サイクロトロンの超伝導化

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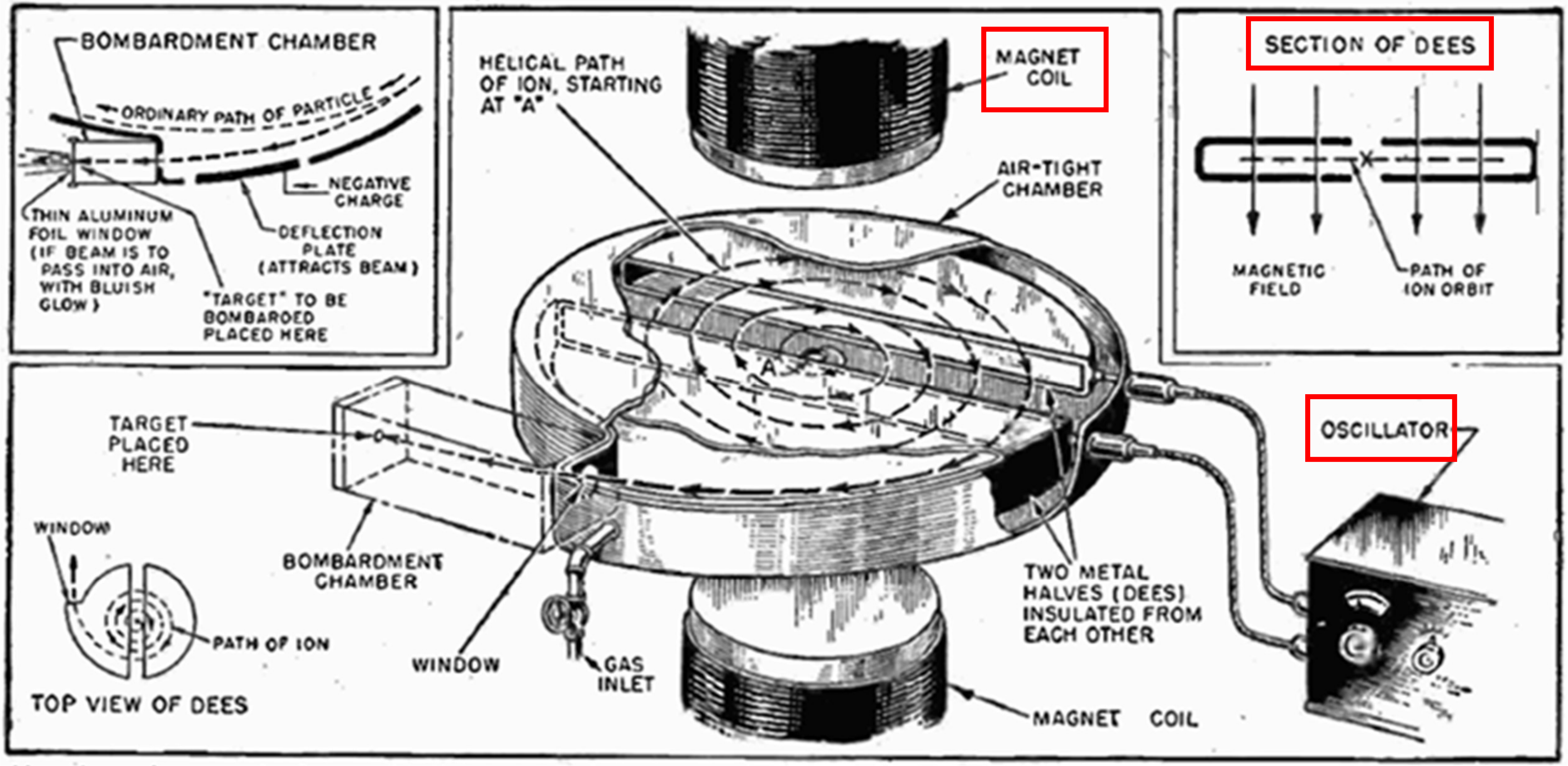
サイクロトロンの概要


BOMBARDMENT CHAMBER
ORDINARY PATH OF PARTICLE
NEGATIVE CHARGE
THIN ALUMINUM FOIL WINDOW (IF BEAM IS TO PASS INTO AIR, WITH BLUISH GLOW)
DEFLECTION PLATE (ATTRACTS BEAM)
"TARGET" TO BE BOMBARDED PLACED HERE
HELICAL PATH OF ION, STARTING AT "A"
MAGNET COIL
AIR-TIGHT CHAMBER
A
SECTION OF DEES
MAGNETIC FIELD
PATH OF ION ORBIT
TARGET PLACED HERE
WINDOW
BOMBARDMENT CHAMBER
PATH OF ION
TOP VIEW OF DEES
WINDOW
GAS INLET
OSCILLATOR
TWO METAL HALVES (DEES) INSULATED FROM EACH OTHER
MAGNET COIL

