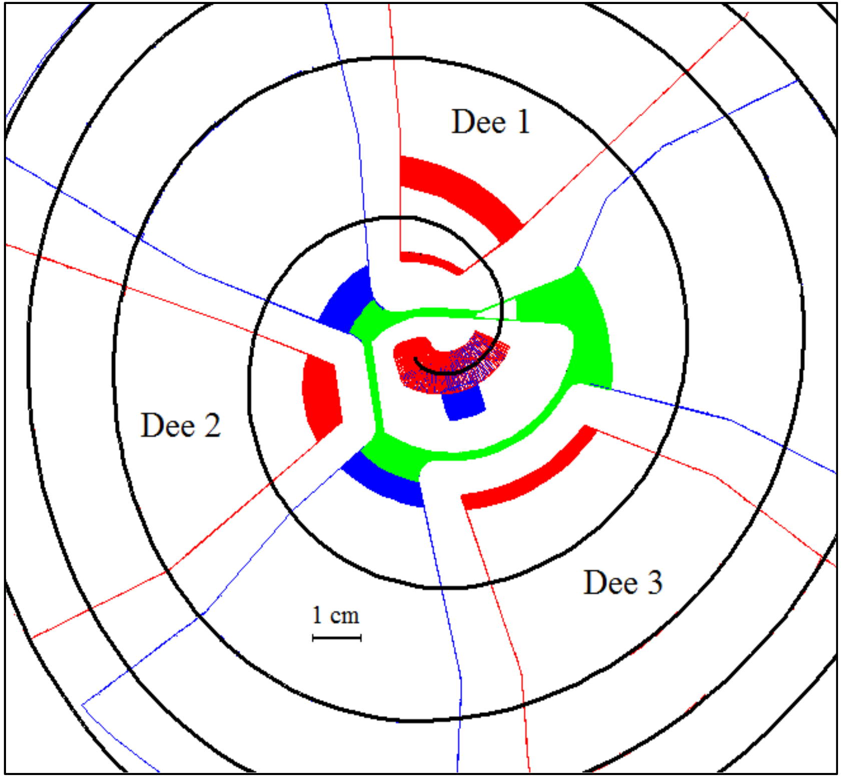


Spiral electrostatic inflector for K280 cyclotron

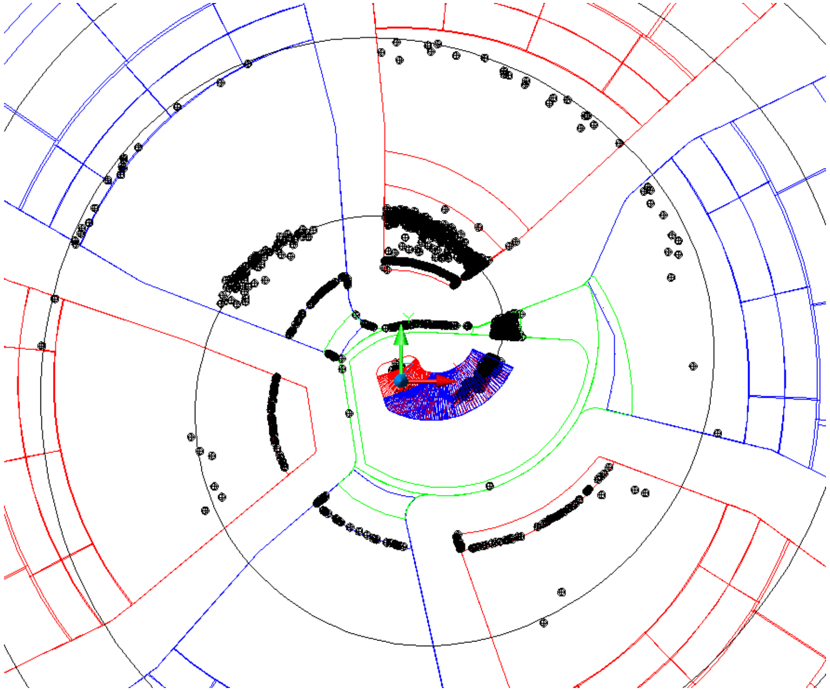


Ion type	$^{12}C^{6+}$, H_2^+
Injection energy	30 kV × Z
Magnetic field	2.64 T
Gap	4 mm
Voltage	12 kV
Magnetic radius	13.4 mm
Electric radius	20.0 mm
K	0.709

