



한국원자력의학원

초전도 사이클로트론 기술 개발 현황 및 계획

한국원자력의학원
김현욱

15.10.28

의료용중입자기속기사업단
KOREA HEAVY ION MEDICAL ACCELERATOR

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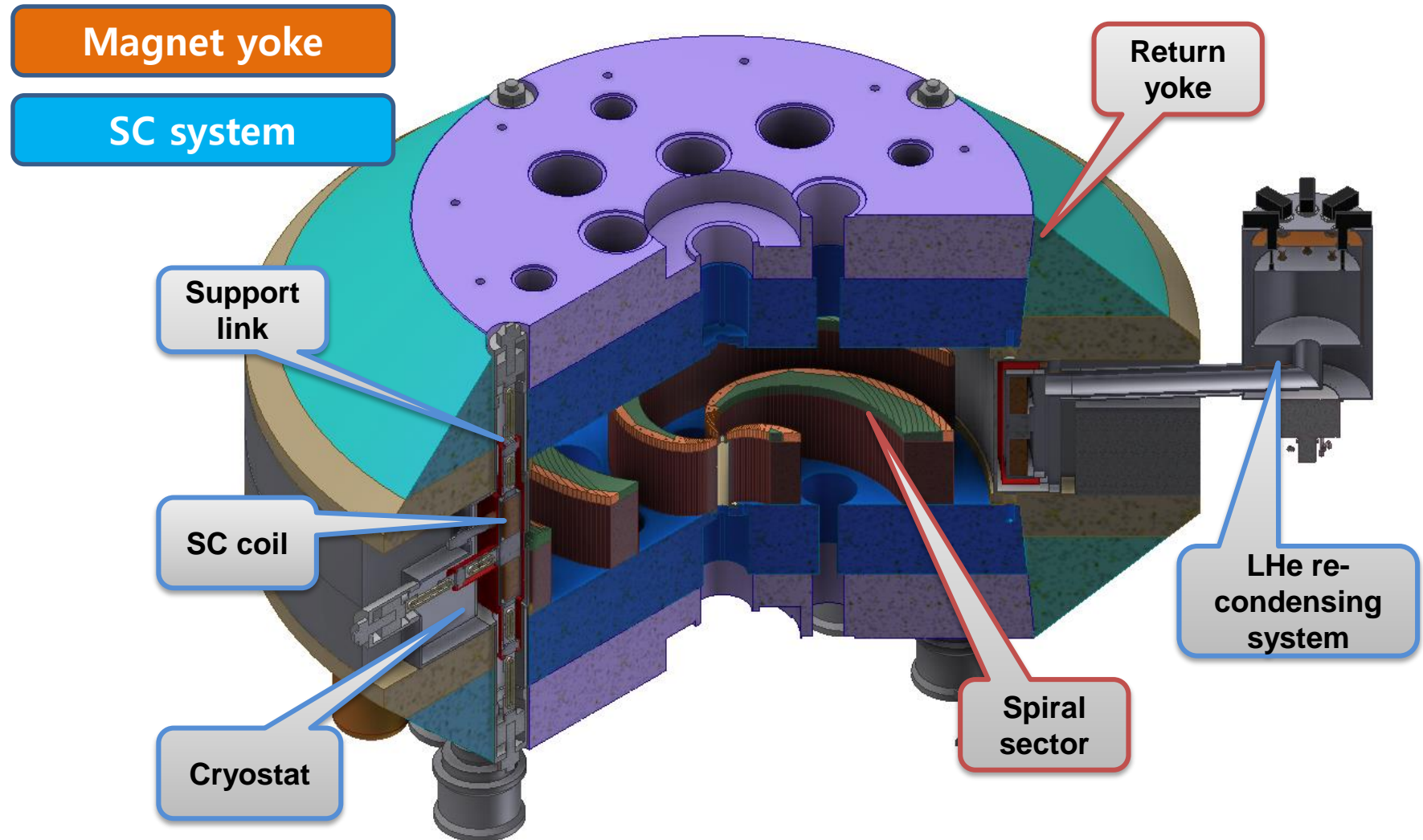
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초전도 사이클로트론 개요

초전도 사이클로트론

- 초전도 선재의 개발로 1970년대 이후 개발 시작
- 나선형 섹터 compact 사이클로트론에 적용
 - 고자장의 도입으로 빔 집속의 문제
 - 초전도 선재의 winding 문제
- ~5 T 또는 그 이상의 고자장 형성 가능
 - 기존 전자석의 약 3배 이상의 자기장 세기
 - 전자석 크기의 감소로 타 부품 크기 역시 감소
 - 동일 인출 에너지 기준, 상전도 전자석의 9배 면적 감소
 - 제작비 및 운영비의 절감이 가능

KIRAMS-430 Cyclotron Magnet



초전도 사이클로트론

- 저온 기술 및 초전도 선재 기술 필요
- 전자석 크기 감소로 인한 빔 인출의 어려움
 - 턴 간격 감소로 인출이 어려움
 - 협소한 공간으로 인출 시스템 크기 및 수 제한
- 고자장에 의한 문제 발생
 - Flutter 감소로 빔 집속 한계, $E_k = k(q/A)^2$
 - 전자석 pole과 yoke 구조의 제한



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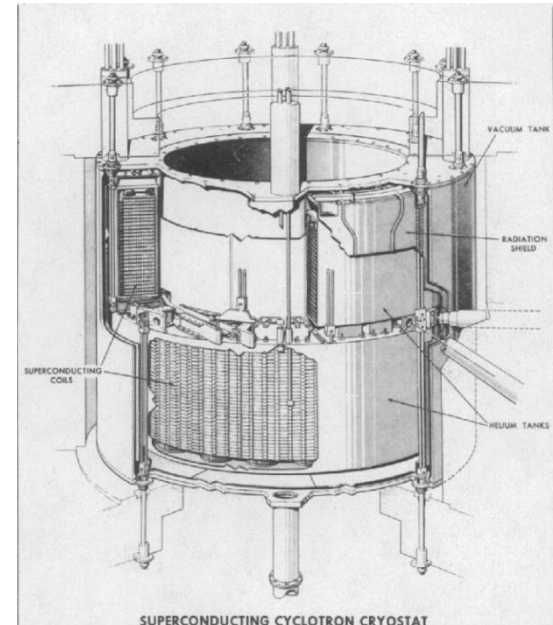
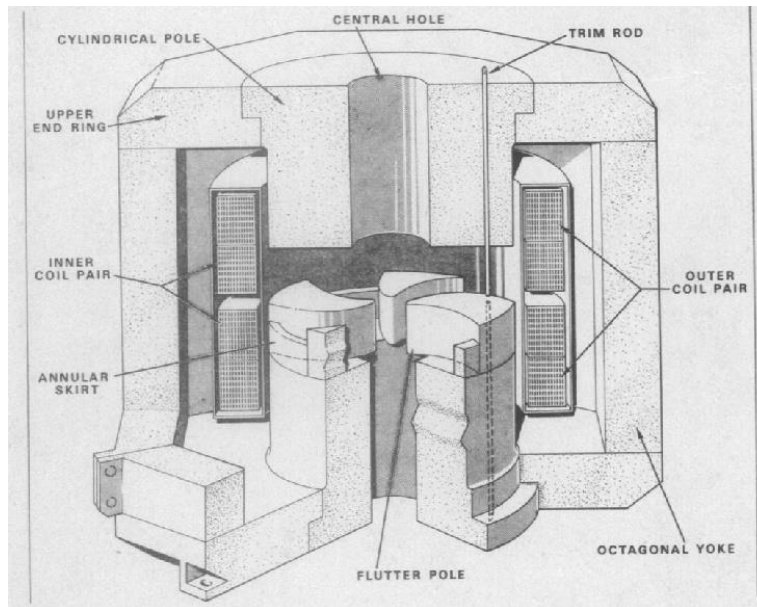
초전도 사이클로트론 현황

초전도 사이클로트론 현황 (compact)

		폴 직경 (m)	전자석 무게(t)	섹터 수	에너지 (MeV)	빔 인출
NSCL	MSU	1.42	90	3	K520	1982
AECL,	Chalk	1.39	170	4	K520	1985
NSCL	MSU	2.2	265	3	K1200	1988
Harper	Hosp.	0.64	22	3	50(d)	1988
Texas	A&M	1.42	90	3	K520	1988
Oxford	Instr.	0.5	1.5	3	12(H-)	1990
LNS,	Catania	1.8	176	3	K800	1994
KVI,	Groningen	1.88	320	3	200(p)/K600	1994
ACCEL	PSI, RPTC	1.69	90	4	250(p)	2006
Kolkata		1.42	90	3	K520	2008
Mevion	Barnes-Jewish Hosp.	~0.54	<20	0	250	2013
IBA/JINR		3.74	660	4	260(p)/K1600	
LNS,	Catania	~2.7	350	4	260(p)/K1200	
KIRAMS		4.1	860	4	K1720	
IBA		1	50	0	230/250(p)	
SKKU		1.55	80	4	245(p)	
SKKU		1	46	0	240(p)	

초기 초전도 사이클로트론

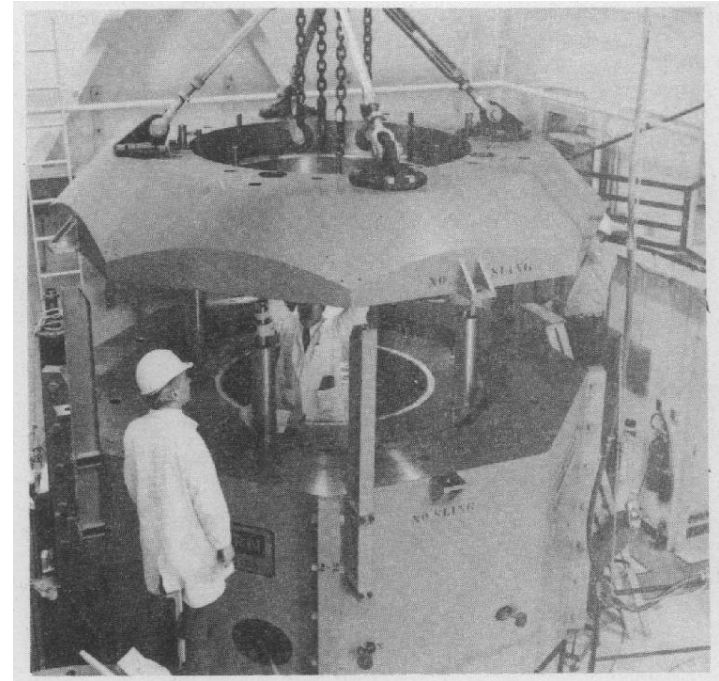
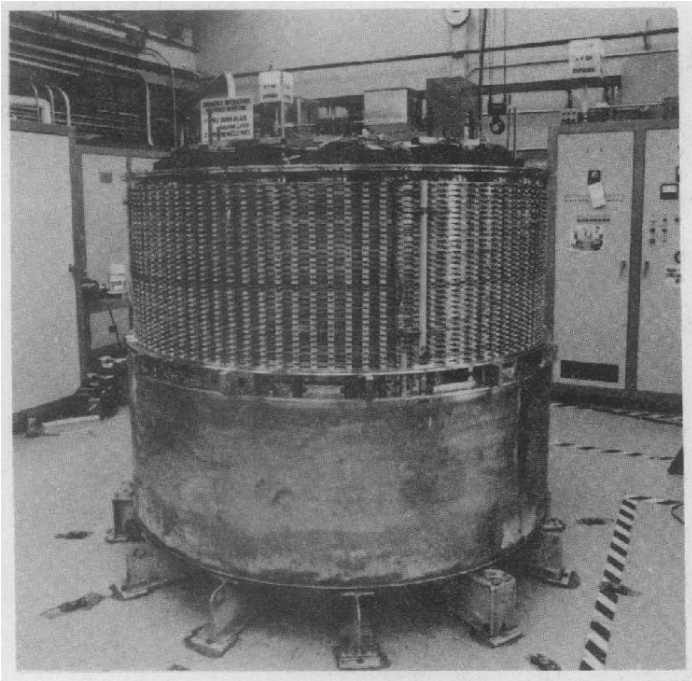
- 1977년 최초의 초전도 사이클로트론 설계
 - Atomic Energy of Canada Limited's Chalk River Lab.
 - Li(50 MeV/u) ~ U(10 MeV/u)



J. H. Ormrod et al., Proc. PAC' 77, IEEE Trans.NS-24, 1093 (1977)

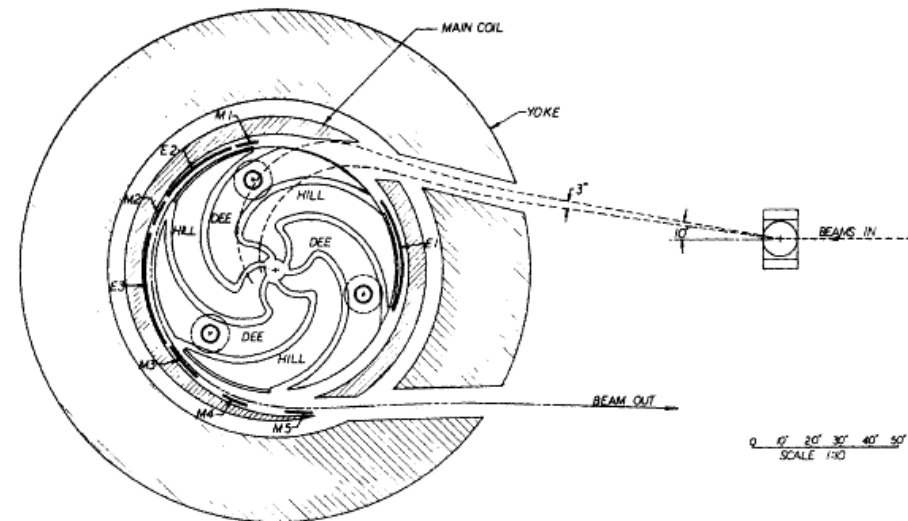
초기 초전도 사이클로트론

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J. H. Ormrod et al., Proc. PAC' 77, IEEE Trans.NS-24, 1093 (1977)

- 1979년 MSU-NSCL 초전도 사이클로트론 설계
 - K500 , K800 for Ca(200 MeV/u) ~ U(20 MeV/u)



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초전도 사이클로트론 현황

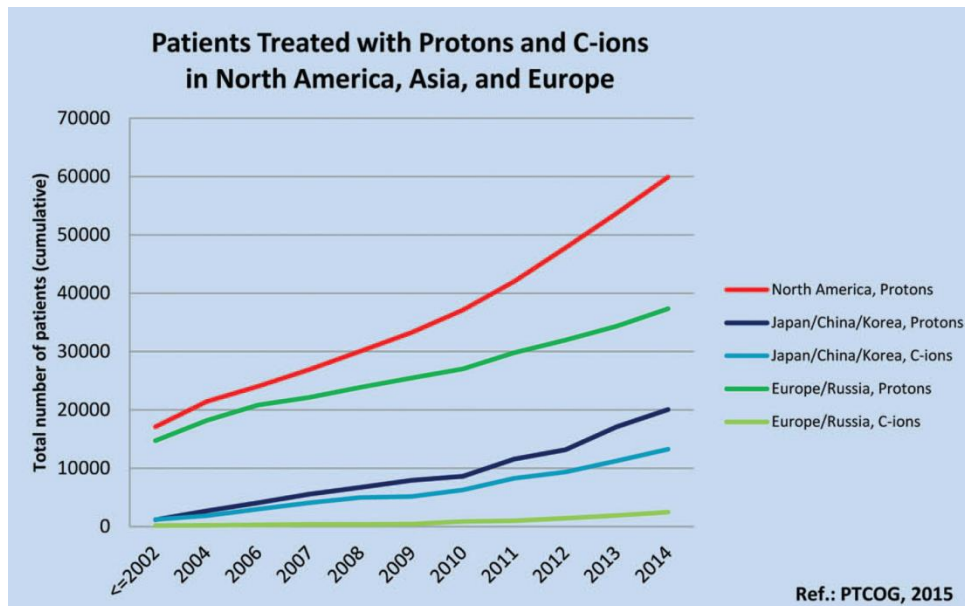
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초전도 사이클로트론 현황

- 초기~1994년 초전도 사이클로트론
 - 핵물리 실험을 위한 중이온 가속용 사이클로트론
 - 에너지의 한계
 - 섹터분리형 사이클로트론, 싱크로트론, 선형가속기
 - 1994년 이후로 개발 감소 추세
- 2006년~현재 초전도 사이클로트론
 - 입자 치료용 가속기로 각광 (주로 양성자 치료)
 - 소형화 가능한 유일한 강입자 치료용 가속기
 - 모델에 따라 다양한 빔 가속 가능 (전자석 자기장 조절)
 - 양성자 치료용 초전도 사이클로트론 시장 확대 가능성

초전도 사이클로트론 현황

- 입자치료 통계 (from PTCOG)
 - ~2014년 까지 14만여 환자 중 86%가 양성자 치료
 - 전 세계에 현재 32 개 양성자 치료센터가 건설 중
 - 20cyclotrons(6synchrocyclotron+14cyclotron)+12 synchrotron
 - 초전도 사이클로트론은 13대(65%)



He	2054	1957 - 1992
Pions	1100	1974 - 1994
C-ions	15736	1994 - present
Other	433	1975 - 1992
Protons	118195	1954 - present
Total	137179	



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초전도 사이클로트론 개발 현황

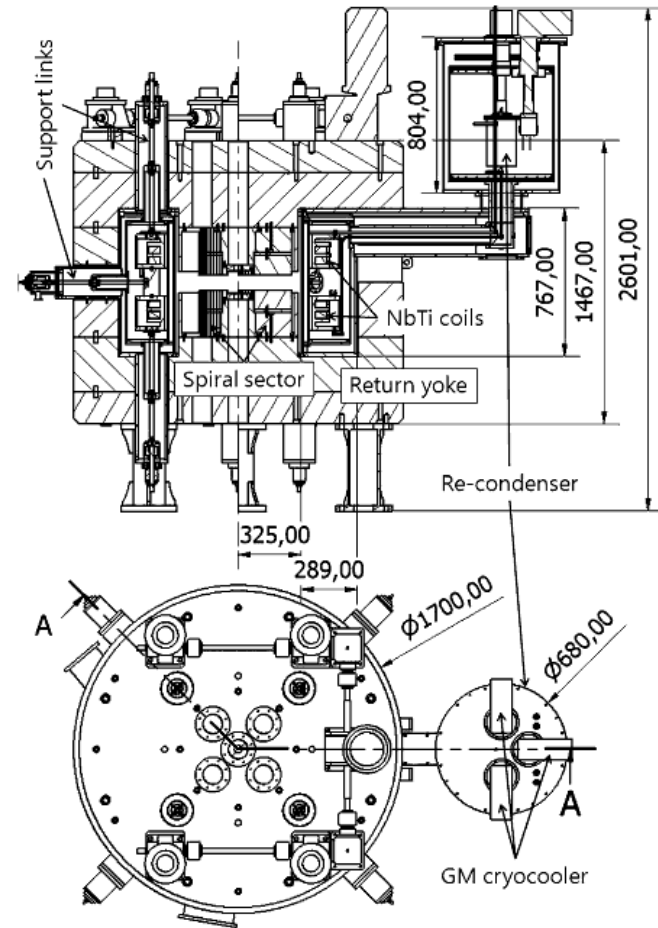
초전도 사이클로트론 개발 현황

- K22 – 한국원자력의학원
 - 2007년~2009년 설계 및 개발
 - K120 초전도 사이클로트론 개발 위한 시제품
 - $^{12}\text{C}^{2+} \sim ^{12}\text{C}^{6+}$ 이온 운전

Bending limit, K	22 MeV	Stored energy	~0.2 MJ per coil at 200 A
Particles accelerated range	$0.13 \leq Z/A \leq 0.5$	Coil installation	12 support links (vertical 8, horizontal 4)
Extraction radius	0.25 m	Field at center	2.683–2.698 T with yoke
Number of sectors	4	Field at extraction	2.696–2.705 T with yoke
Conductor	NbTi (Cu/Sc = 4.9, 35 filaments, RRR > 70, $I_c > 500$ at 5 T, W 1.4 mm, T 0.95 mm, insulated)	Cooling	LHe re-condensing type by 3 GM cryocoolers (1.5 W at 4.2 K)
Winding	Wet winding	Cryostat	4.2 K shield, 60 K shield, vacuum vessel
Coil dimension	ID 0.8 m, OD 0.92, Coil-A: H 0.035 m, 25 layer \times 63 turns \times 2 Coil-B: H 0.0364 m, 26 layer \times 63 turns \times 2	IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 20, NO. 3, JUNE 2010	
Inductance	$L_A = 9.8 \text{ H}$, $L_B = 10 \text{ H}$, $M = 9.8 \text{ H}$		

초전도 사이클로트론 개발 현황

- K22 – 한국원자력의학원



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 20, NO. 3, JUNE 2010

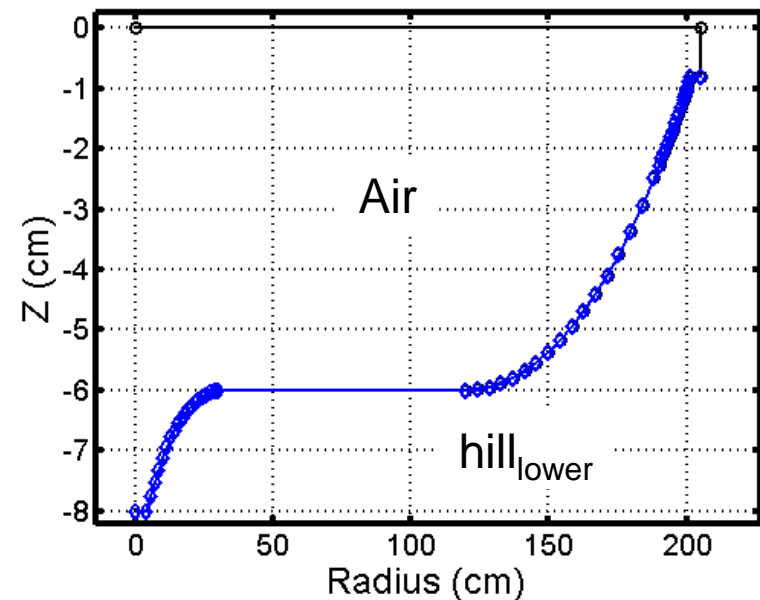
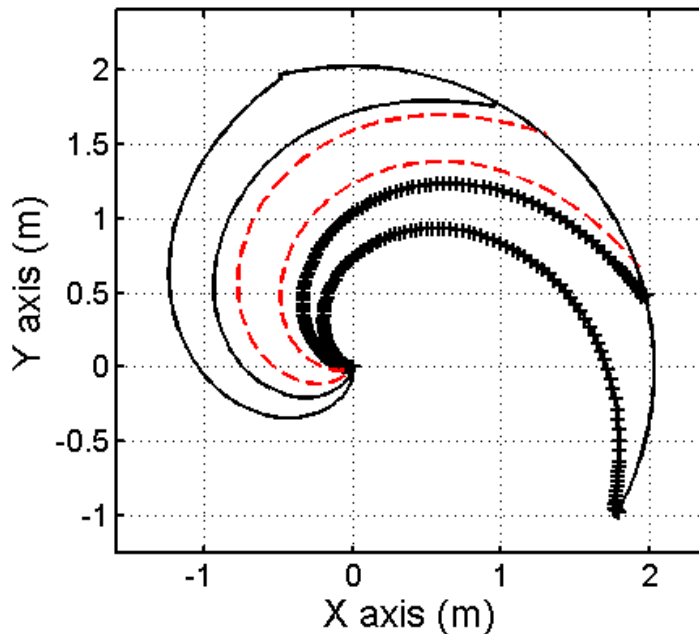
초전도 사이클로트론 개발 현황

- Kirams 430 – 2011년 ~ 2013년 한국원자력의학원

Magnetic field	<ul style="list-style-type: none">• Isochronous field, $B/B_{iso}-1 < 2 \times 10^{-4}$• Spiral field, spiral angle $< 90^\circ$• Beam tunes, $\nu_r, \nu_z > 0$• Avoidance of resonances• RF phase shift, $F(E) < 30^\circ$
SC coil	<ul style="list-style-type: none">• LHe cooled, 4.2 K• Hoop stress < 150 MPa• Quench protection
Cryostat	<ul style="list-style-type: none">• The total amount of heat penetration < 50 W

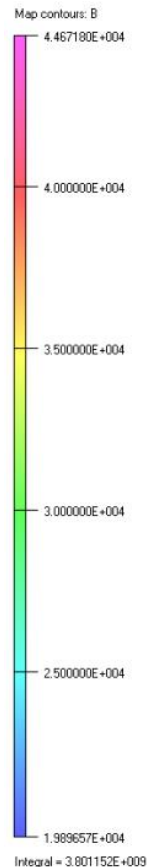
초전도 사이클로트론 개발 현황

- K430 - Spiral sector
 - Angular width : $19^\circ - 42.5^\circ$
 - Spiral angle: $0^\circ - 72.6^\circ$
 - Hill gap: 16 cm (max.) – 1.6 cm (min.)