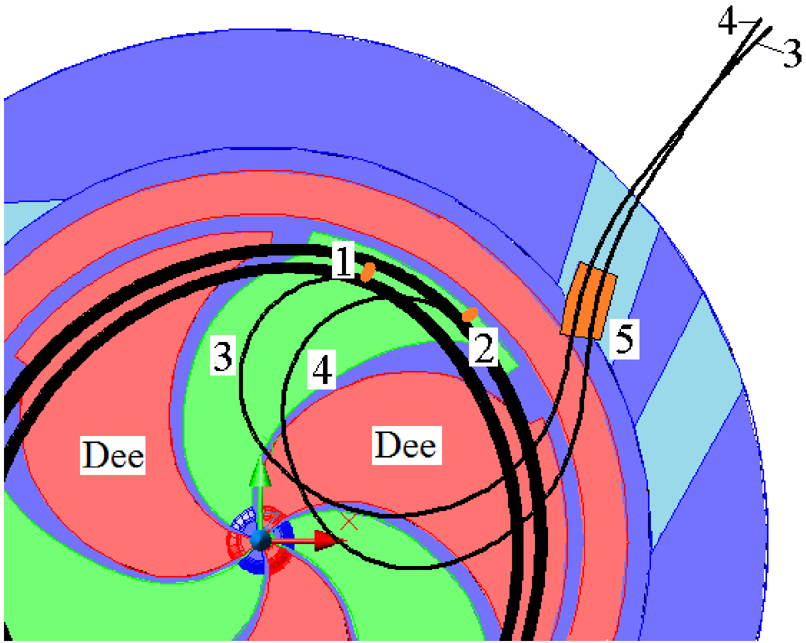
Trajectory of the reference ion in the central region



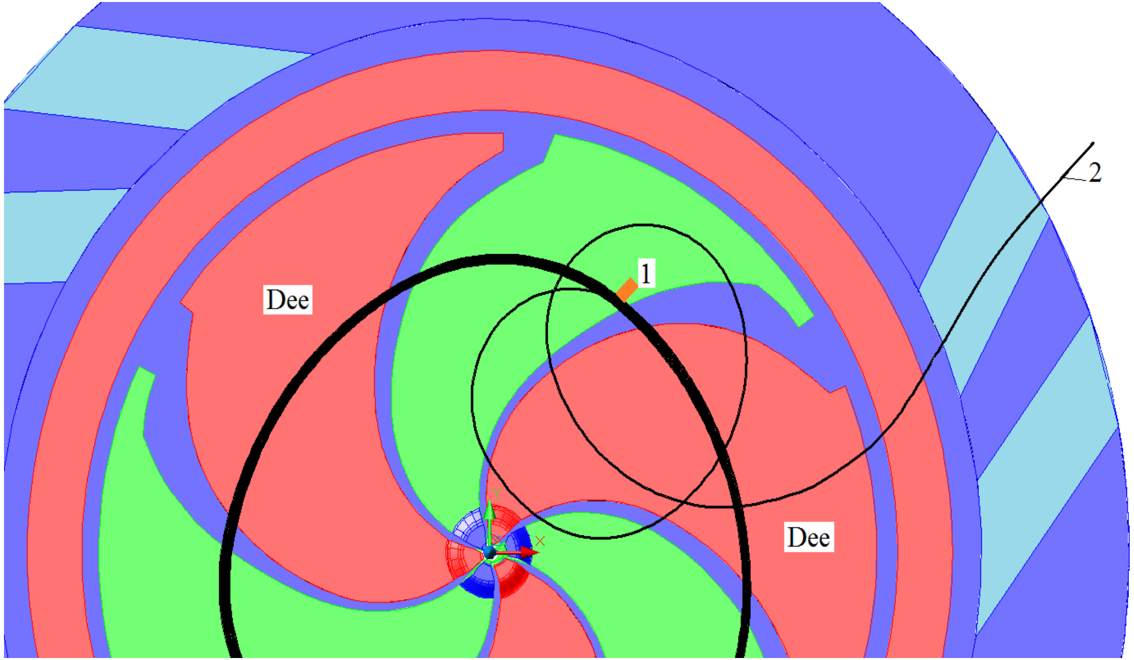
Particle losses in the central region: axial ~30 %, radial ~16%, inflector ~10%



Extraction system layout: 1 – stripping foil location for extraction of protons 60 MeV, 2 – stripping foil location for extraction of protons 70 MeV, 3 – trajectory of 60 MeV proton, 4 – trajectory of 70 MeV proton, 5 – bending magnet for steering the proton beams with output energy in range (60-70) MeV.