초전도 사이클로트론 개발 현황

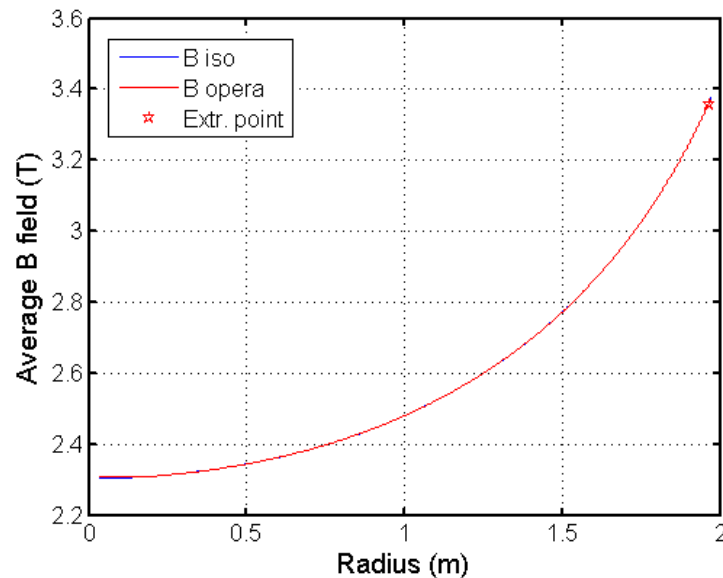
- K430 - Magnetic field distribution in mid-plane



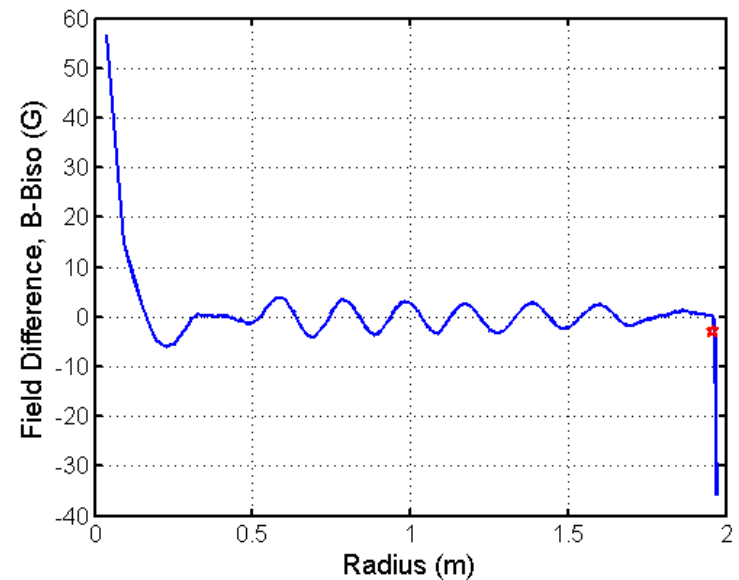
1.99 T < Bz < 4.47 T

초전도 사이클로트론 개발 현황

- K430 - Magnetic field distribution in mid-plane



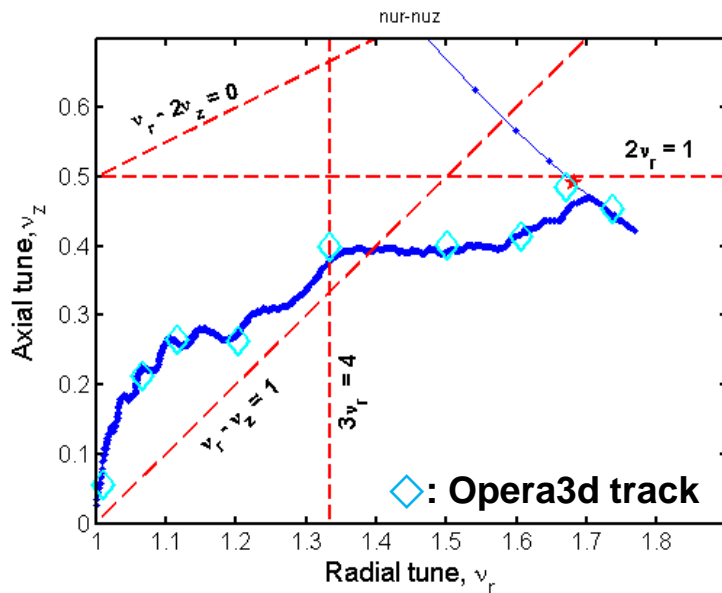
B0 = 2.3034 T



$\Delta B < \pm 5\text{G}$ after central region

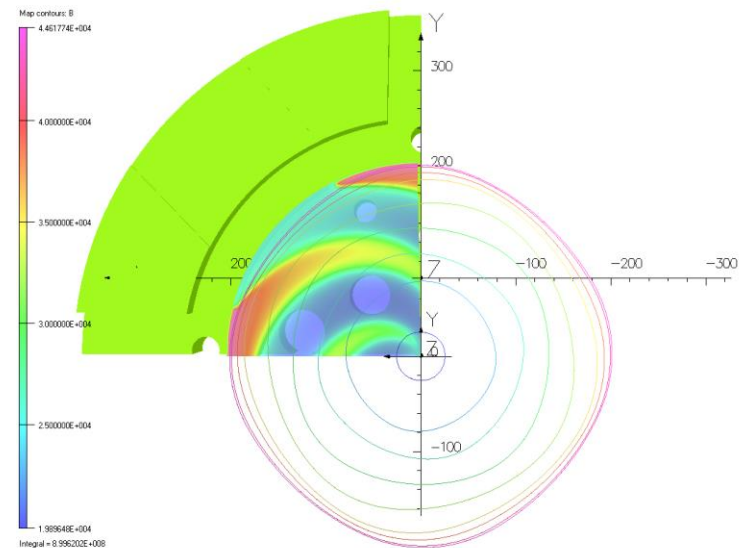
초전도 사이클로트론 개발 현황

- K430 - Beam stability (tune & working diagram)



Dangerous resonances

- $3v_r = 4$: radial beam blow up (Bz1)
- $v_r - v_z = 1$: axial beam blow up (Br1)
- $2v_r = 1$: axial beam blow up (Br)

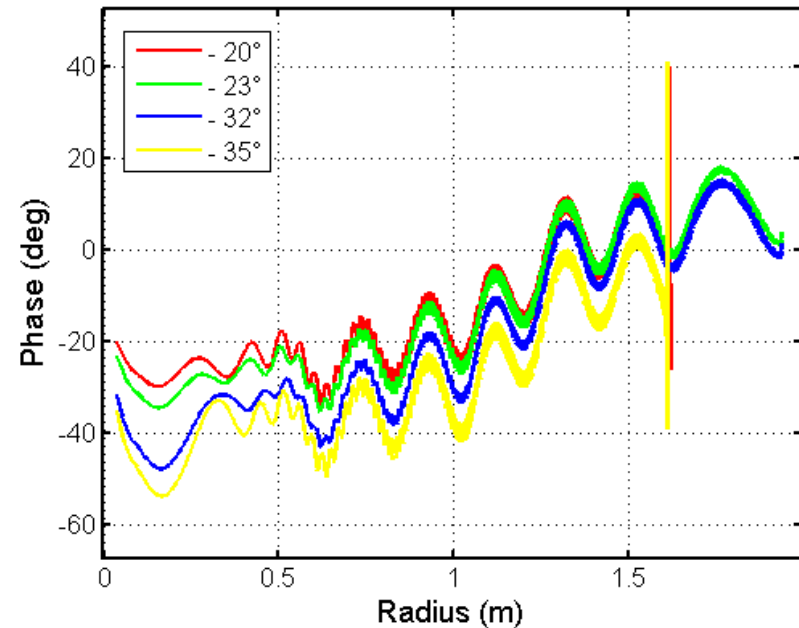
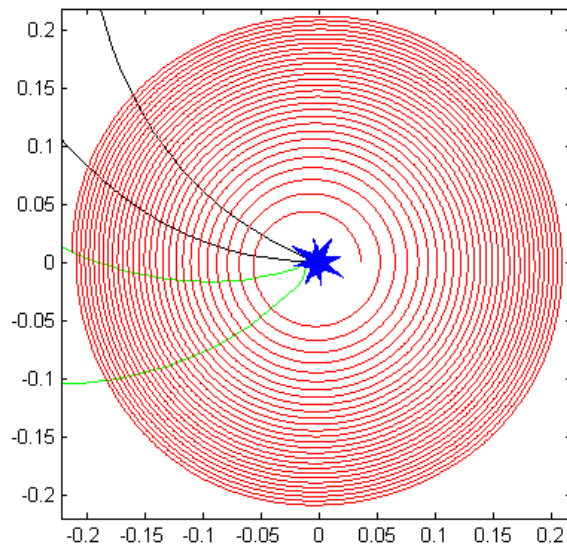


EO tracking in Opera3d

opera
simulation software

초전도 사이클로트론 개발 현황

- K430 - Single particle tracking(cyclone)

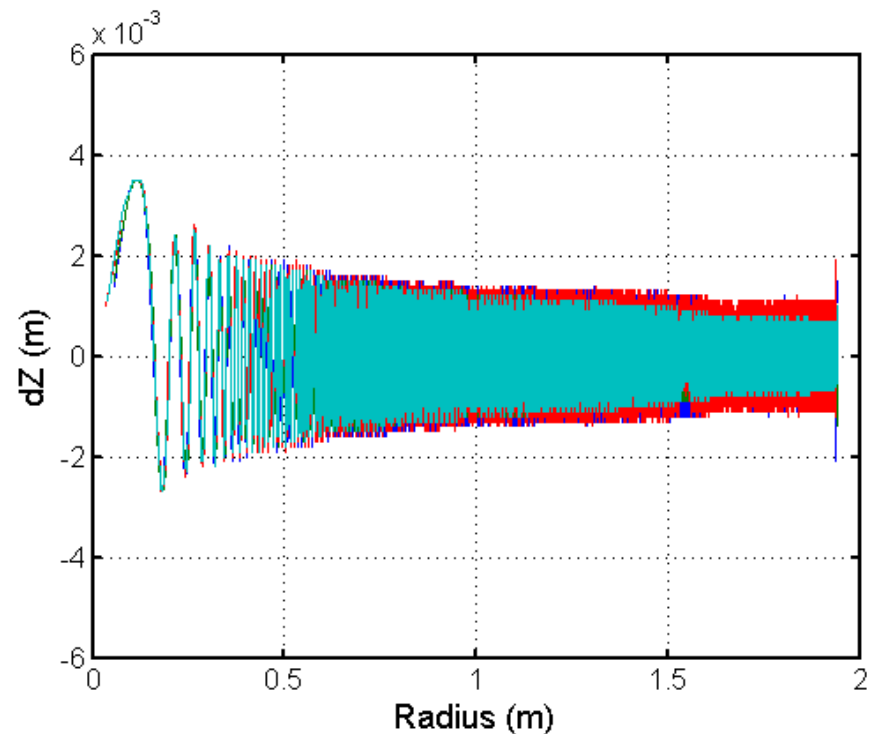
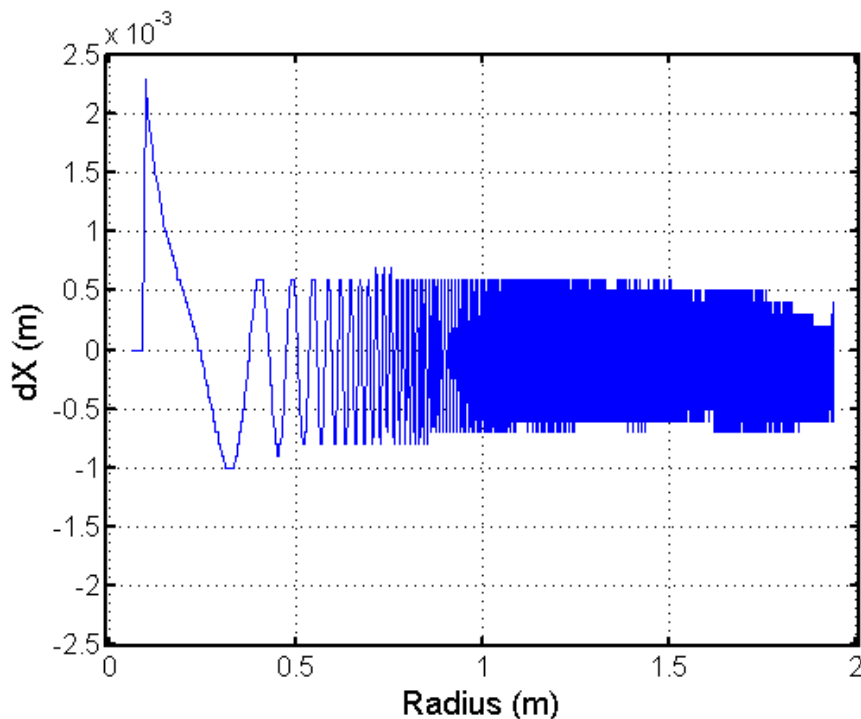


Calculation condition

- 1 MeV – 5160 MeV (2648 turns)
- Vdee= 70 kV, 70 – 140 kV ($R > 1.2\text{m}$)
- Adee = 30°

초전도 사이클로트론 개발 현황

- K430 - Single particle tracking (cyclone)



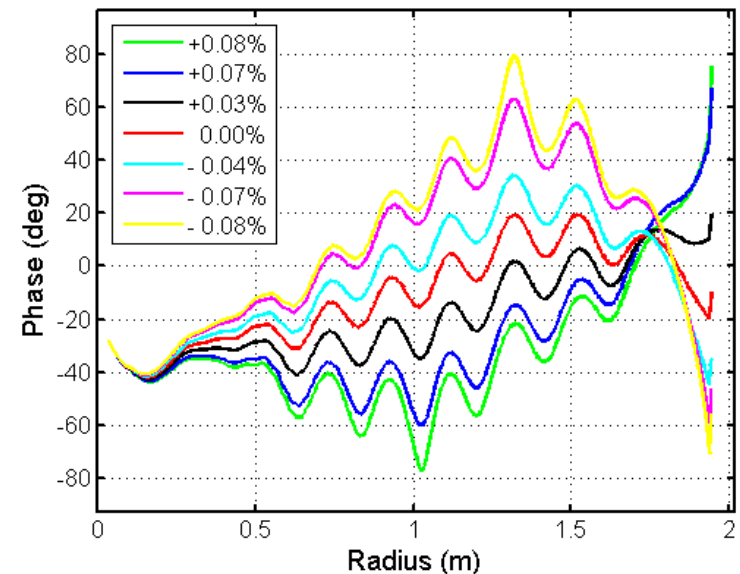
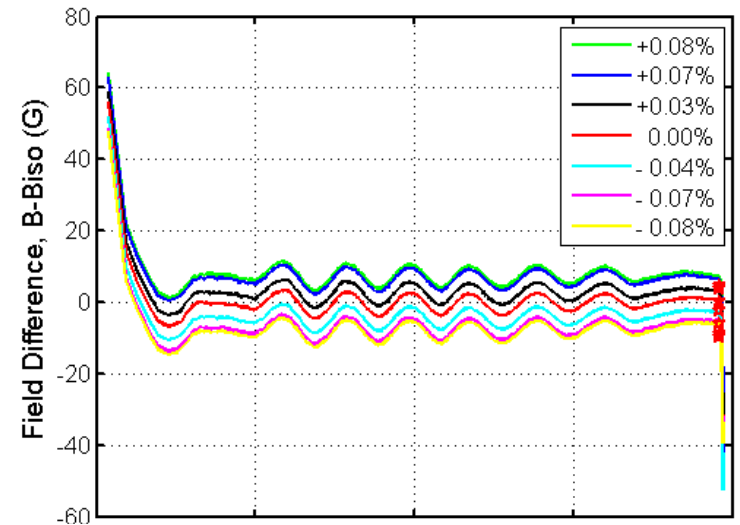
Radial & axial beam motion from 1 MeV to 5160 MeV at the acceleration gap

초전도 사이클로트론 개발 현황

● K430 - Operating current variation

- f_{RF} shift range: $< \pm 80$ deg
- I_{op} (A): 458.388 ± 0.367 (± 800 ppm)
- B_0 (T): $2.30264 \leq 2.30330 \leq 2.30397$ (13.3 G)
- f_{RF} (MHz): $70.73855 \leq 70.7589 \leq 70.77953$ (40.98 kHz)

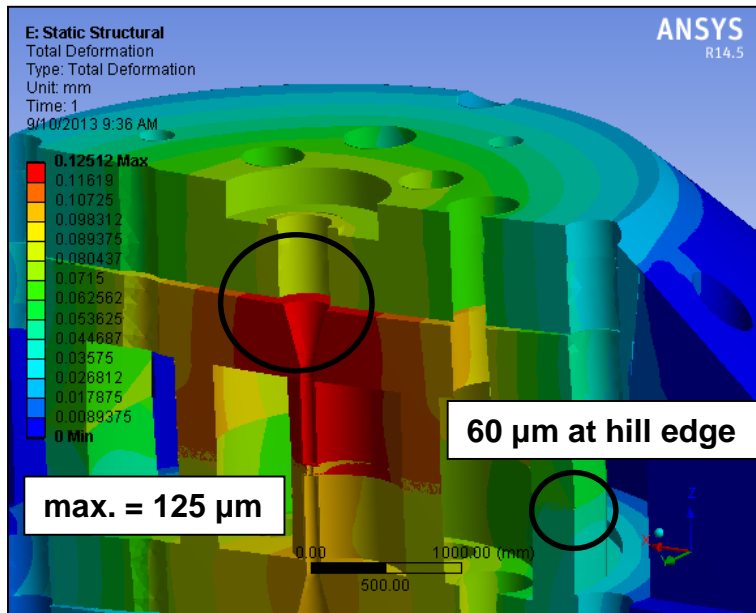
	Current (A)	B_0 (T)	f_{RF} (MHz)	#. of Turns
+0.0800%	458.755	2.30397	70.77953	3465
+0.0700%	458.709	2.30389	70.77707	3105
+0.0300%	458.526	2.30355	70.76662	2726
0.0000%	458.388	2.30330	70.75890	2648
-0.0400%	458.205	2.30296	70.74850	2721
-0.0700%	458.067	2.30272	70.74107	3090
-0.0800%	458.022	2.30264	70.73855	3501



초전도 사이클로트론 개발 현황

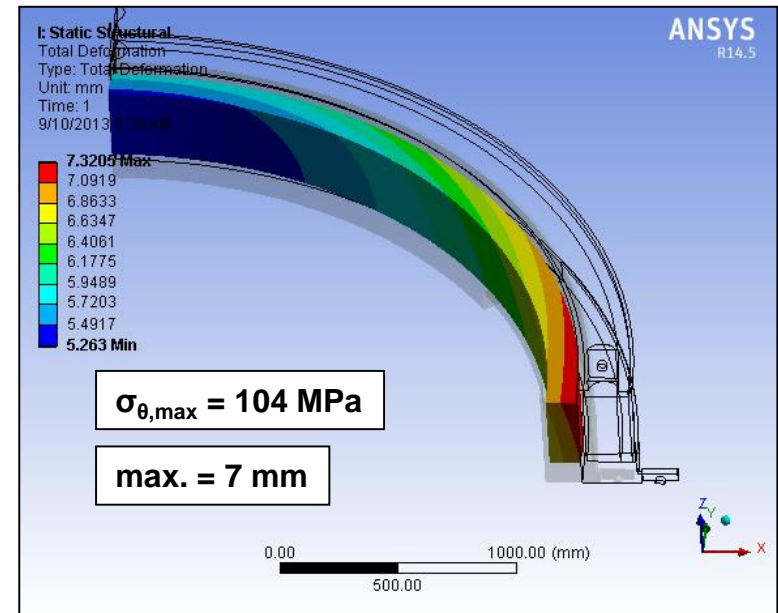
- K430 - Misalignment & Deformation effect

Gravity, mass and magnetic force



Four pieces top yoke plate model

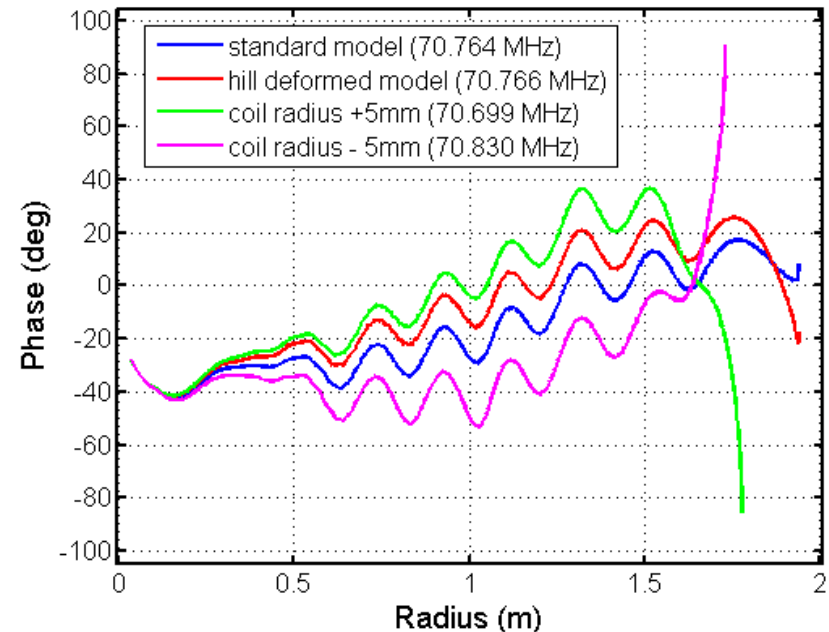
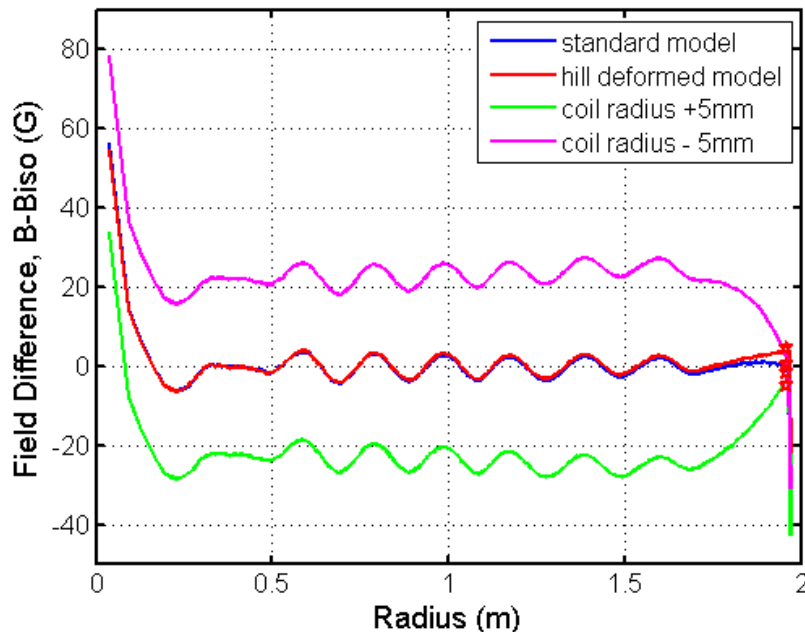
Thermal contraction & hoop stress



by Dr. Hong

초전도 사이클로트론 개발 현황

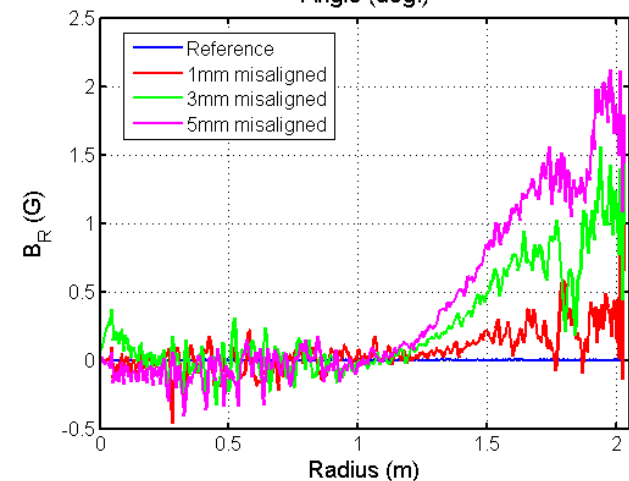
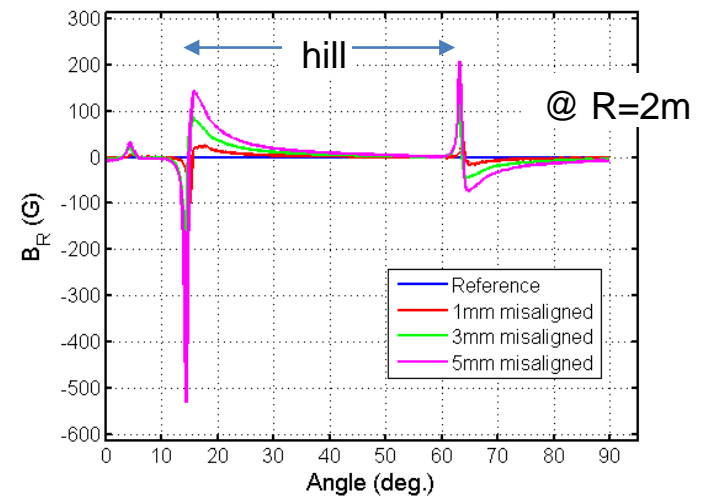
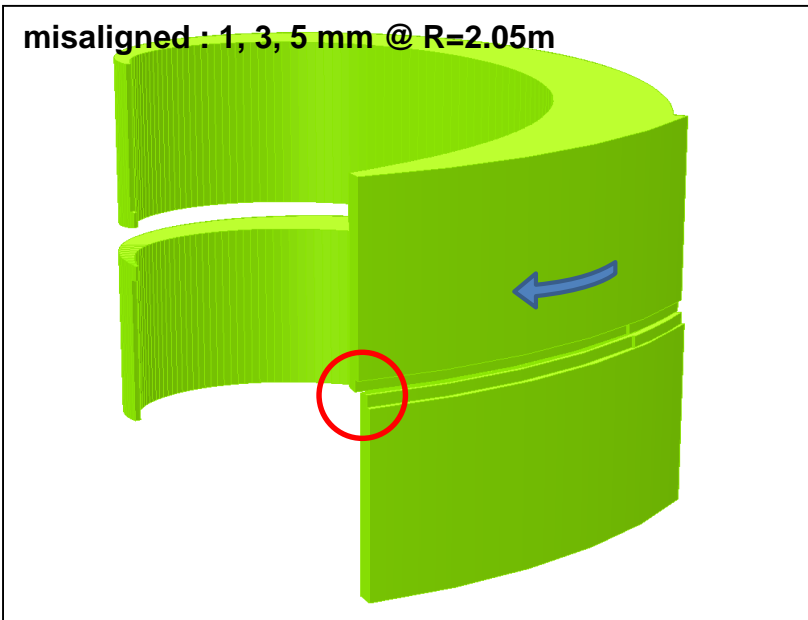
- K430 - Deformation effect
 - Increased & decreased coil radius by 5 mm
 - Decreased hill gap by 200 μm



초전도 사이클로트론 개발 현황

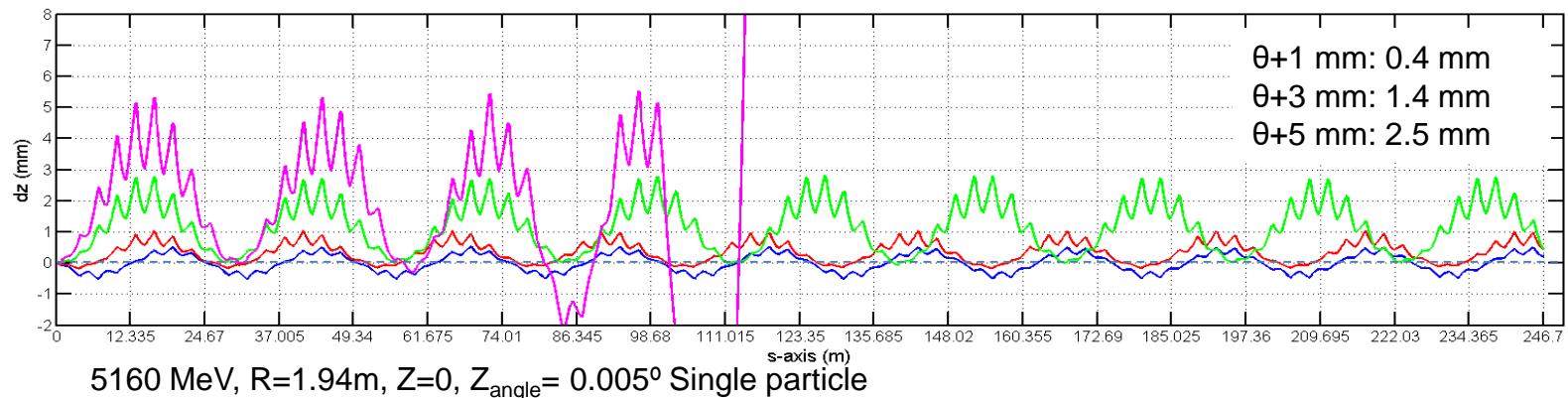
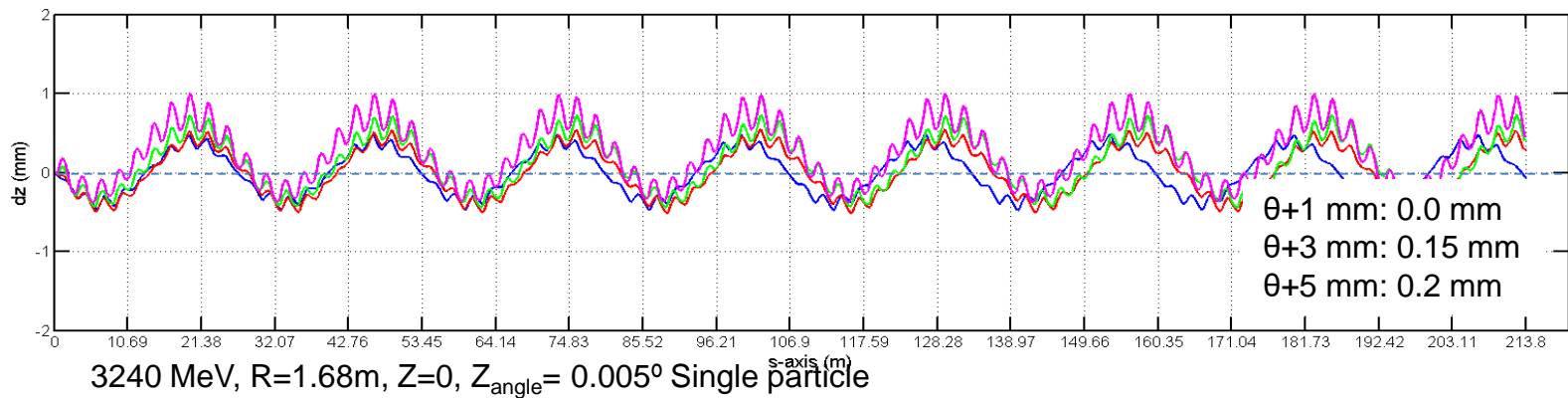
- Misaligned sector effect

misaligned : 1, 3, 5 mm @ R=2.05m



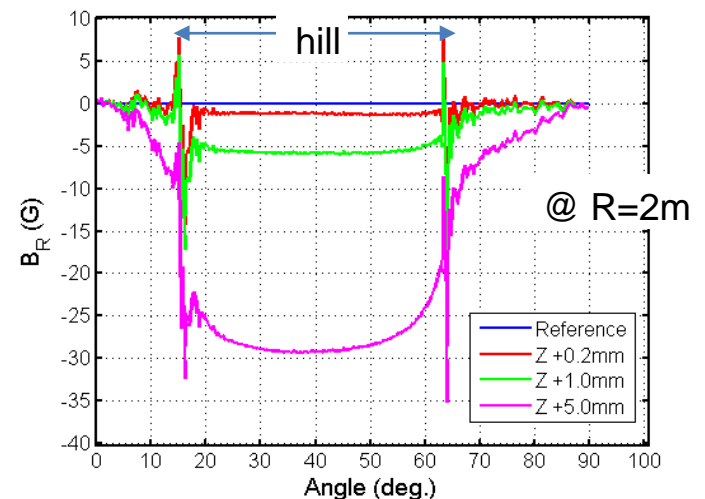
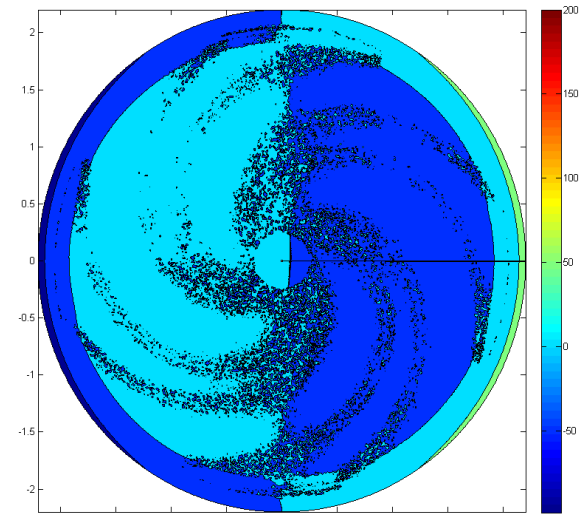
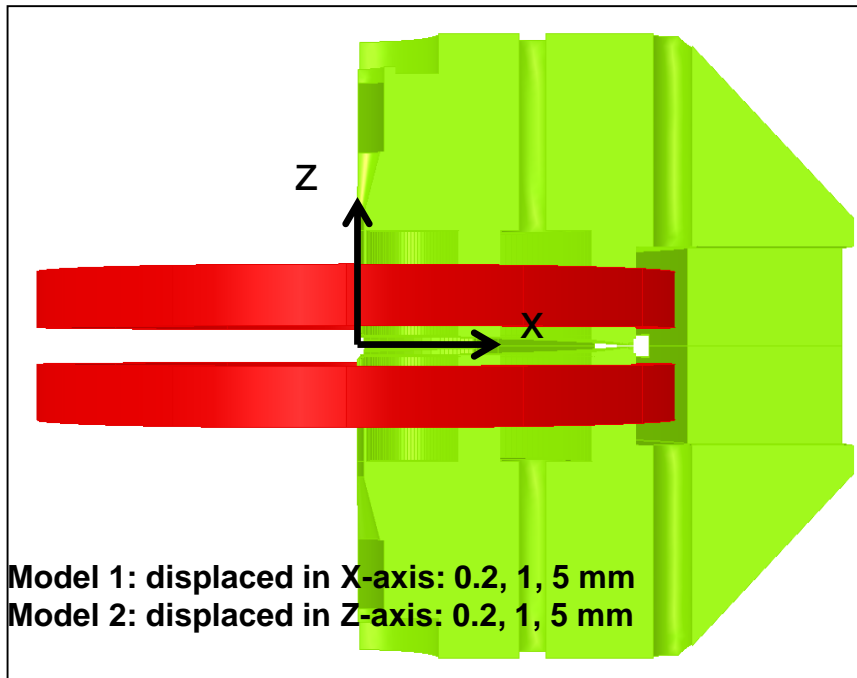
초전도 사이클로트론 개발 현황

- K430 - Misaligned sector effect



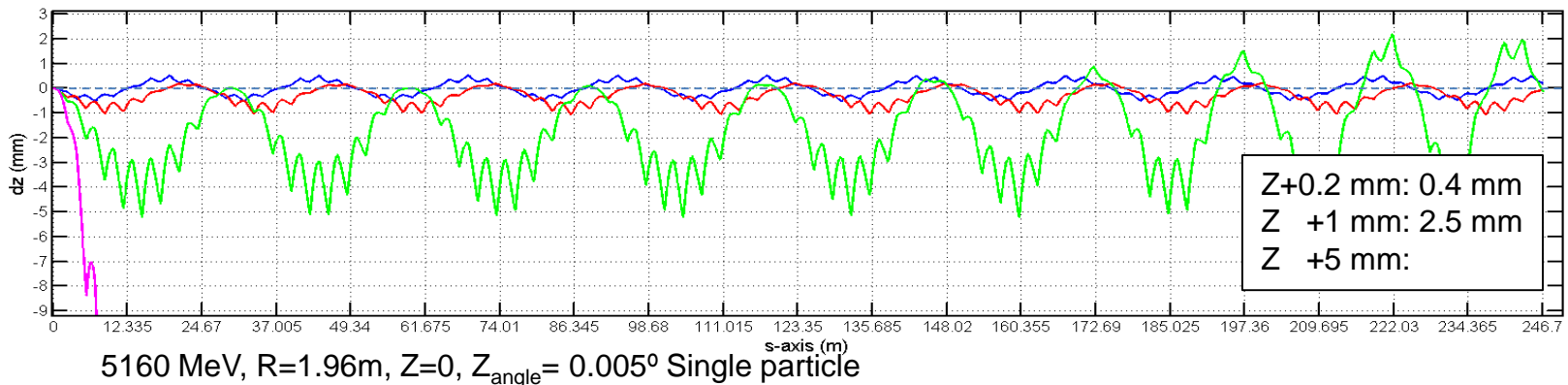
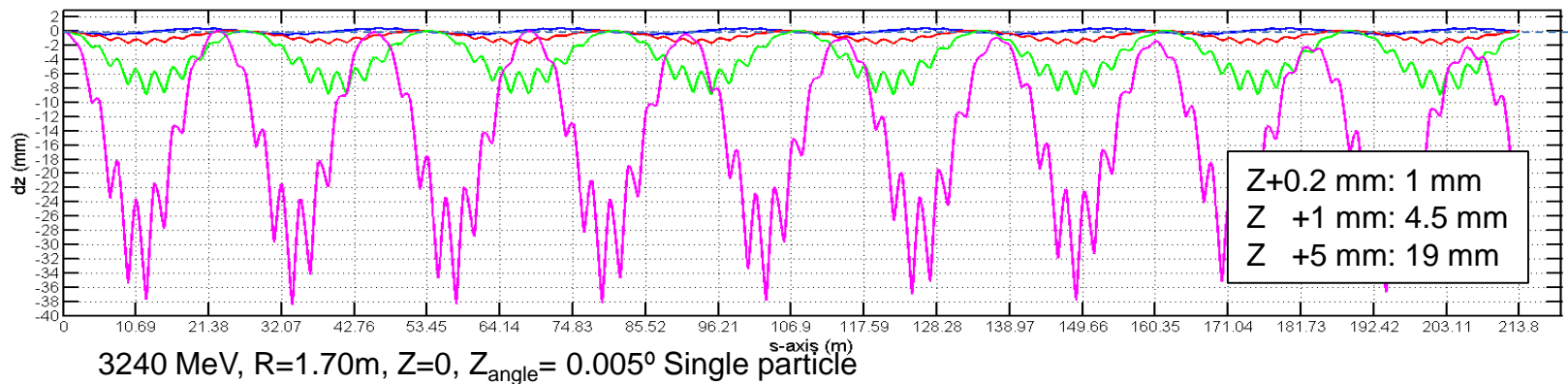
초전도 사이클로트론 개발 현황