35 MeV proton beam extraction by stripping H_2^+ ions at the foil: 1 – foil, 2 – extracted proton trajectory.



Summary table of the beam parameters
(Limitation for beam power losses at extraction is 1 kW)

Ion: accel./ extrac.	Beam current from ion source, µA	Beam transmission through the central region, %	Beam extraction method	Beam extraction efficiency, %	Output beam current, µA	Output beam emittances hor./axial, π·mm·mrad	Output beam energy spread, %
$^{12}C^{6+}$	3	44	Deflector	73	0.9	23/22	±0.26
2H+	50		Deflector	65	14	21/20	±0.28
2H+/p	1000		Stripping	95	800	30/20	±0.67

K280:
weight ~70 t, proton current ~800 µA, energy variation 60-70 MeV

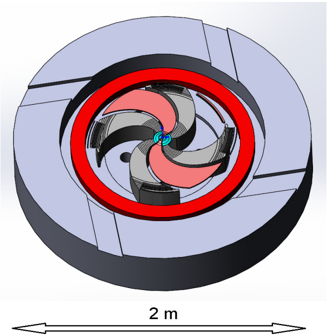
Comparison table

	K70	K280	BEST 70	IBA Cyclone 70	NIIEFA C80	Hyperferric Cyclotron*
Accelerated ion	p	H^+_2	H^-	H^-	H^-	p
Energy, MeV	70	60-70	35-70	30-70	40-80	70
Beam intensity, μA	100	800	1000	750	100	>0.1
Injection type	Cusp/PIG	ECR	Cusp	Cusp	Cusp	ECR
Central magnetic field, T	2.89	2.64	0.95	1.0	1.35	4.52
Extraction type	ESD	Stripping	Stripping	Stripping	Stripping	ESD
Extraction efficiency, %	>80	~100	~100	~100	~100	~80
Acceleration frequency, MHz	88	61	56	62	41	206
RF voltage	30	90	70	50	60	40
Power, kW	~150	~200	400	350	500	
Dimensions: D×H, m	2.0/1.0	3.0/1.4	4.5/1.7	4.0/3.8	5.7/2.6/3.4	1.3/0.9
Weight, t	~18	~70	150	140	200	<9

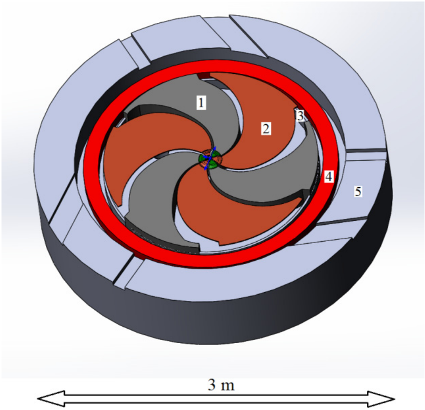
*Jacob Kelly, et.al., Compact Rare-Earth Superconducting Cyclotron, arXiv:1906.07642v1 [physics.acc-ph], 18 Jun 2019

From super- to normal-conducting cyclotron…

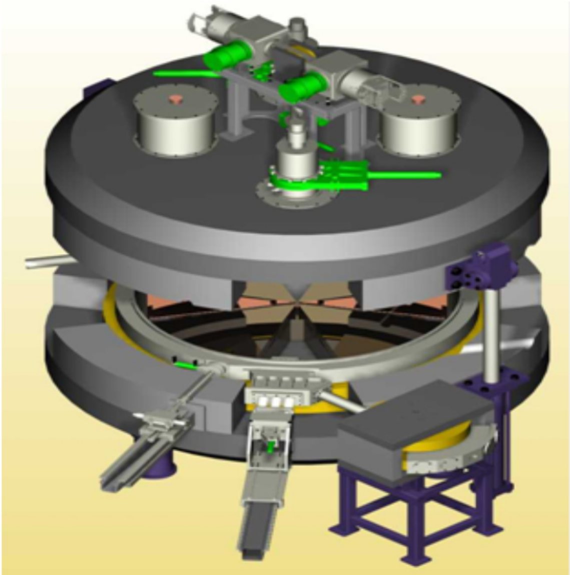
K70: diameter ~2 m,
weight ~18 t



K280: diameter ~3 m,
weight ~70 t



IBA C70: diameter ~4 m,
weight ~140 t



Thanks...