- Misaligned coil effect



초전도 사이클로트론 개발 현황

- K430 - Misaligned coil effect



Magnet yoke parts view

U Yoke plate part 1, 69.2

U Yoke plate part 2, 77.1

U Yoke plate part 3, 67.9

U Yoke plate part 4, 72.0

U Four sectors

Side yoke, <21.8

L Shimming hill

L Big hill, 5.4

L Yoke plate part 4

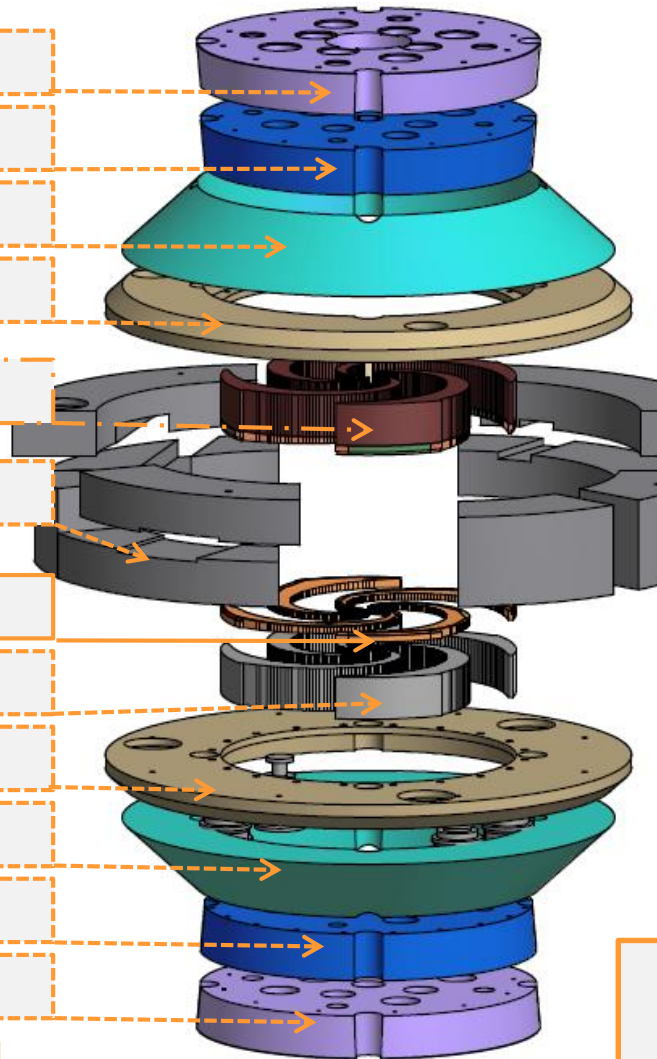
L Yoke plate part 3

L Yoke plate part 2

L Yoke plate part 1

Casting

Forging

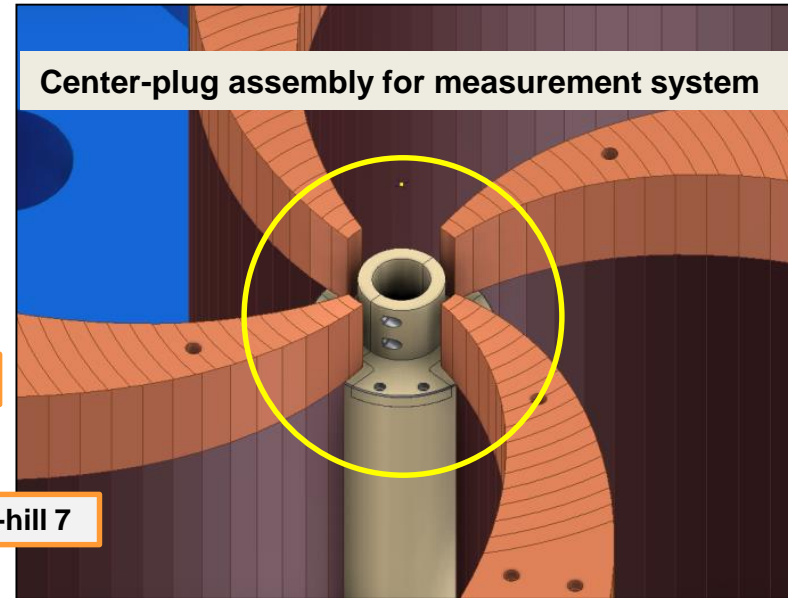
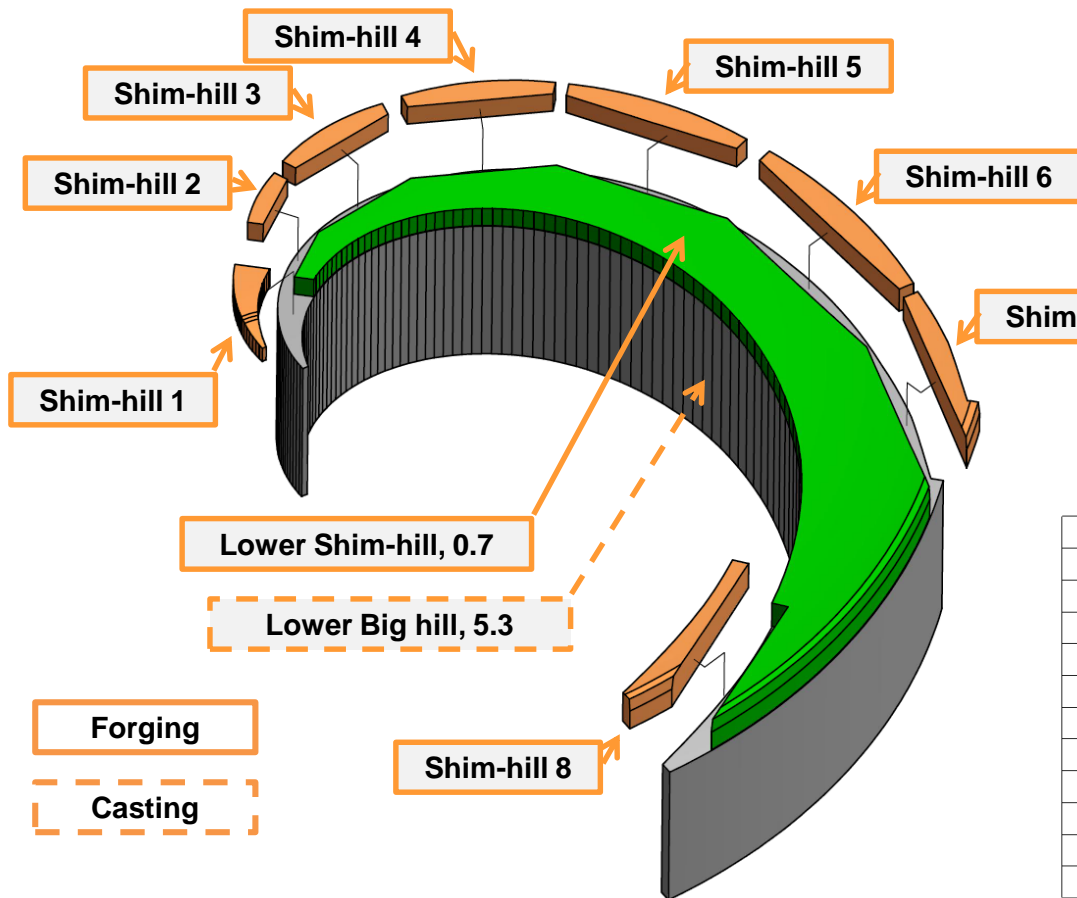


부품 리스트				
항목	수량	부품 번호	설명	질량
1	1	yoke_bot3_assem		286354 kg
2	1	yoke_center		35 kg
3	4	Sector Assem Lower		6216 kg
4	4	Sector Assem Upper		6216 kg
5	1	yoke_top3_assem		286354 kg
7	1	yoke_sideAA		12565 kg
8	1	yoke_sideB		21786 kg
9	1	yoke_sideB_MIR		21613 kg
10	1	yoke_sideD		20859 kg
11	1	yoke_sideEA		18040 kg
12	1	yoke_sideEA_MIR		18040 kg
14	3	BigLiftCyliner		2017 kg
15	3	BigLiftRod2		3808 kg
16	1	yoke_sideG		3108 kg
17	1	yoke_sideG_MIR		3108 kg
18	1	yoke_sideH		3032 kg
19	1	yoke_center_assy		35 kg

Total magnet yoke weight: ~820 ton

Total SC magnet weight: 860 ton

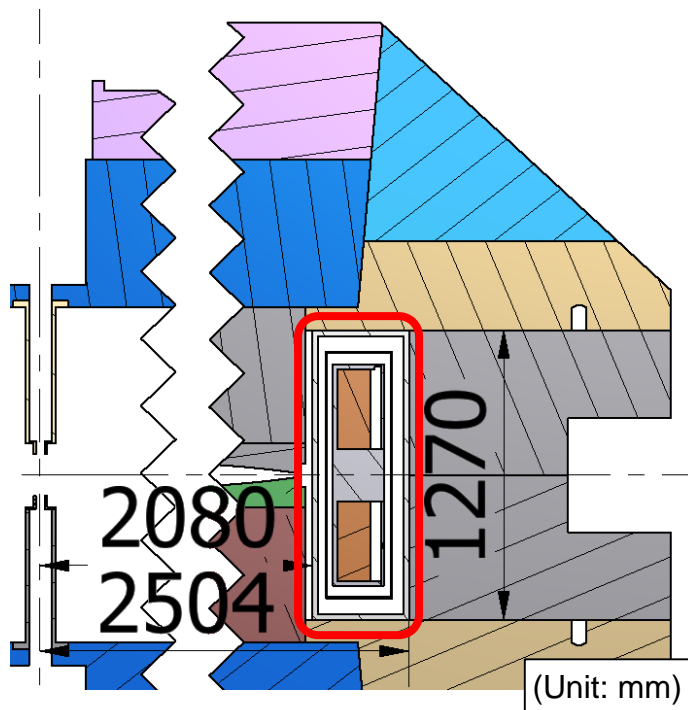
Spiral hill structure for field correction



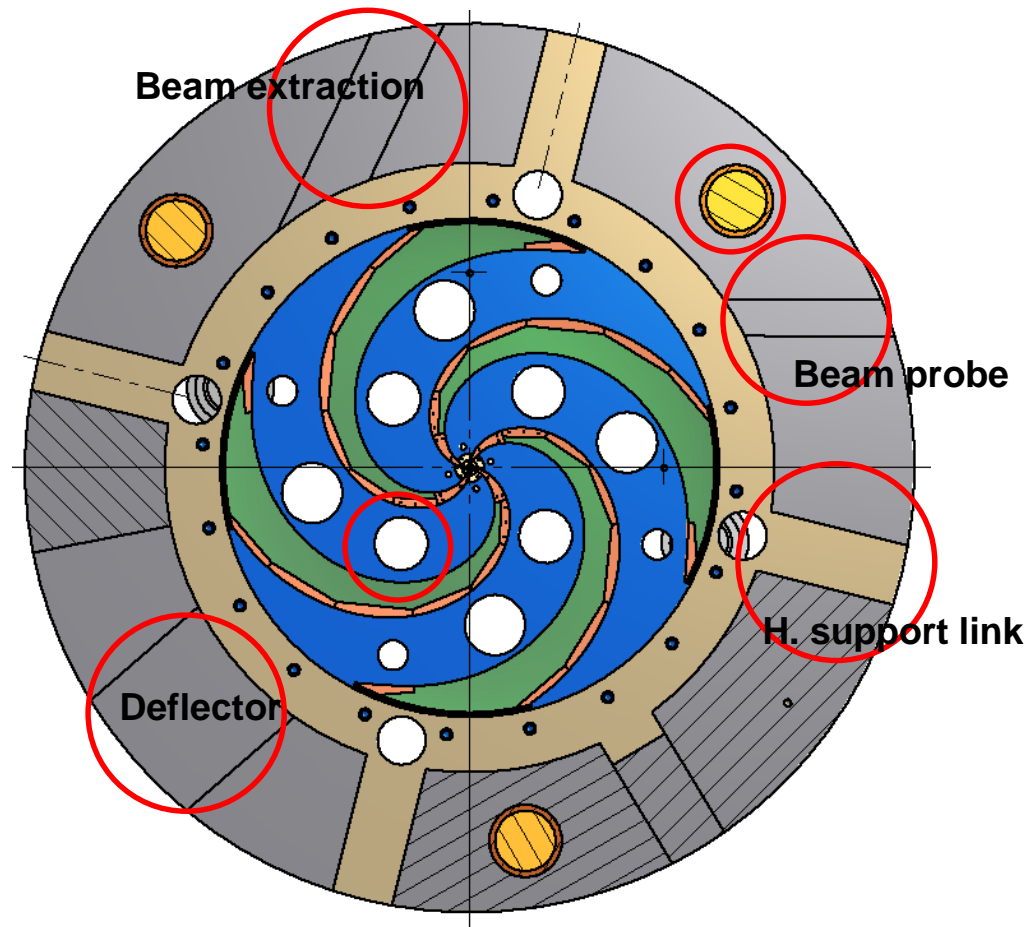
부품 리스트				
항목	수량	부품 번호	설명	질량
1	1	Sector hill big		5354.624 kg
2	1	Sector hill shim big		660.841 kg
3	1	Sector hill shim pt01		13.253 kg
4	1	Sector hill shim pt02		15.594 kg
5	1	Sector hill shim pt03		17.048 kg
6	1	Sector hill shim pt04		21.228 kg
7	1	Sector hill shim pt05		32.705 kg
8	1	Sector hill shim pt06		34.150 kg
9	1	Sector hill shim pt07		32.009 kg
10	1	Sector hill shim pt08		34.121 kg

Rooms for other systems

- Cryostat
- Support links for SC coil
- Lifting system(Hydraulic / screw jack)
- RF cavity
- Vacuum system
- Beam extraction system
- Beam probe

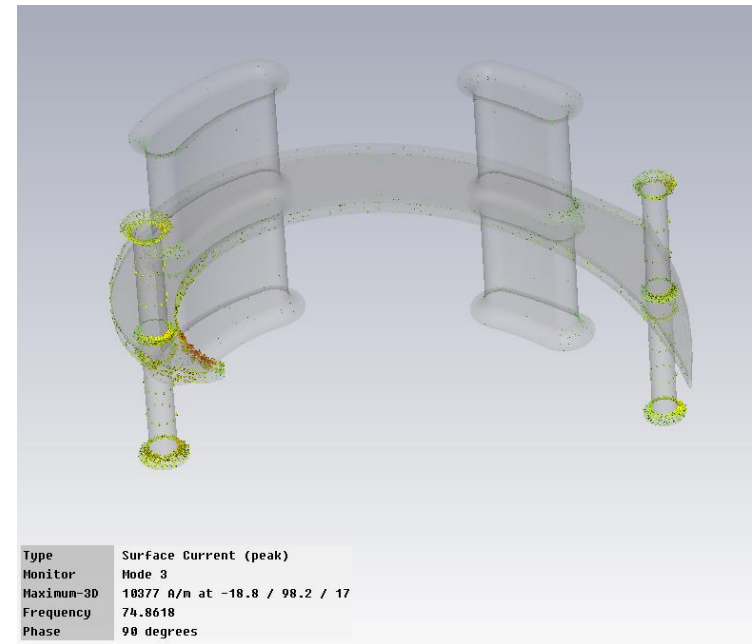
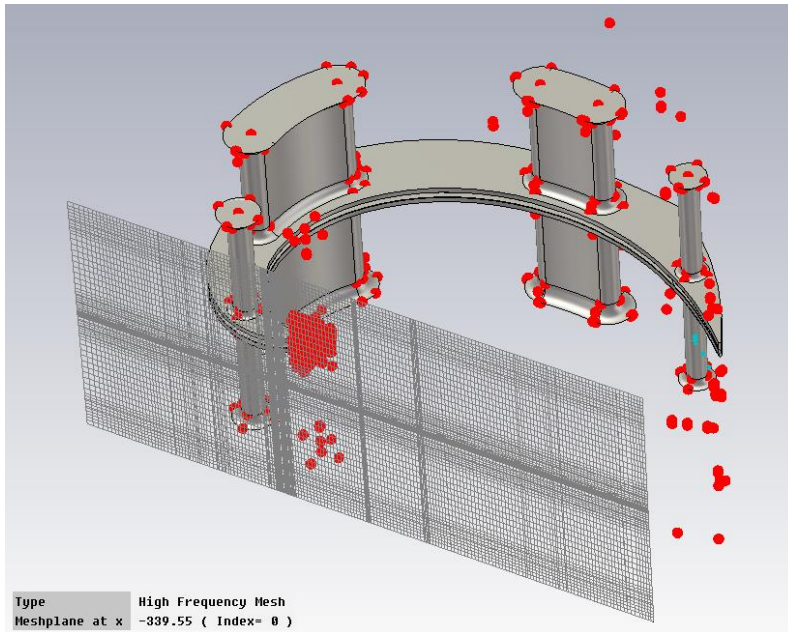


Room for cryostat & its dimension



초전도 사이클로트론 개발 현황

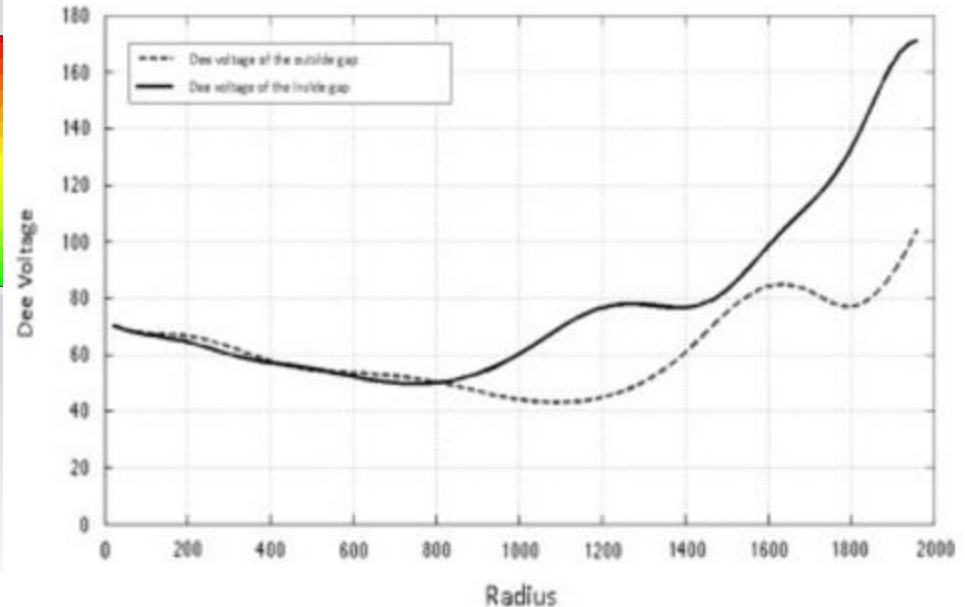
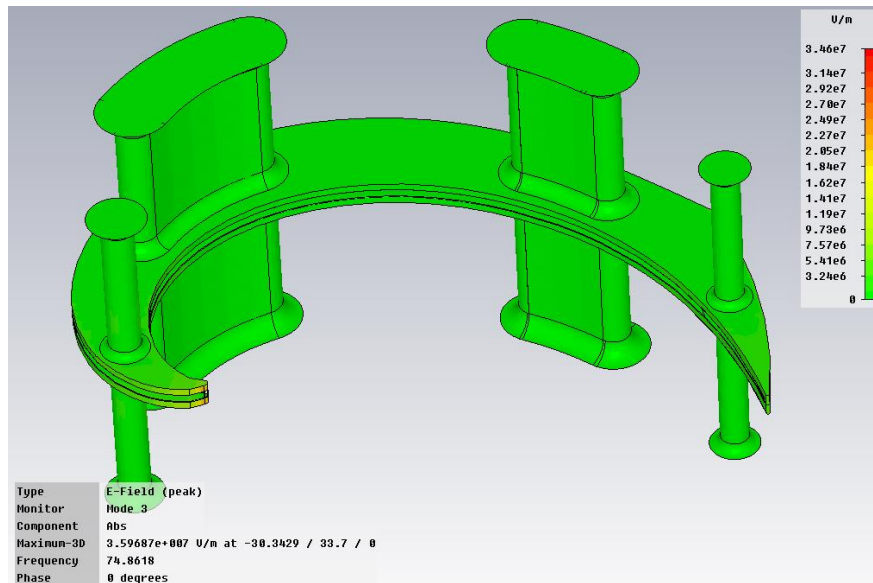
- K430 – CST analysis



Nuclear Instruments and Methods in Physics Research Section A, Vol 777, P199-201

초전도 사이클로트론 개발 현황

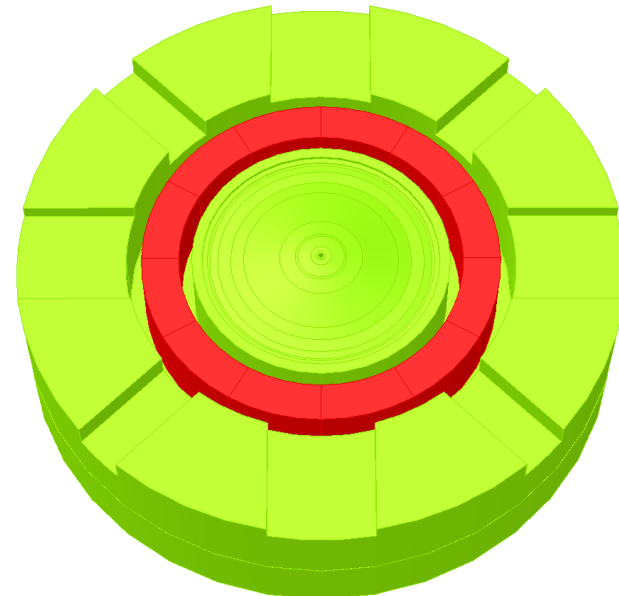
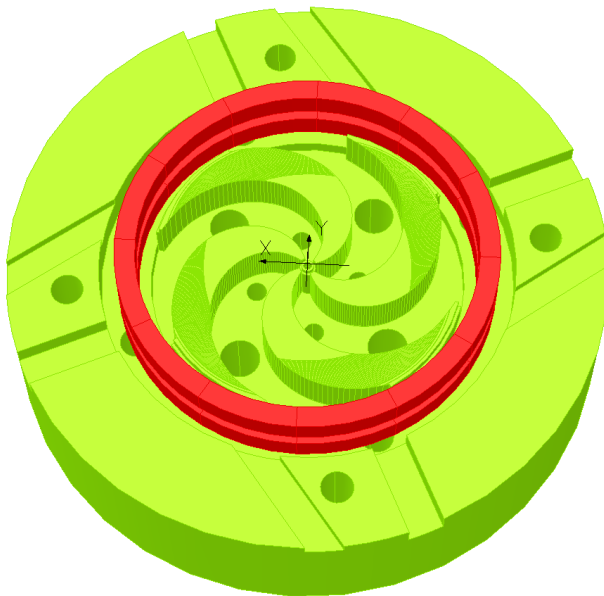
- K430 – CST analysis



Nuclear Instruments and Methods in Physics Research Section A, Vol 777, P199-201

초전도 사이클로트론 개발 현황

- SKKU 250 – 2014 ~ 현재 설계 진행
 - Sector-focused isochronous cyclotron & synchrocyclotron
 - 전자석 설계 완료 후 빔 시뮬레이션 수행

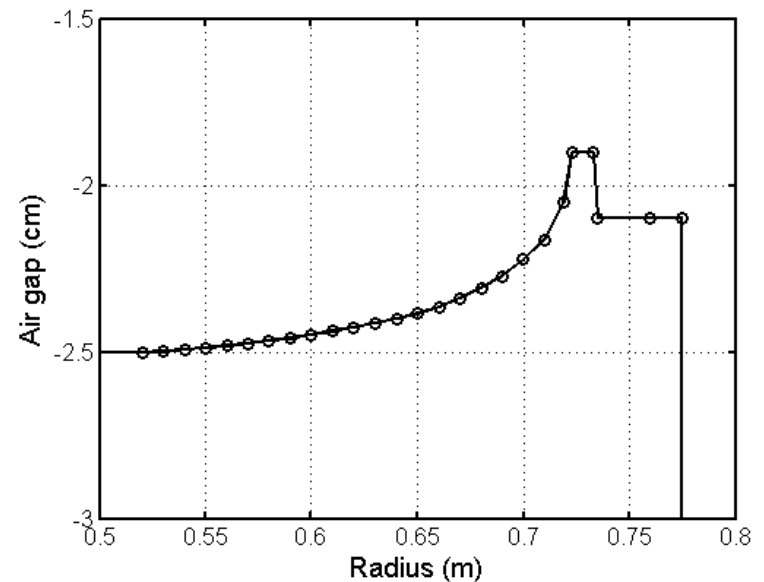
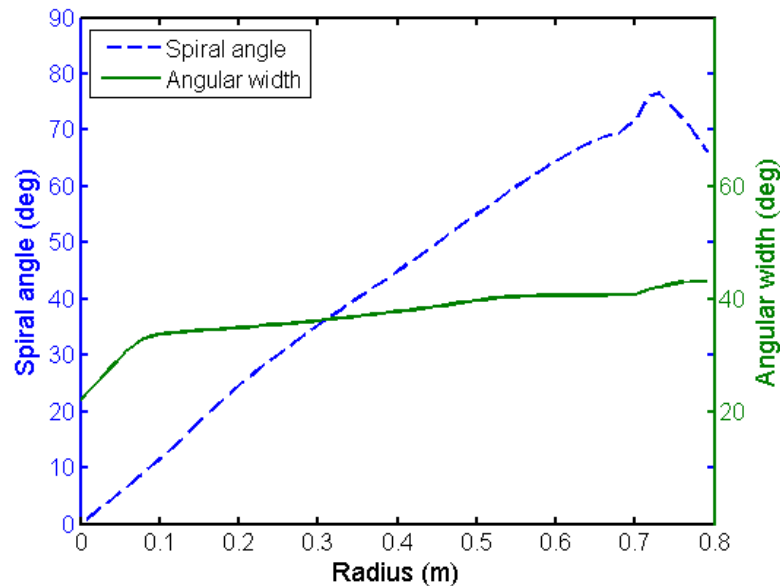


초전도 사이클로트론 개발 현황

Parameters	Sector focused isochronous cyclotron	Synchrocyclotron
Max. energy	244 MeV	239.5 MeV
Magnet dimension	H 1.7 m, D 3.0 m	H 1.65 m, D 2.35 m
Yoke weight	Approx. 79.4 tons	Approx. 46.2 tons
Pole radius	0.775 m	0.5 m
No. of sectors	4	0
Air gap size	Hill 0.038 m, Valley 0.52 m	0.04 m
Magnetic field range	2.04 T - 4.01 T	3.74 T - 5.55 T
Coil dimension	H 10.2 cm, V 13.0 cm	H 14.4 cm, V 26.0 cm
Current density	3970 A/cm ²	3700 A/cm ²
RF frequency	78.8 MHz	84.43 MHz - 60.35 MHz
RF harmonic	2nd harmonic	1st harmonic
No. of dees	2	1
Dee voltage	Approx. 70 kV - 140 kV	Approx. 15kV - 20 kV

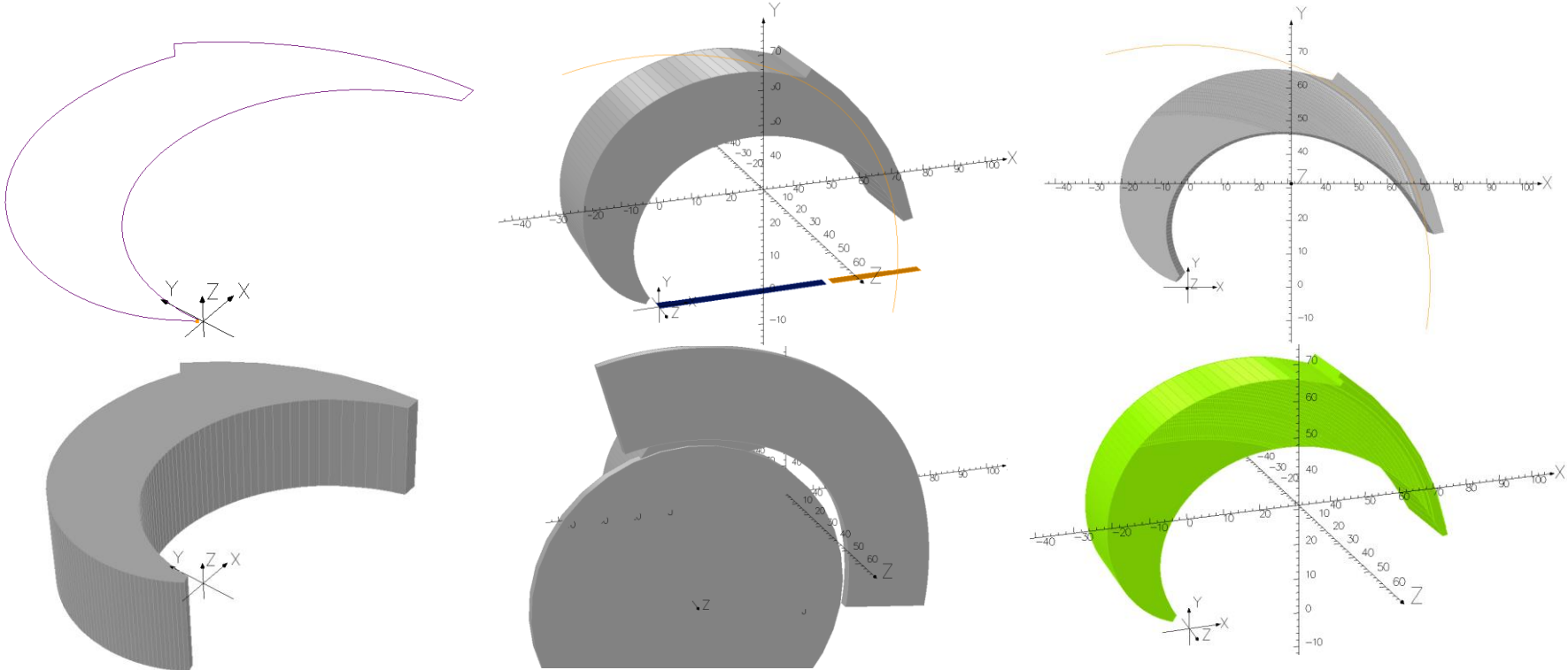
초전도 사이클로트론 개발 현황

- SKKU 250 – 섹터 설계



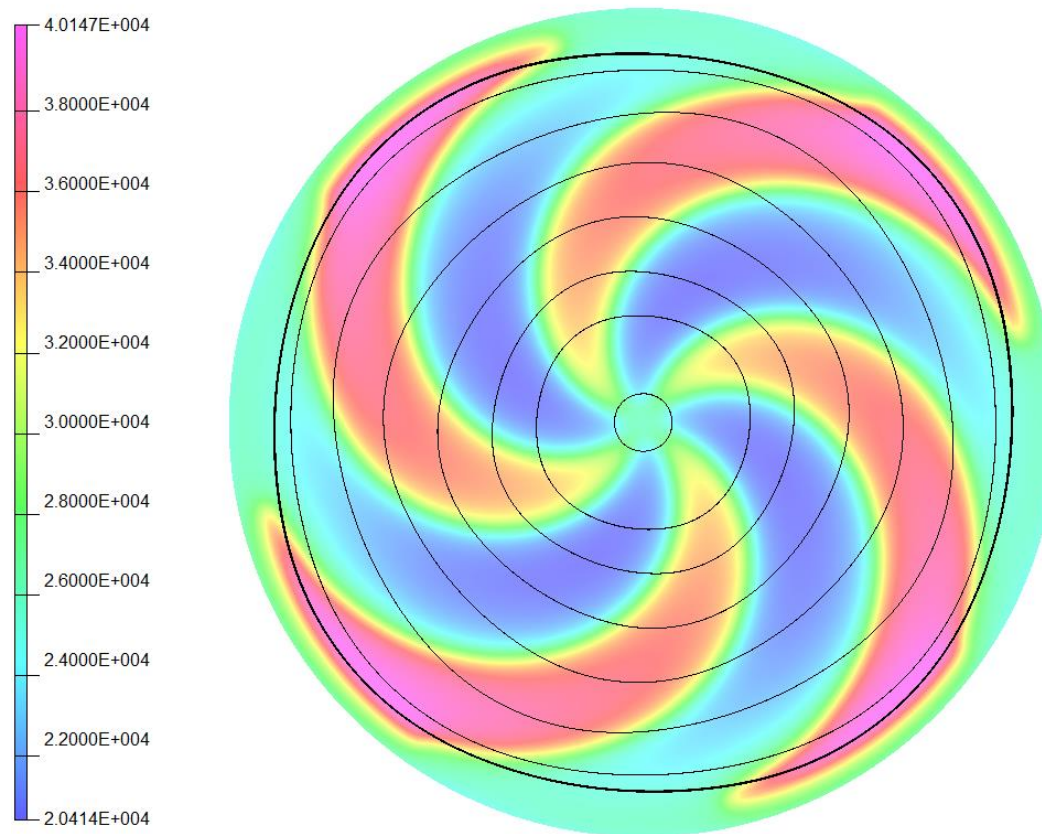
초전도 사이클로트론 개발 현황

- SKKU 250 – 섹터 설계
 - 섹터 DATA 파일에서 자동으로 모델 작성 COMI 코드
 - 공극 단면을 240 MeV EO를 따라 회전



초전도 사이클로트론 개발 현황

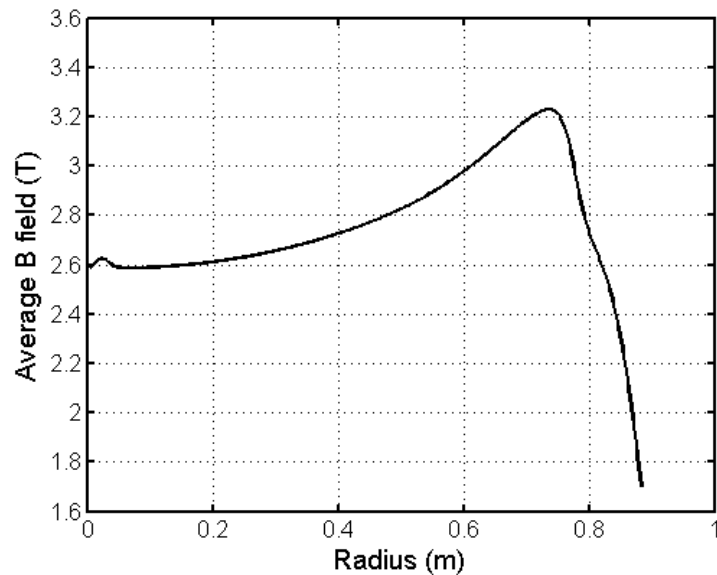
- SKKU 250 – 중심면 자기장



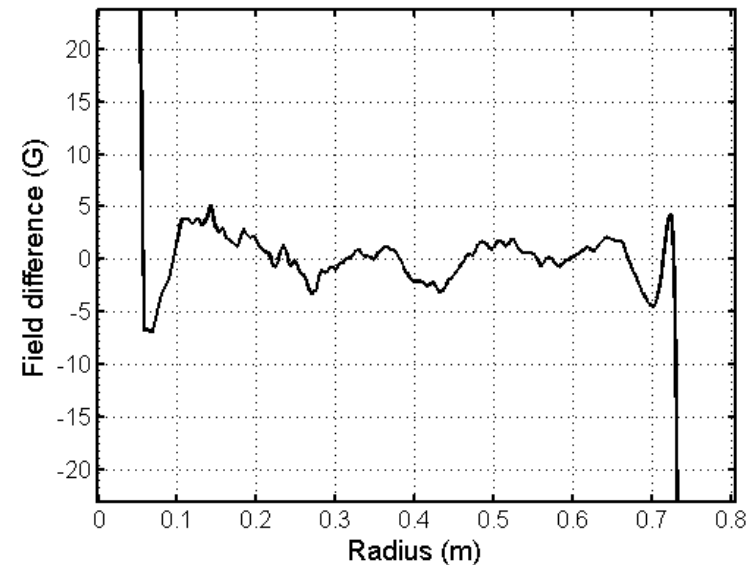
2.04 T < Bz < 4.01 T

초전도 사이클로트론 개발 현황

- SKKU 250 – 중심면 자기장



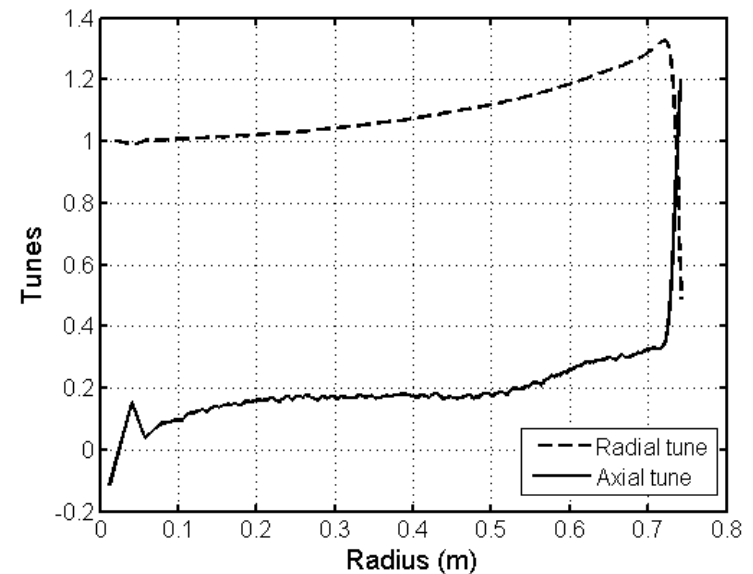
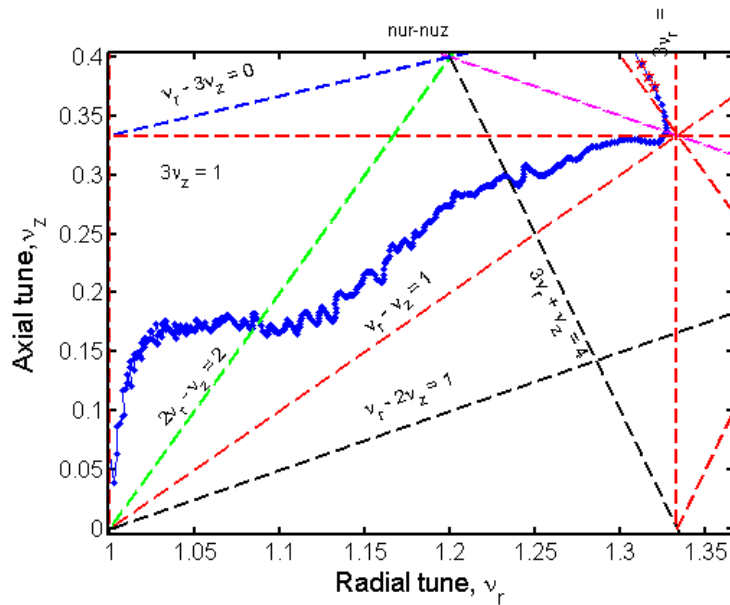
$B_0 = 2.59 \text{ T}$



$\Delta B < \pm 5 \text{ G}$ after central region

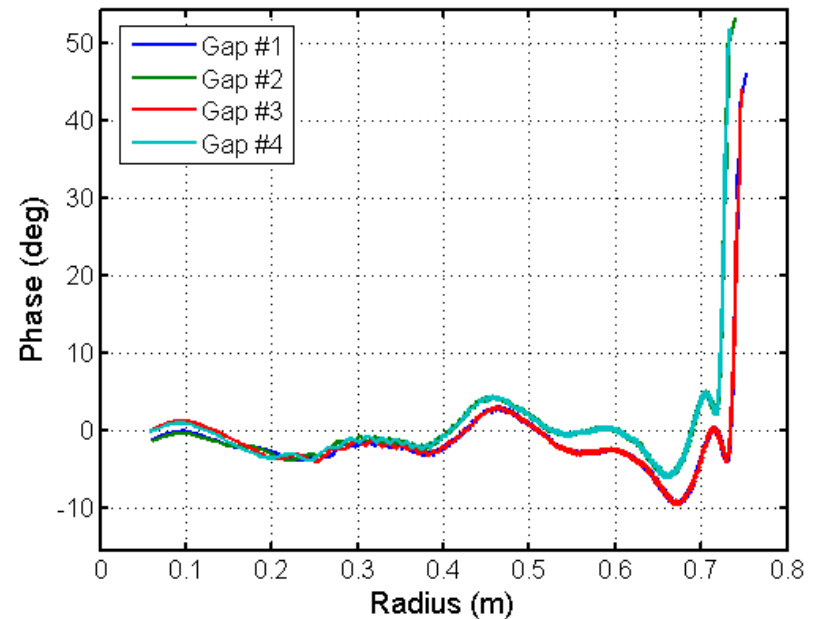
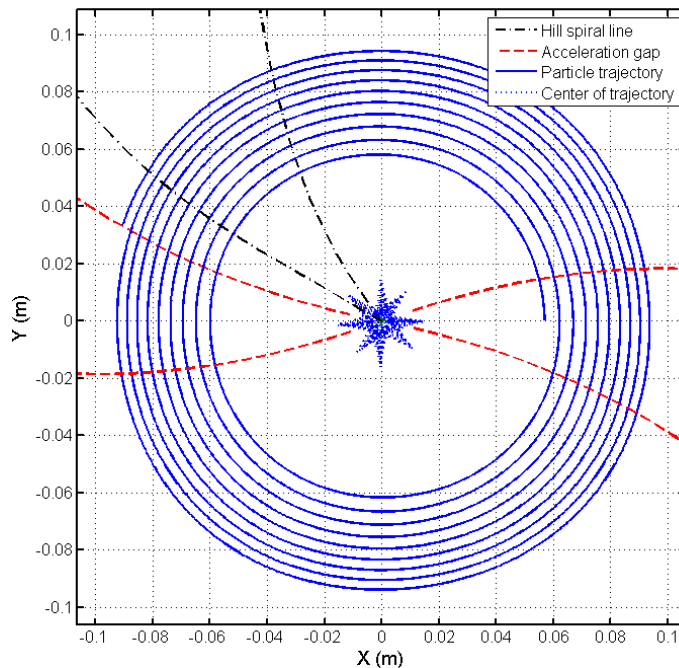
초전도 사이클로트론 개발 현황

- SKKU 250 – 빔 안정도, working diagram



초전도 사이클로트론 개발 현황

- SKKU 250 – Single particle tracking(cyclone)

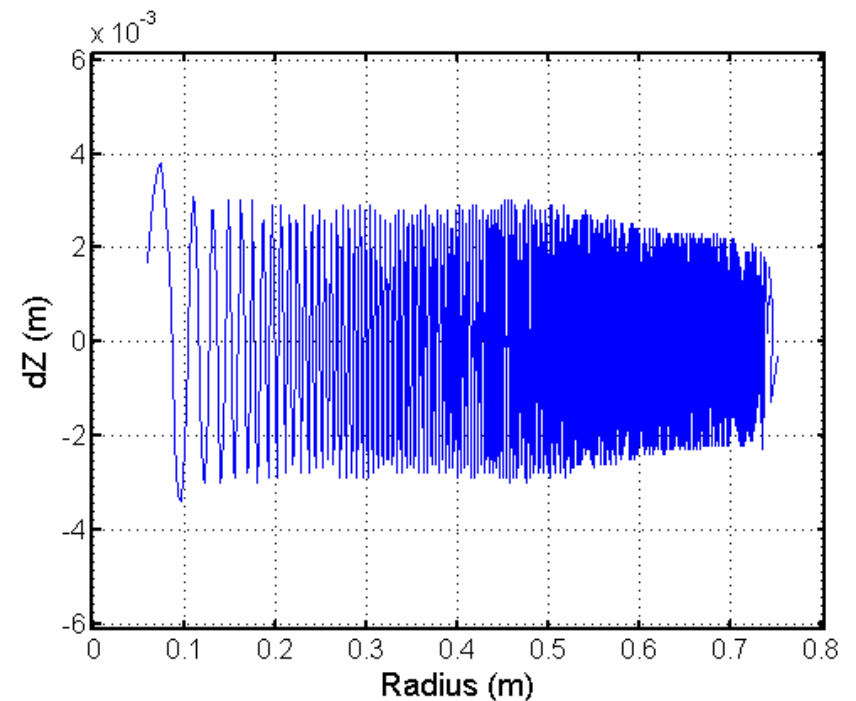
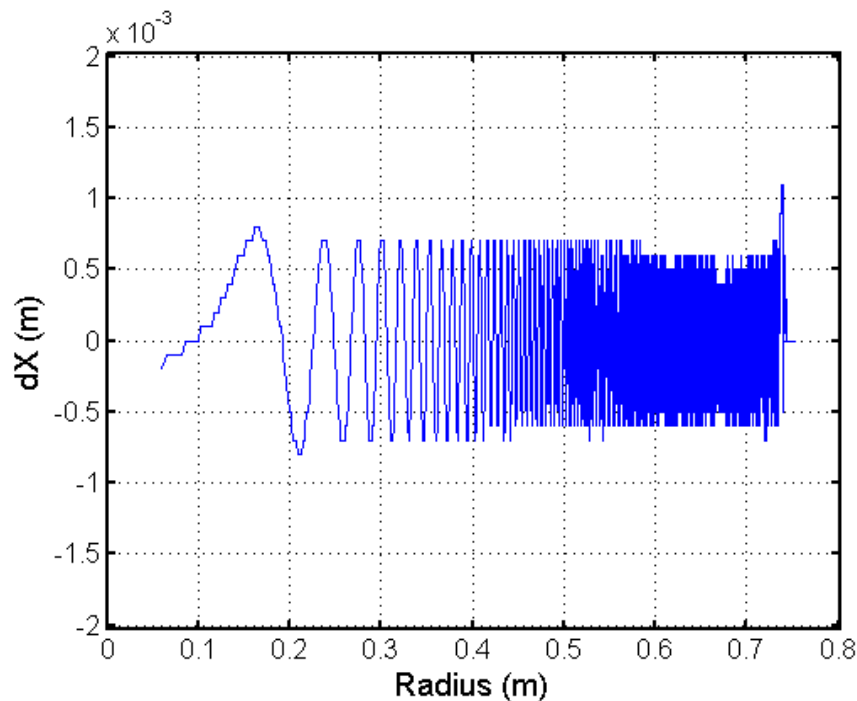


Calculation condition

- 1 MeV – 244 MeV (1146 turns)
- Vdee= 100 kV

초전도 사이클로트론 개발 현황

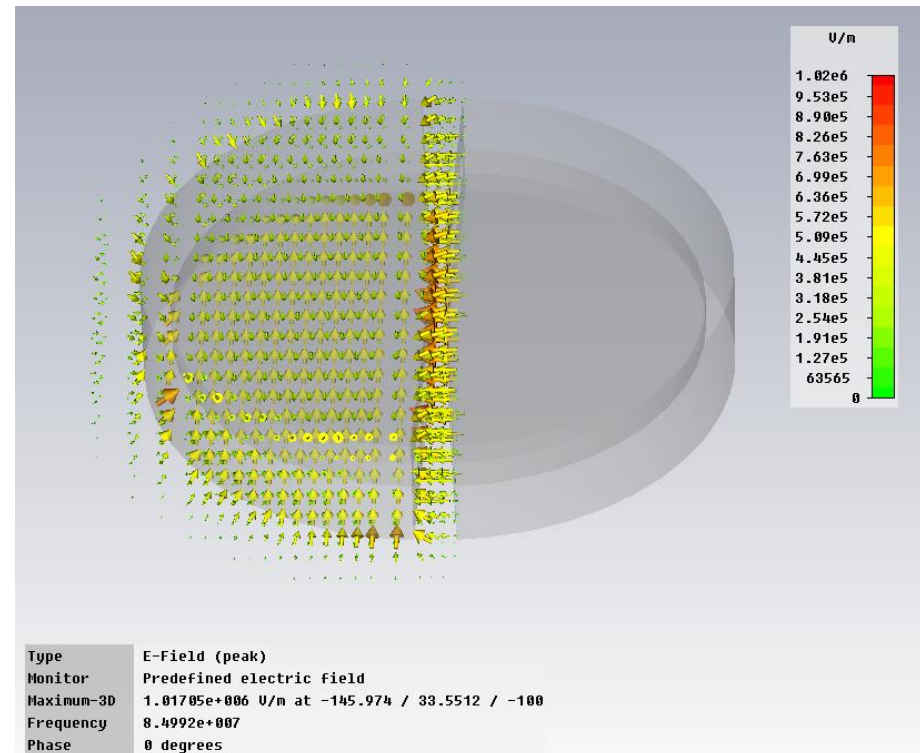
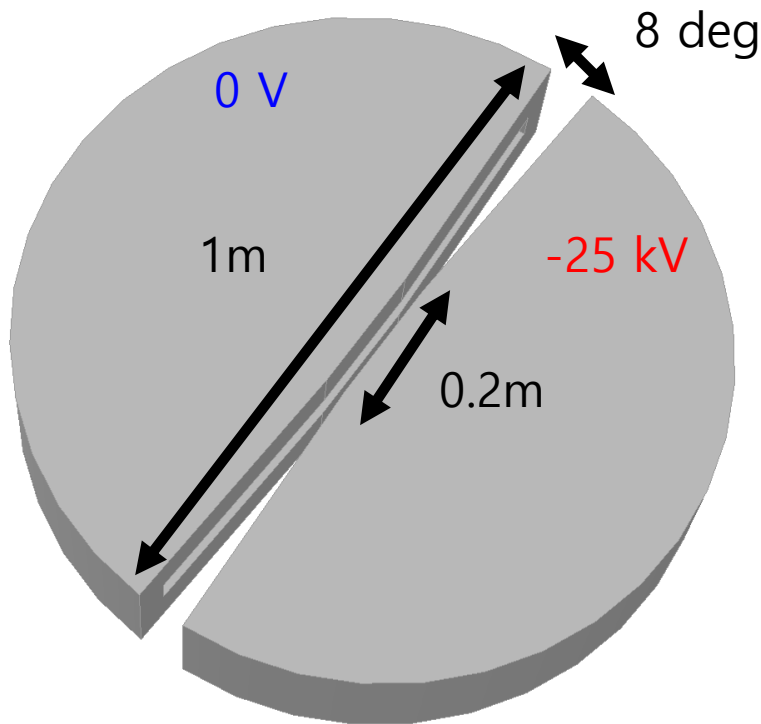
- SKKU 250 – Single particle tracking (cyclone)



Radial & axial beam motion from 1 MeV to 244 MeV at the acceleration gap #1

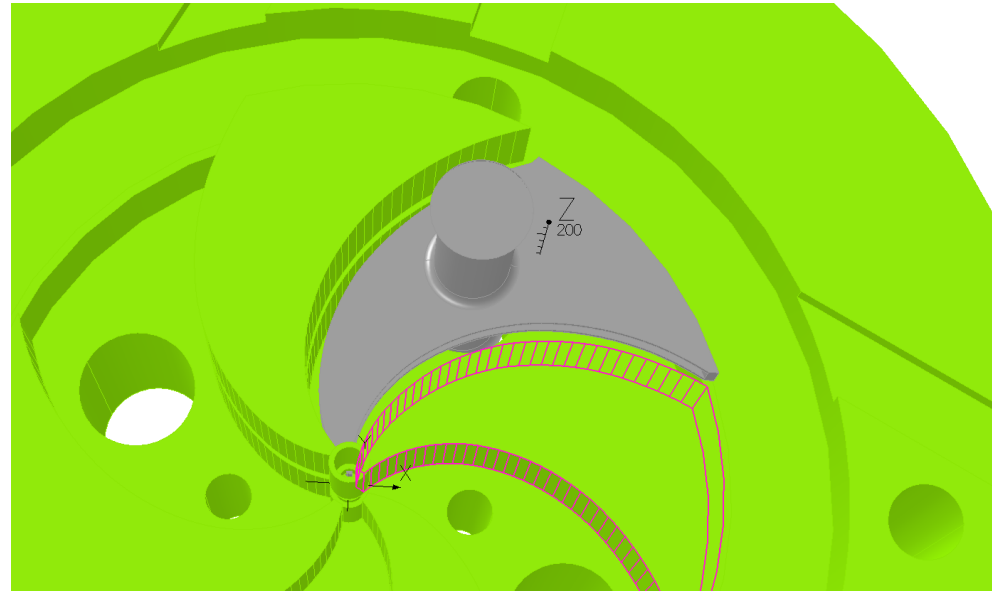
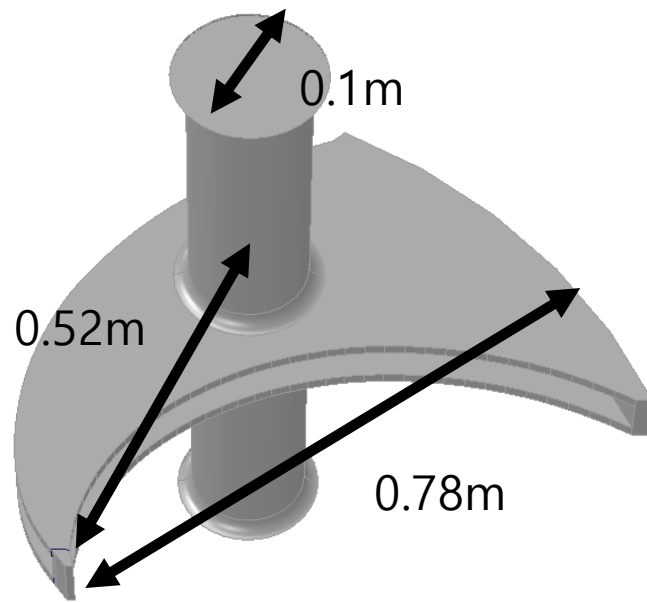
초전도 사이클로트론 개발 현황

- SKKU 250 – CST Model
 - Conceptual design of Synchro-Cyclotron Dee



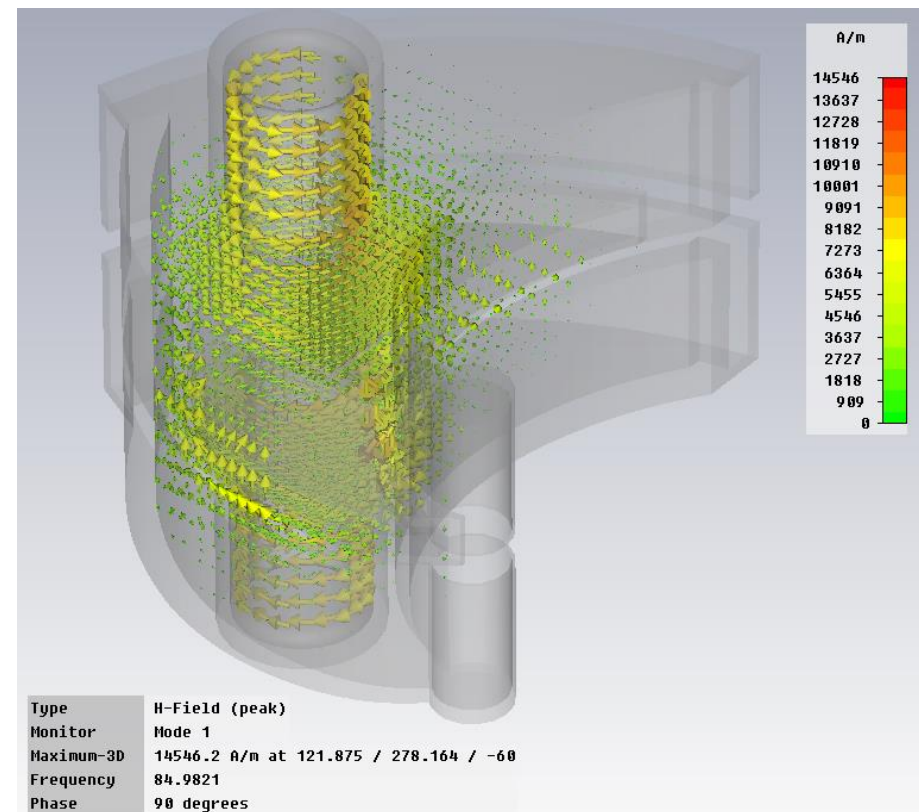
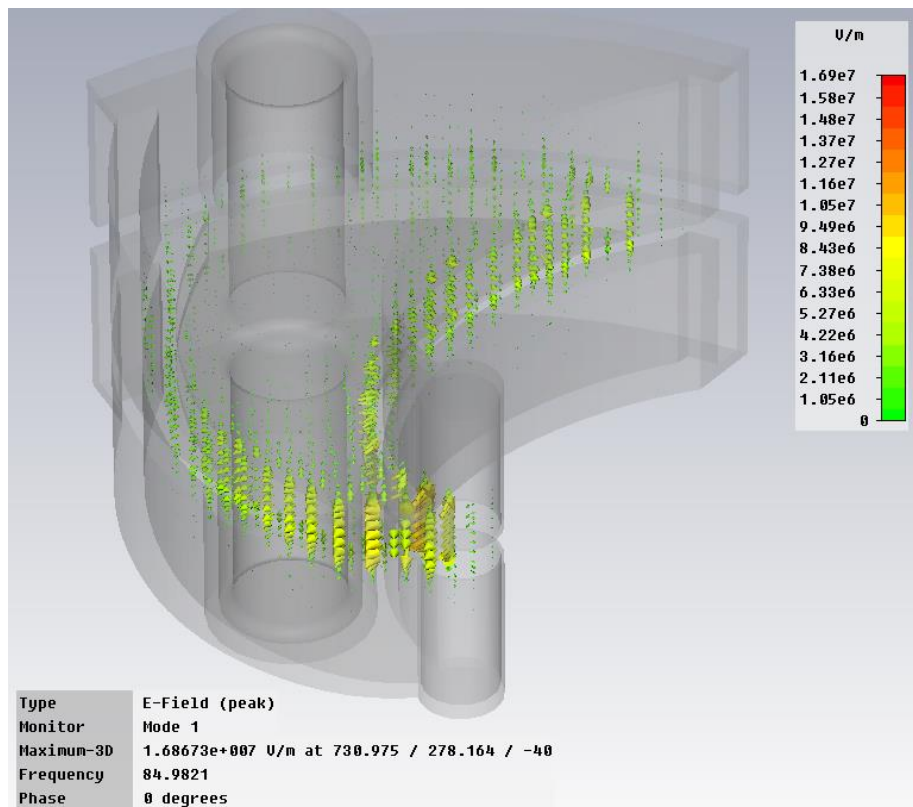
초전도 사이클로트론 개발 현황

- SKKU 250 – PRELIMINARY CST Model
 - Conceptual Design of 250 MeV Proton cyclotron RF Cavity



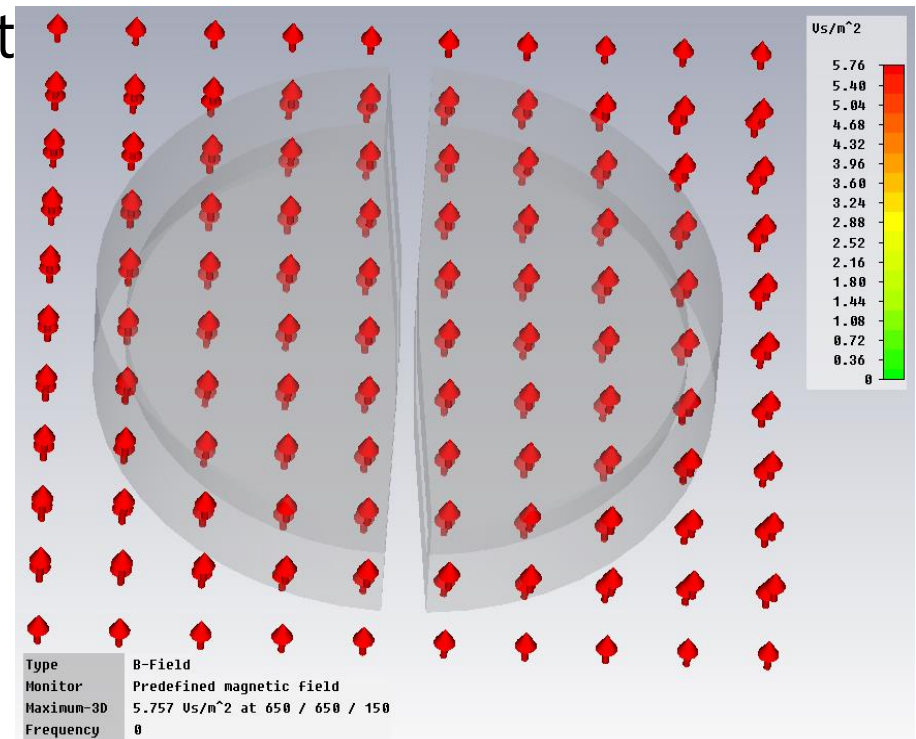
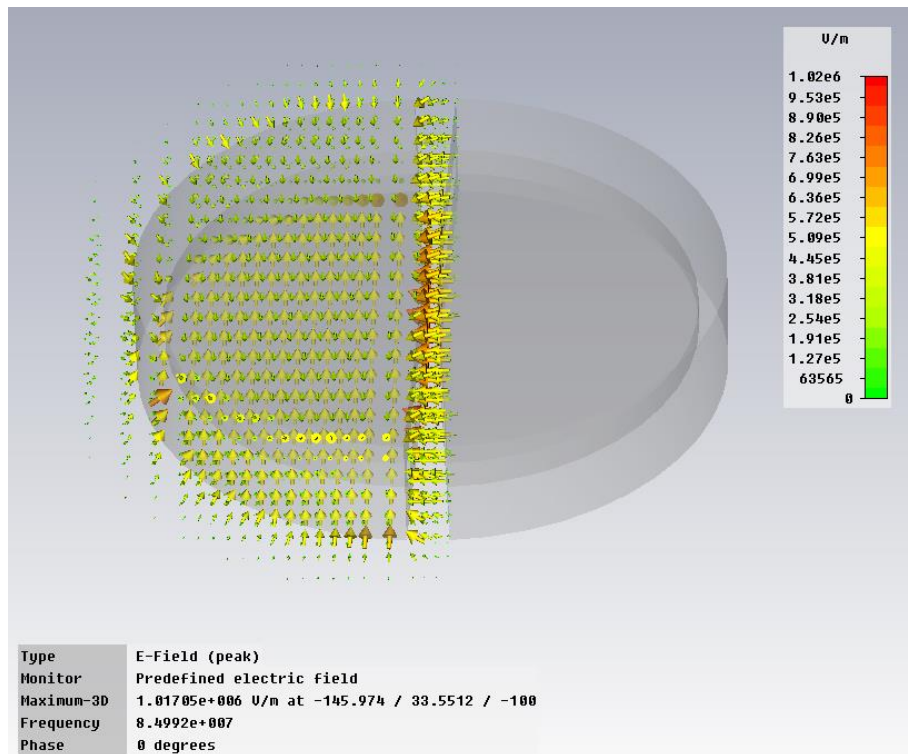
초전도 사이클로트론 개발 현황

- SKKU 250 – CST Model
 - Conceptual Design of 250 MeV Proton cyclotron RF Cavity



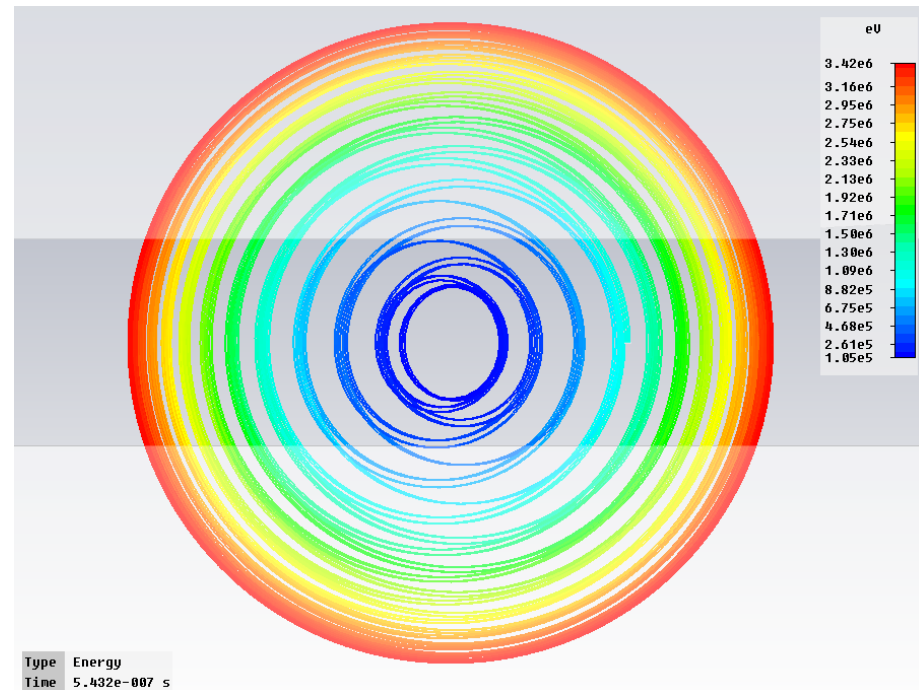
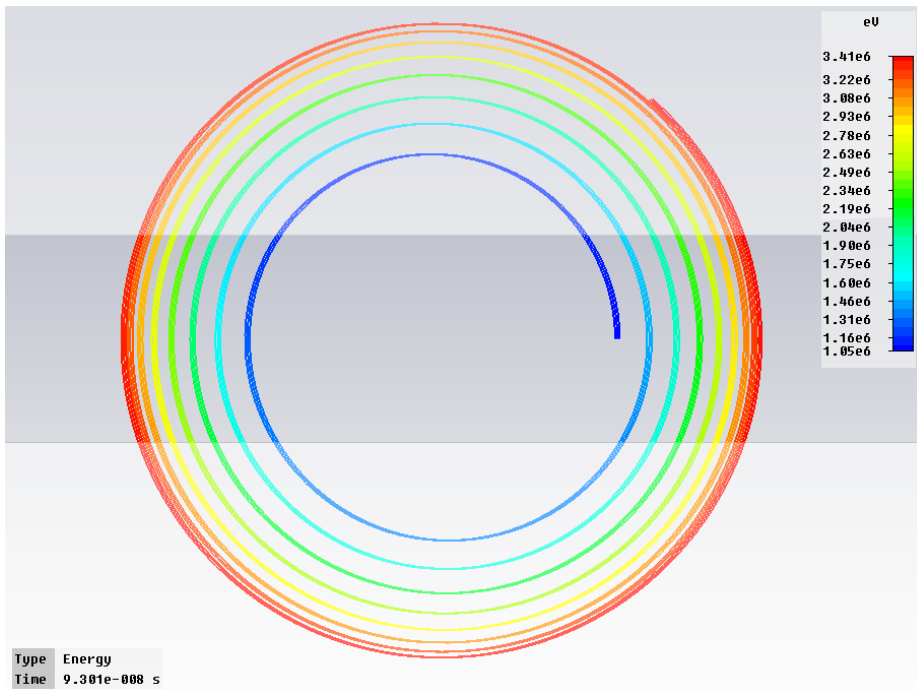
초전도 사이클로트론 개발 현황

- SKKU 250 – CST Particle Tracking
 - MWS or PS: E-field (from Eigen or Static solver)



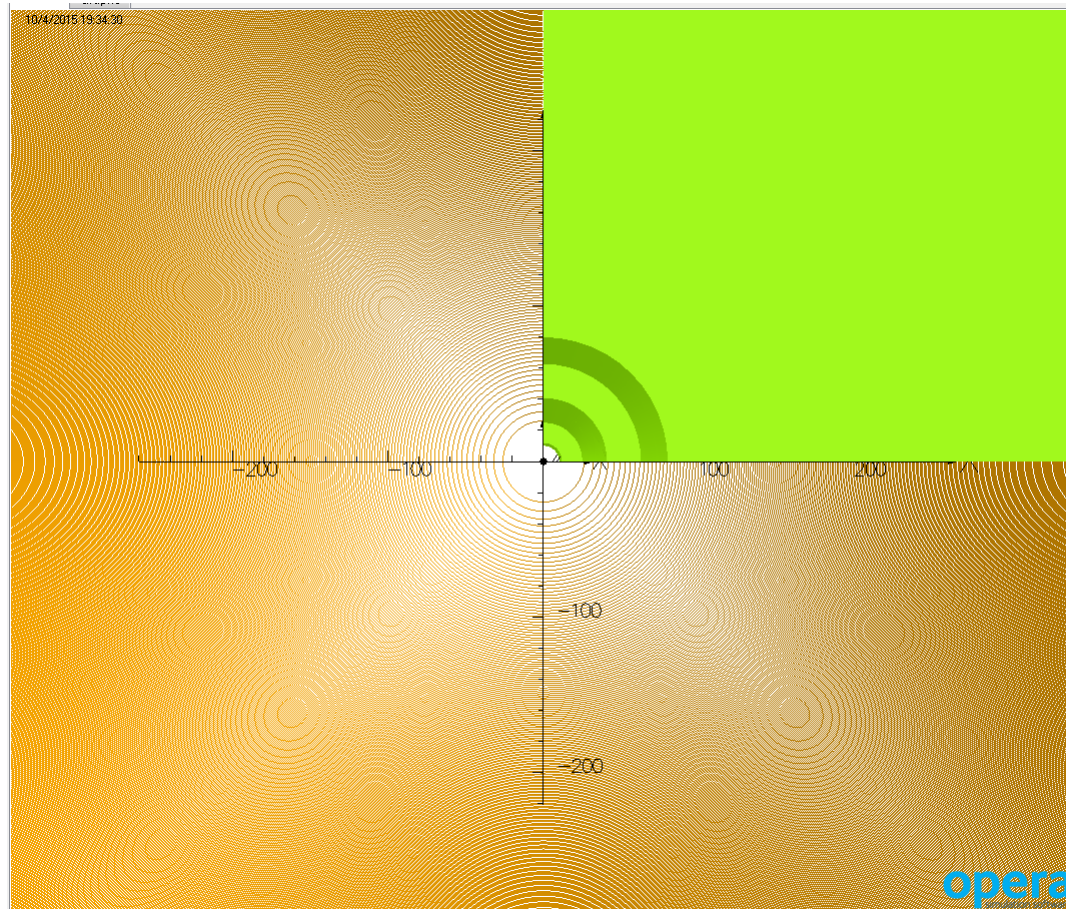
초전도 사이클로트론 개발 현황

- CST Particle Tracking
 - MWS or PS: E-field (from Eigen or Static solver)
 - EMS or PS : B-field (Static solver)



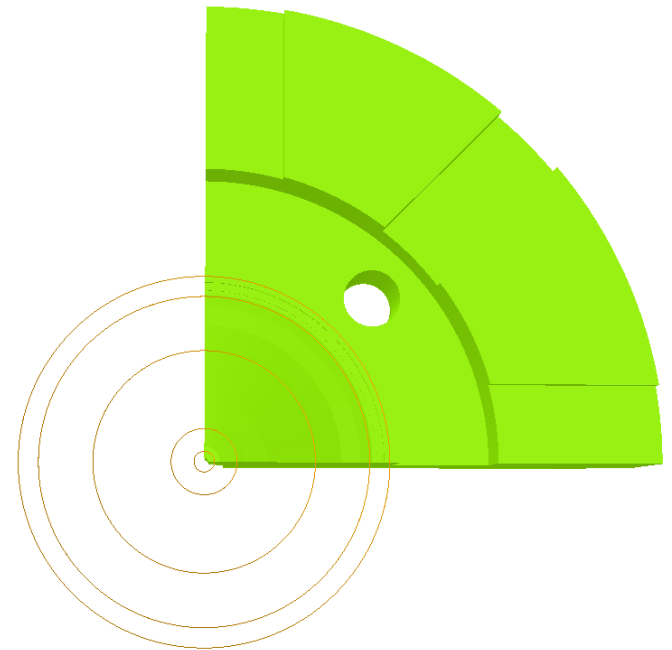
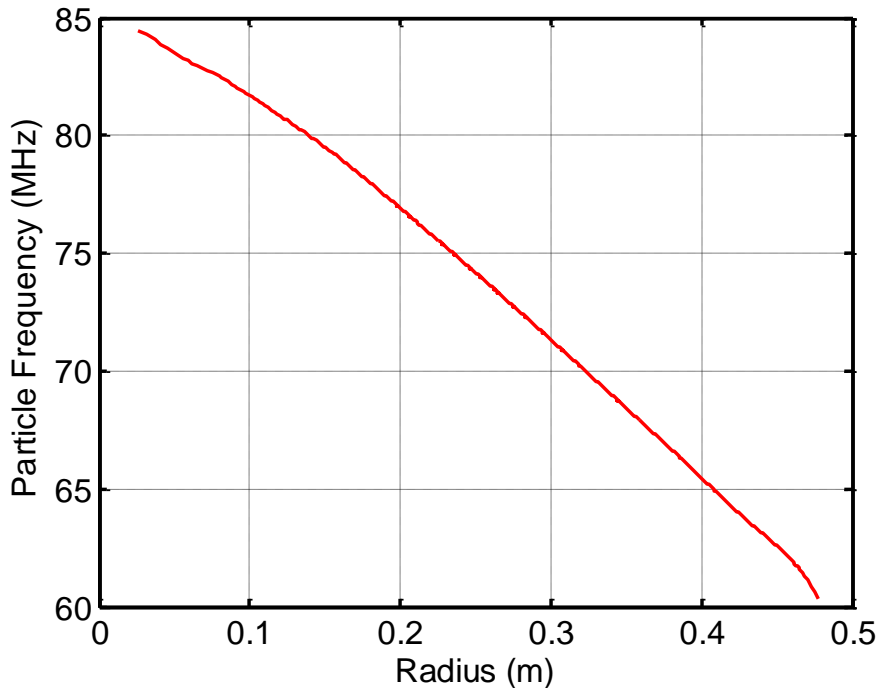
초전도 사이클로트론 개발 현황

- SKKU 250 – EO check SC: 1MeV ~ 239.5MeV



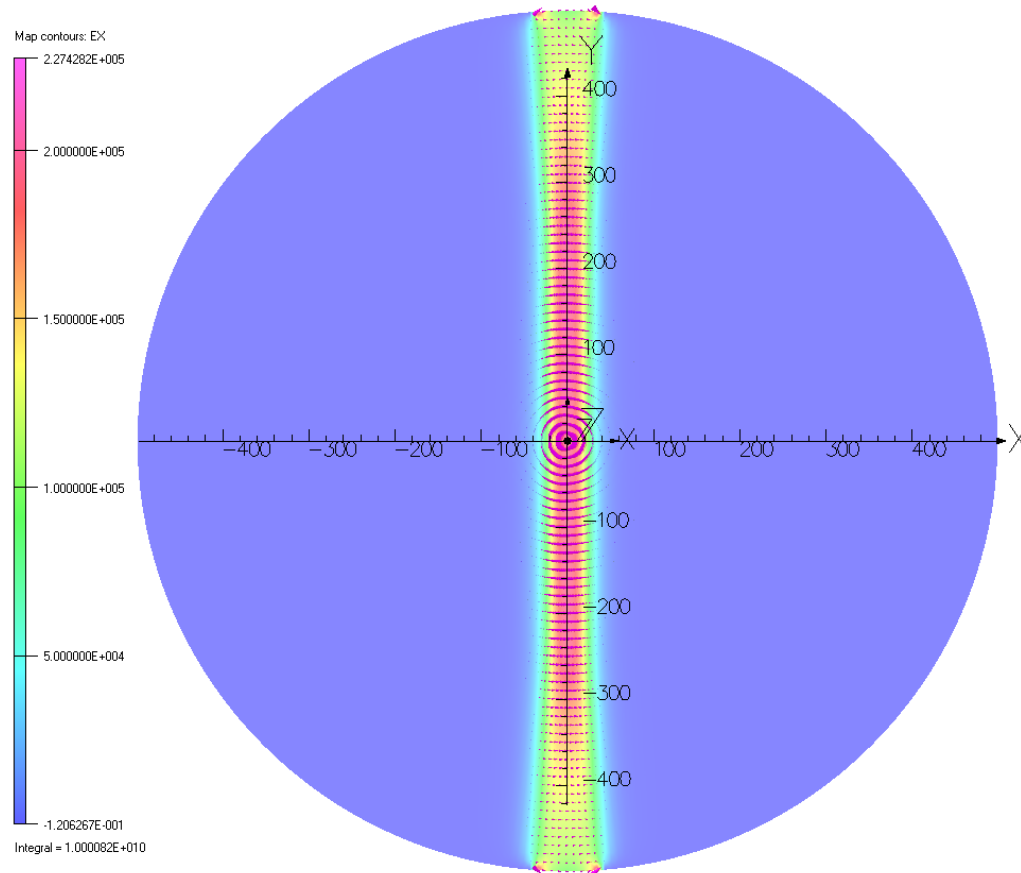
초전도 사이클로트론 개발 현황

- SKKU 250 – Conceptual design model of SC



초전도 사이클로트론 개발 현황

- 1st draft model design for SKKU 250 – SC



초전도 사이클로트론 개발 현황

Trajectories: $\text{PROTONMASS} \cdot C^2 \cdot (1/\text{SQRT}(1 - (0.001 \cdot \text{VELMOD}/C)^2 - 1)) / \text{ELECTRONCHARGE}$

2.420729E+008

2.000000E+008

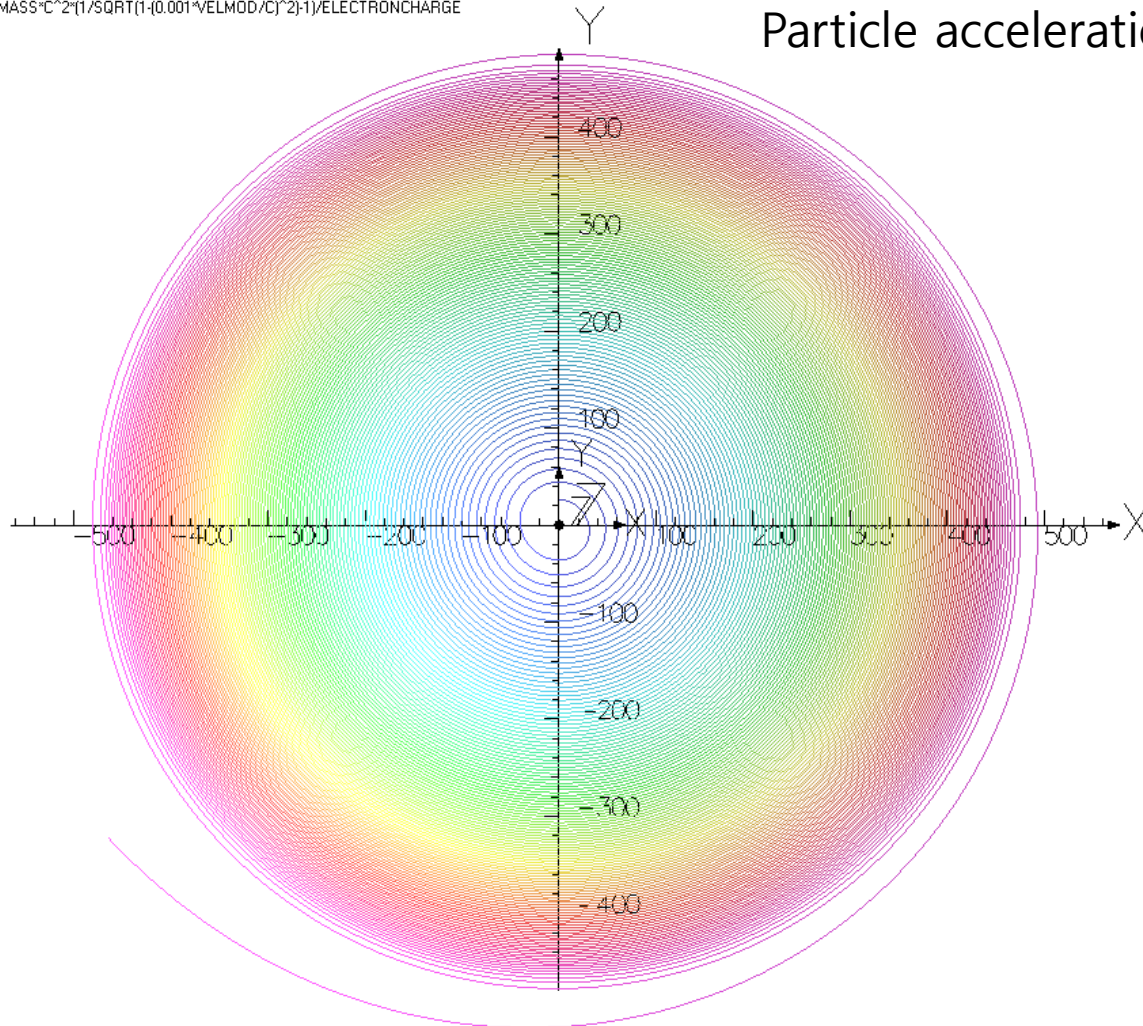
1.500000E+008

1.000000E+008

5.000000E+007

1.000000E+006

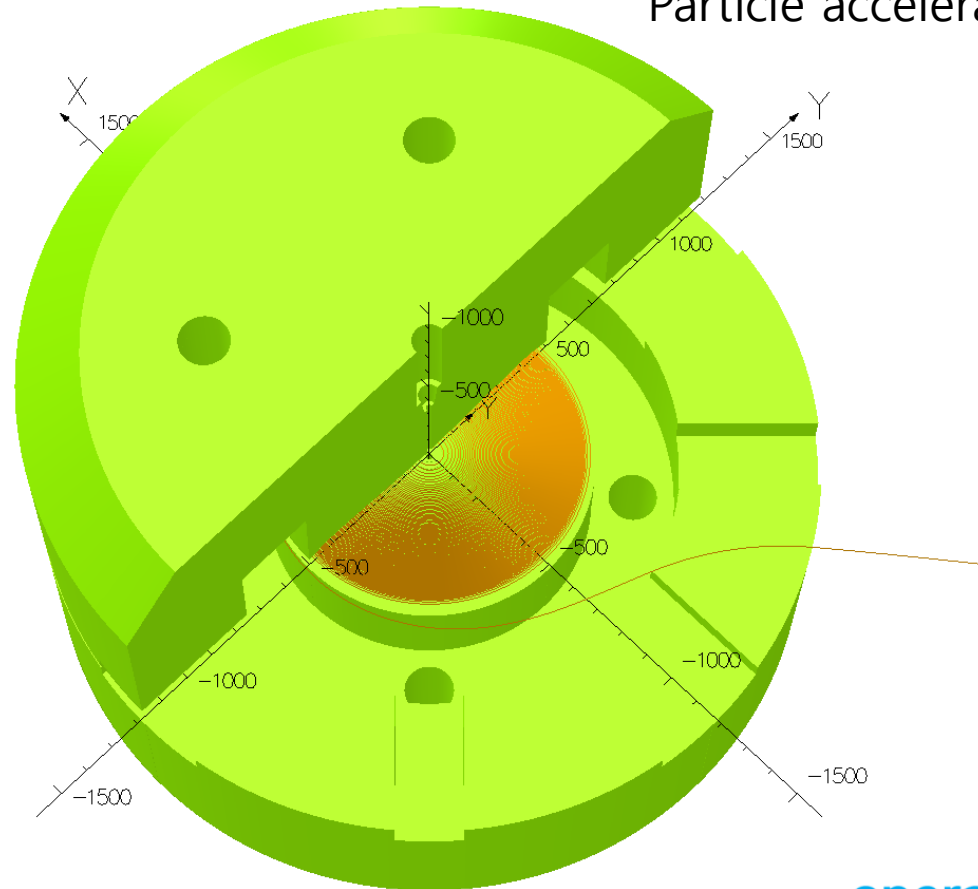
Particle acceleration (B+E field)



초전도 사이클로트론 개발 현황

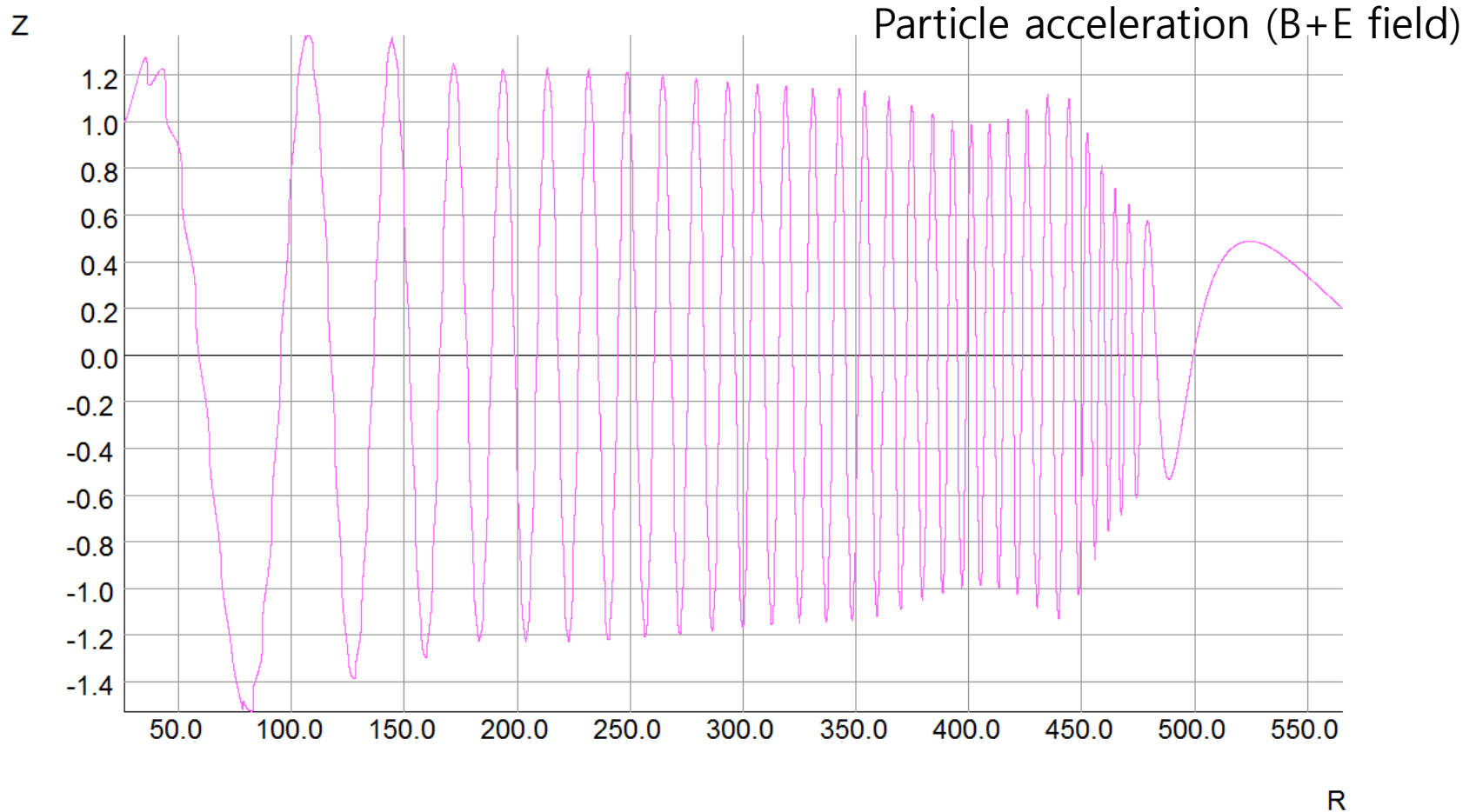
23/4/2015 11:16:24

Particle acceleration (B+E field)

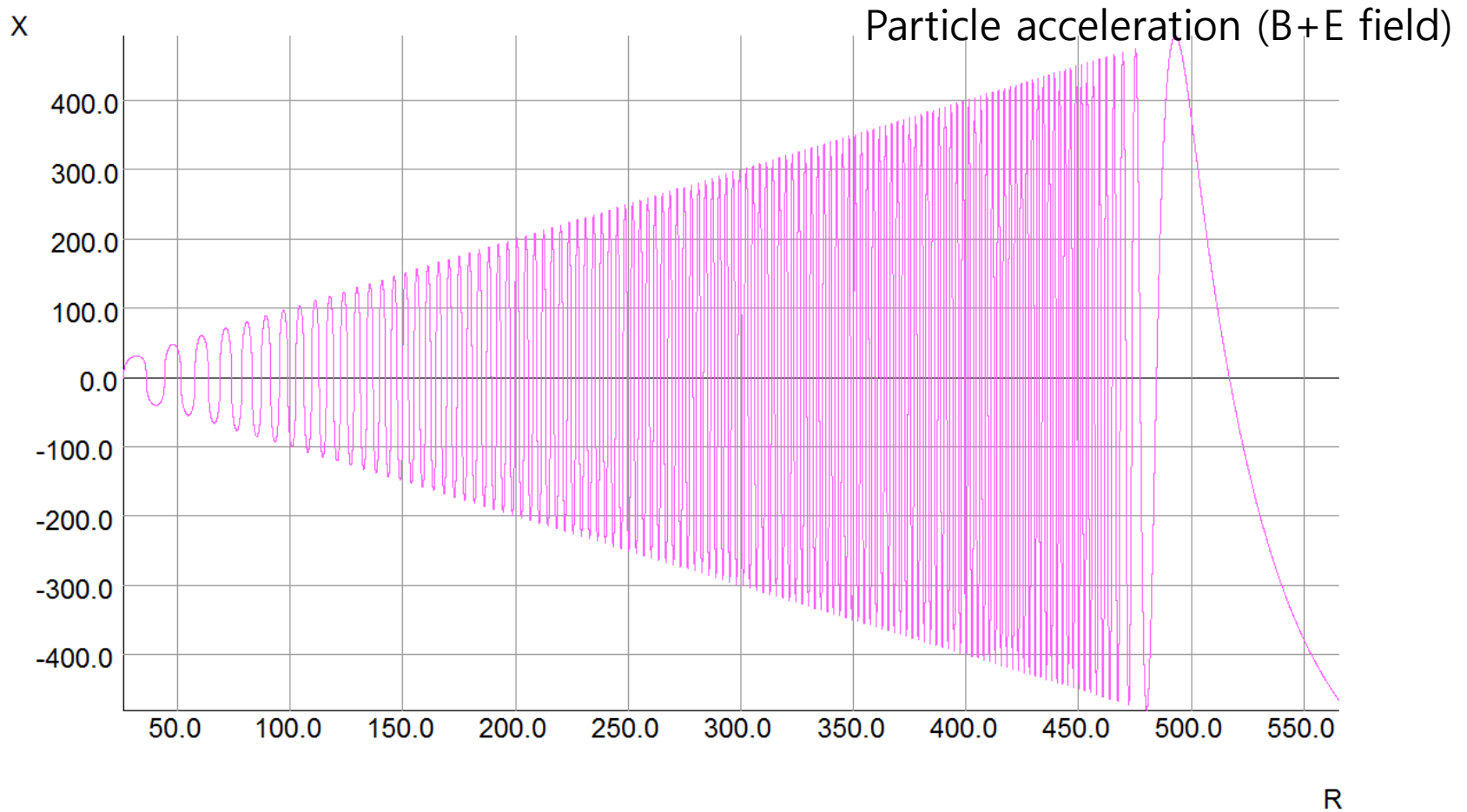


opera
simulation software

초전도 사이클로트론 개발 현황



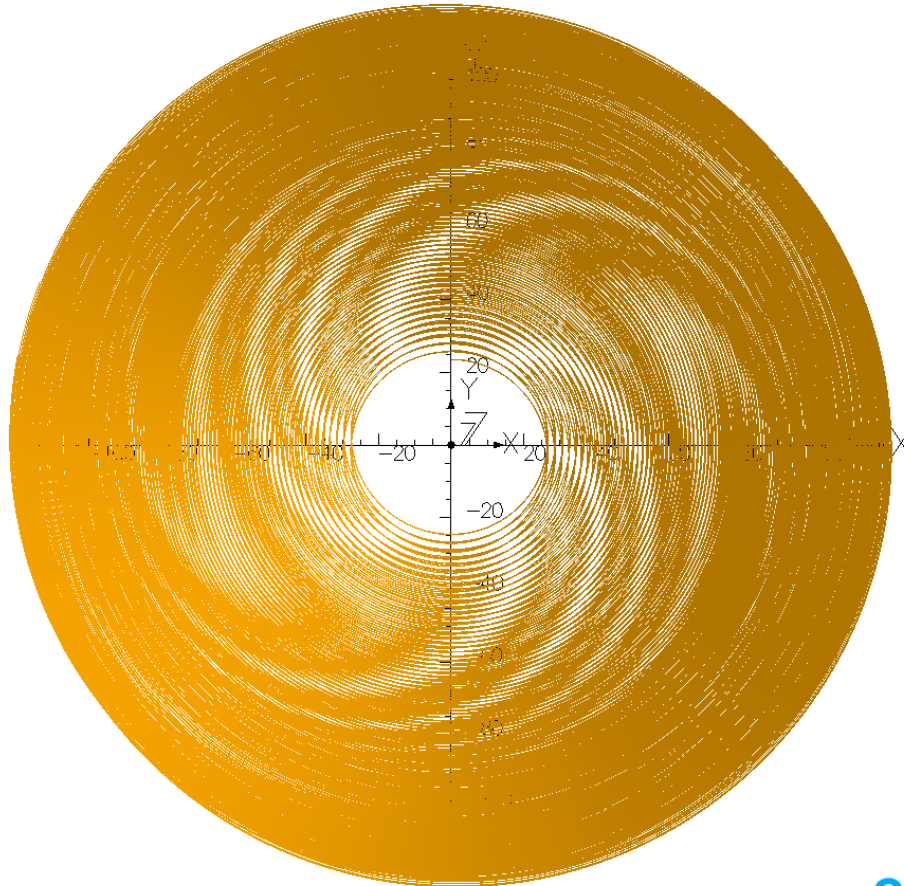
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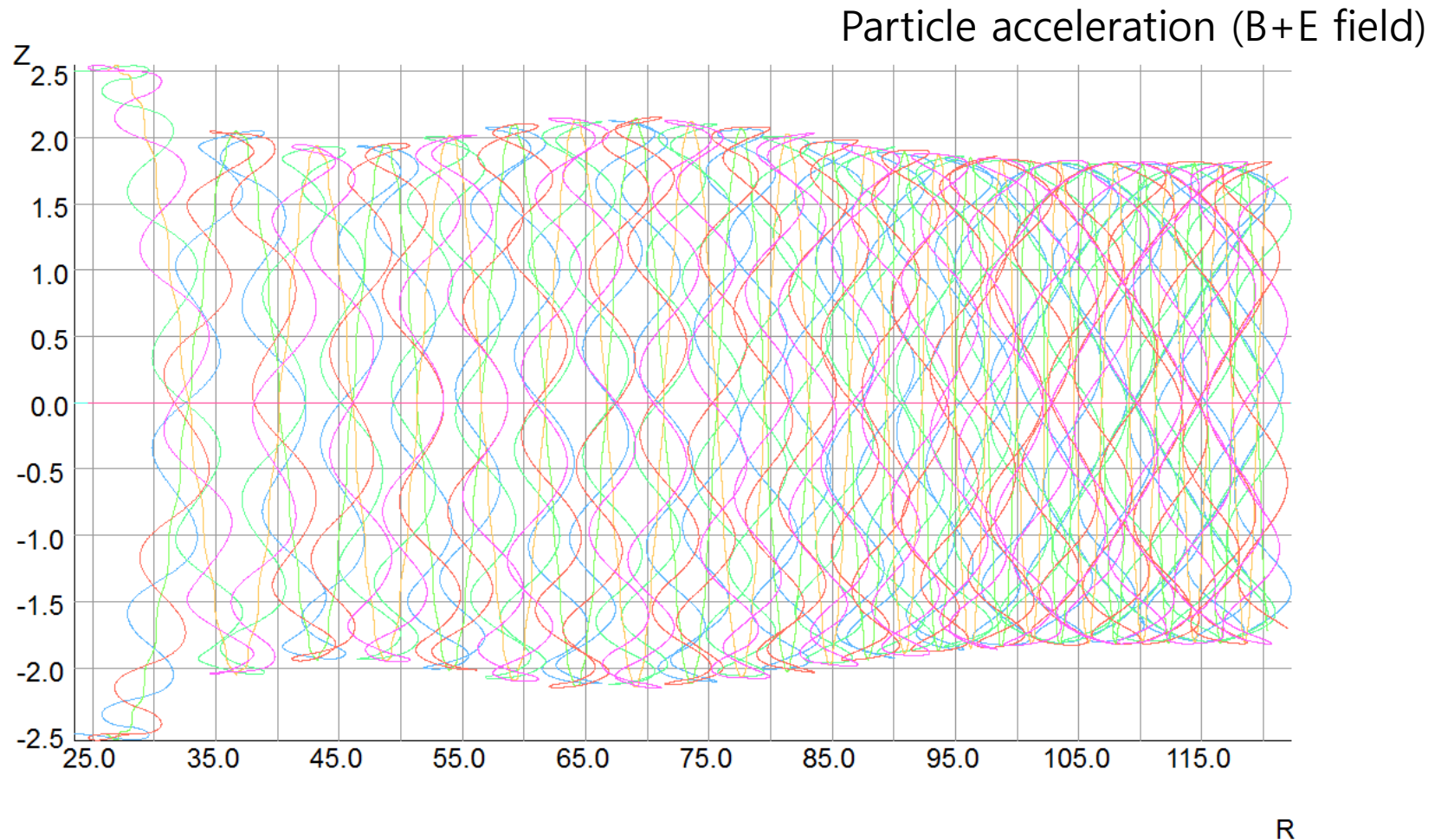
초전도 사이클로트론 개발 현황

- 1MeV @R=26.07mm, ± 5 mm, 3*3 beam

23/4/2015 10:40:18



초전도 사이클로트론 개발 현황





한국원자력의학원

향후 개발 계획

향후 개발 계획

- 초전도 사이클로트론 전자석
 - 다양한 초전도 전자석 설계 경험
 - 초전도 전자석 시제품 제작 및 저온 테스트 수행
 - SKKU 250 전자석 설계 완료 단계
 - 전자석 제작 및 자기장 보정 실험 필요 (코일, 섹터 정렬 등)
- 초전도 사이클로트론 고주파 시스템
 - Kirams-430 고주파 시스템 설계 및 테스트 벤치 제작 경험
 - 나선형 고주파 시스템의 파워 테스트
 - 고주파 시스템 관련 인력

향후 개발 계획

- 초전도 사이클로트론 빔 인출 시스템
 - Deflector 최적 설계를 위한 빔 동력학적 분석
 - 빔 인출용 고전압 전기장치 설계
 - 전자석 및 고주파 시스템과의 공간 활용성 분석
 - 인출용 전자석(GC, regenerator)설계 필요 여부 확인
- 초전도 사이클로트론 이온원 및 입사 시스템
 - 외부 이온원 국산화 가능성
 - Inflector 모델 설계 및 빔 시뮬레이션
 - PIG 이온원의 성능 강화 및 개량
 - 사이클로트론 중심부 설계



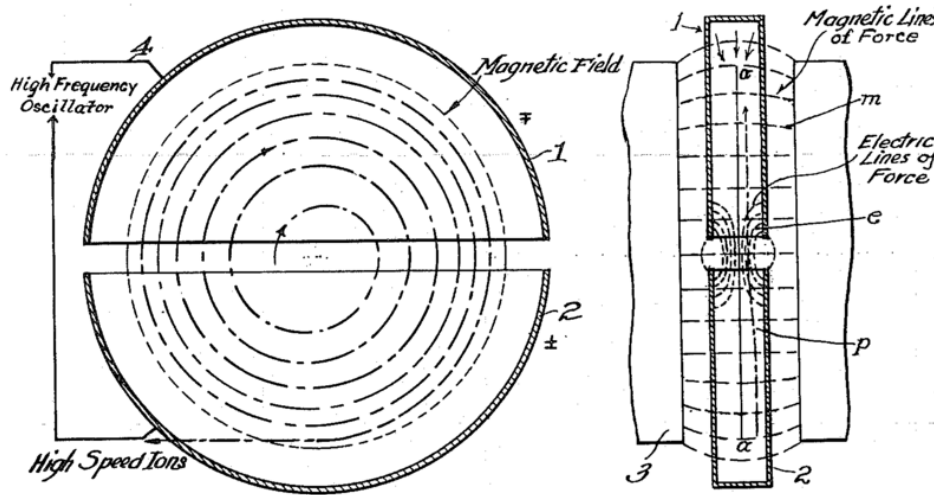
한국원자력의학원

THANK YOU

의료용중입자기속기사업단
KOREA HEAVY ION MEDICAL ACCELERATOR

Operation Principle

- The first cyclotron concept was born by E.O. Lawrence



$$F = q(E + v \times B)$$

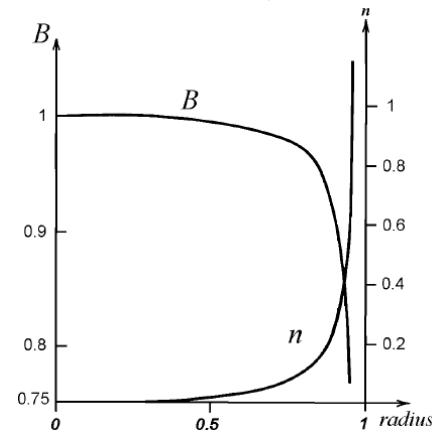
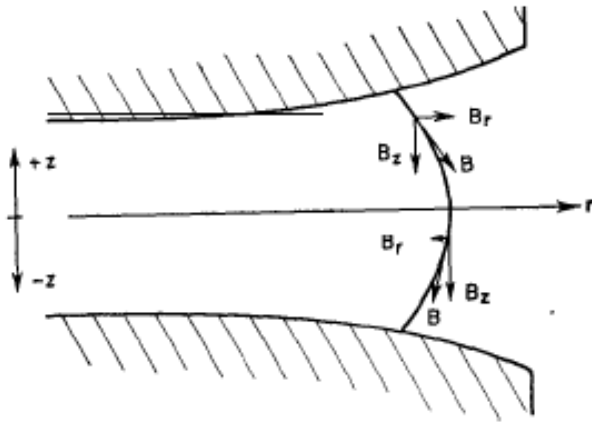
$$\frac{mv^2}{R} = qvB$$

$$\omega = \frac{v}{R} = \frac{qB}{m}, \quad R = \frac{mv}{qB}$$

- For the constant q , m and B , the rotation frequency of ions become constant - independent of ion speed
- However, the orbit radius depend on the ion speed

Historical Background

- Isochronism & Axial focusing for classical cyclotron
 - isochronism require uniform magnetic field
 - axial focusing require decreasing magnetic field
 - relativistic effect need increasing magnetic field ($E > 20$ MeV)



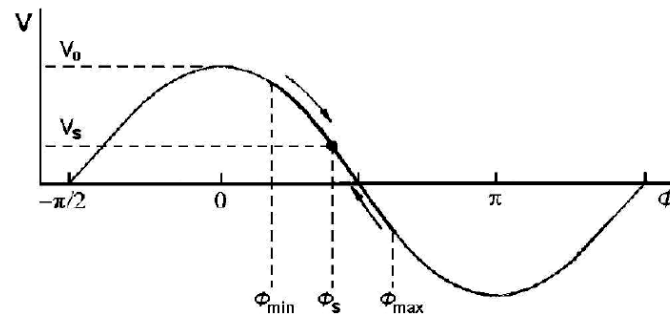
- Using the slightly decreasing magnetic field
 - keep the ions in isochronism and axial focusing
 - limitation of maximum energy by relativistic effect

Historical Background

- Synchrocyclotrons – frequency modulated
 - reducing the RF frequency as the particle frequency
 - pulsed mode operation not CW any more
 - 1 GeV beam but current reduced to max. 1 μA level

$$\omega(t) = \frac{qB}{m(t)}$$

$$m(t) = \gamma(t) \cdot m_0$$

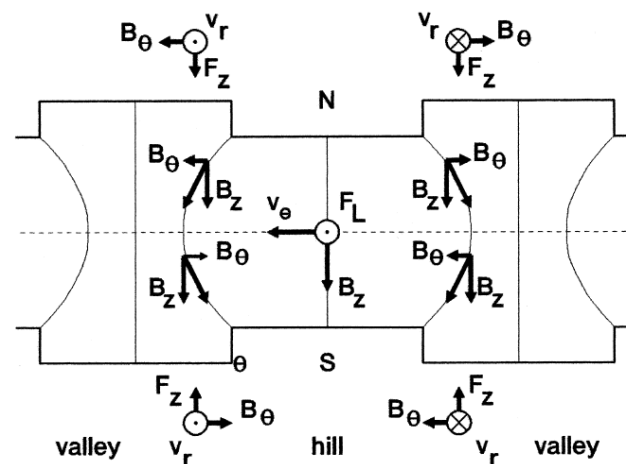
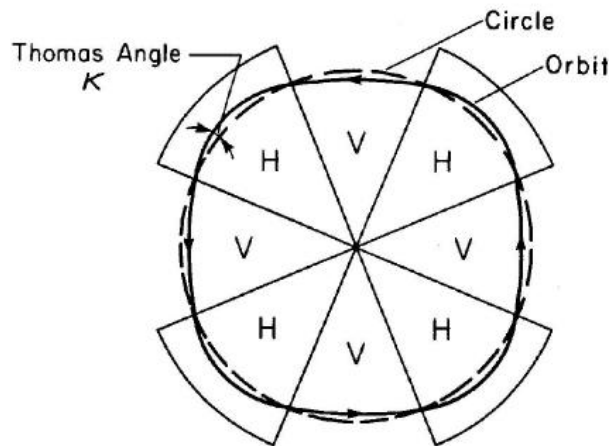


- Phase stability
 - Particles near synchronous phase stay with the RF
 - oscillation around the synchronous phase

Historical Background

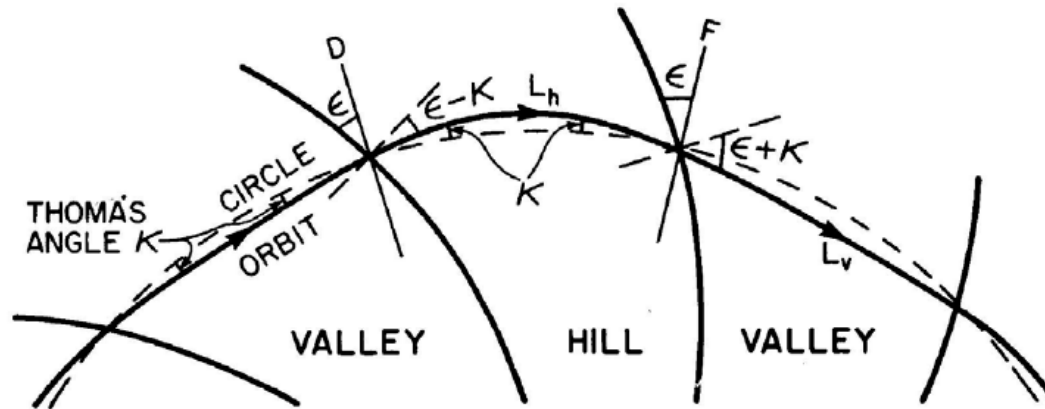
- Isochronous cyclotrons – radial sector
 - keeping the isochronism by increasing magnetic field
 - sectors as known as "hills" and "valleys" introduce
 - azimuthally varying field(flutter) provide axial focusing
 - energy limit at 70 ~ 100 MeV/u

$$w = \frac{v}{R} = \frac{qB}{m}$$



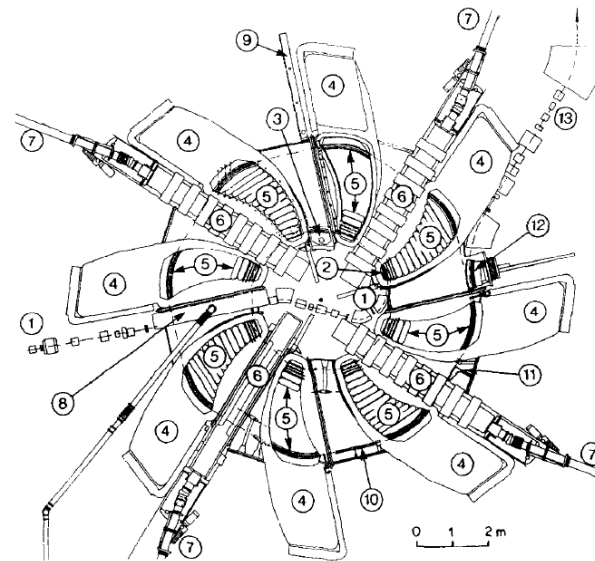
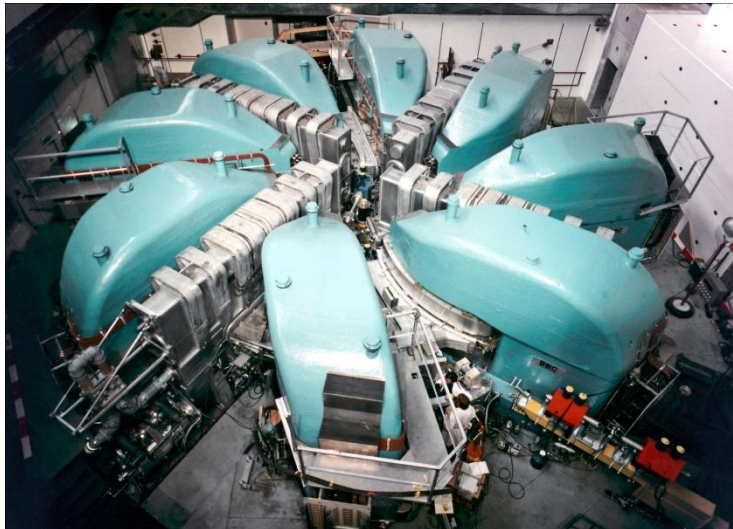
Historical Background

- Isochronous cyclotrons – spiral sector
 - more axial focusing force is needed to overcome the limitation
 - spiraled sector edges work as focusing-defocusing lens
- $$\nu_z^2 \approx -\beta^2 \gamma^2 + F^2(1 + 2\tan^2 \epsilon)$$
- strong focusing principle



Historical Background

- Isochronous cyclotrons – separated-sector
 - maximize the flutter to increase axial focusing force
 - only "hills" exist and no iron in "valleys"
 - structural limit of acceleration in low energy beam
 - injector accelerators are required

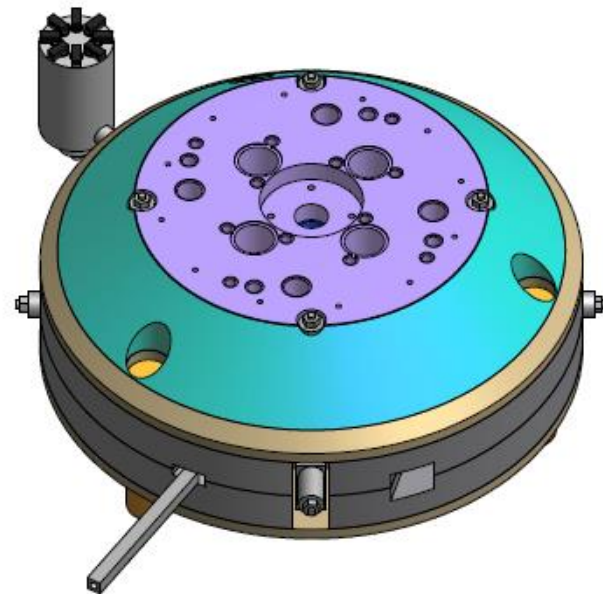
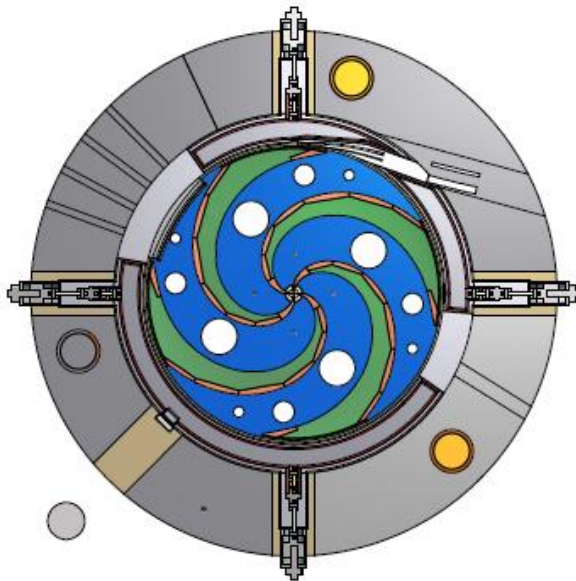


의료용중입자기속기사업단
KOREA HEAVY ION MEDICAL ACCELERATOR

[3] M.K. Craddock and K.P. Symon, Cyclotrons and fixed field alternating - gradient accelerators, Rev. Accl. Sci. Tech. 65 (2008).
[19-1] T. Stambach, et. al., The feasibility of high power cyclotrons, Nucl. Instr. Meth. B 113, 1 (1996).

Historical Background

- Superconductivity for cyclotrons (max. ~ 9 T)
 - remarkable size reducing can be achieved (250 MeV, $R=1.6$ m)
 - low operation cost
 - reducing turn separation
 - reducing the flutter for compact cyclotron



Historical Background

- Texas A&M Univ. – “Strong Focusing Cyclotron”
 - 0.8GeV, 10mA (8 MW beam power) “Strong Focusing Cyclotron”
 - Driver for accelerator driven system
 - 5 layer, 12 sector banding magnet with 35 focusing channels
 - a kind of “Separated-Orbit Cyclotron”