The first cyclotron

Ernest Orlando Lawrence

Taken from
https://en.wikipedia.org/wiki/Ernest_Lawrence

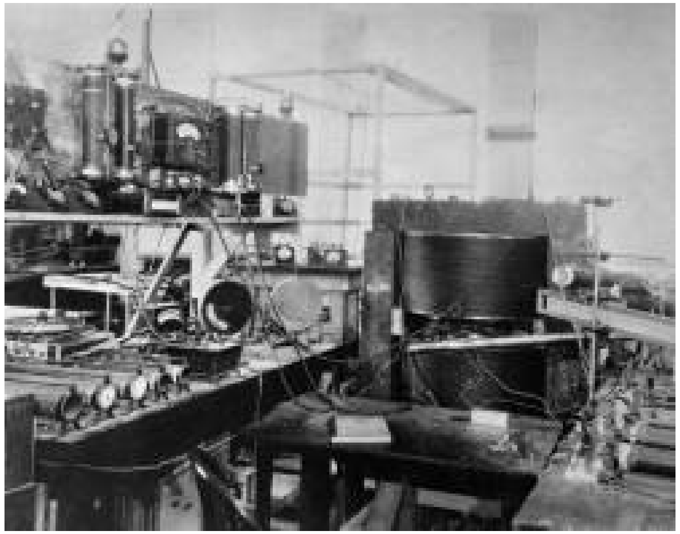
Taken from
https://www2.lbl.gov/Science-Articles/Archive/rev-idea.html

The 4 inch

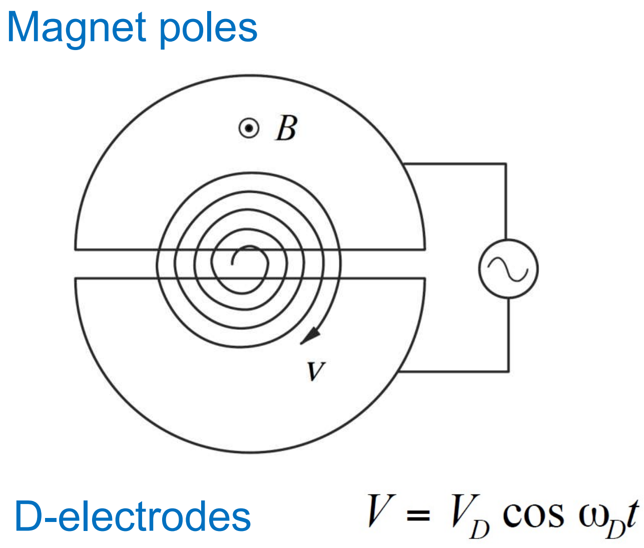
80-keV H_2^+, 1931

The 11 inch

1.1-MeV proton, 1932



Cyclotron principle: isochronism



$V = V_D \cos \omega_D t$

(Cyclotron frequency)

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

$$\omega = \frac{v}{\rho} = \frac{qB}{m}$$

Cyclotron is a resonance phenomenon.

Resonance condition

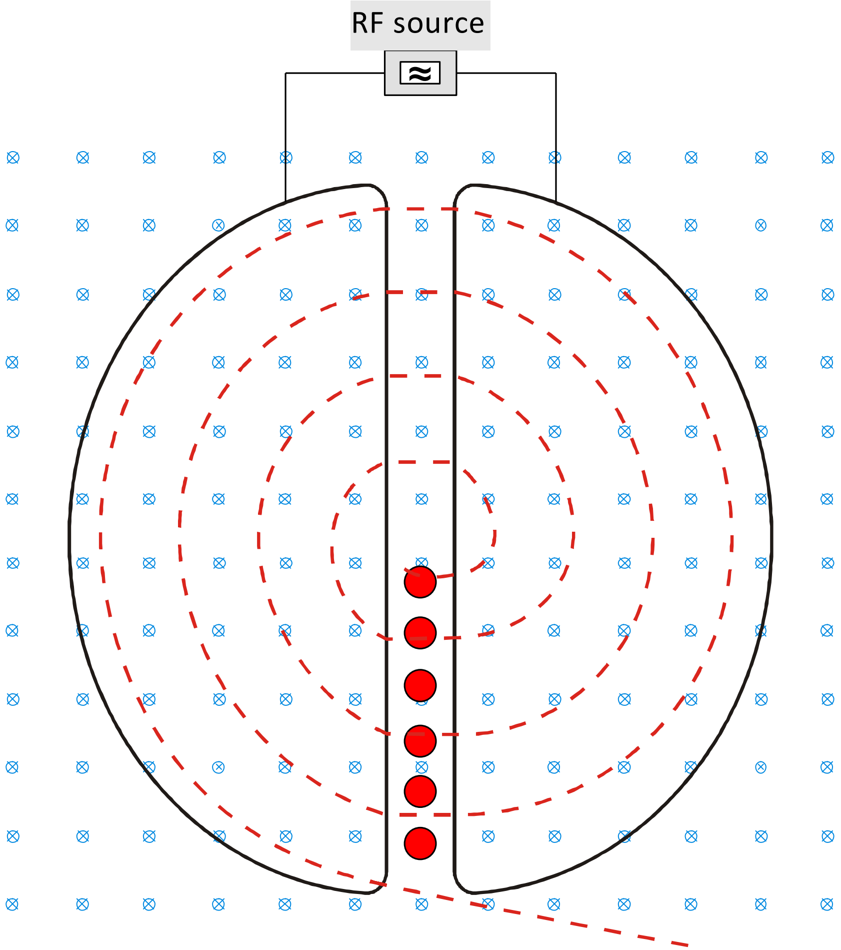
$\omega_D = \omega$ (Cyclotron frequency)

The *cyclotron frequency* of a non-relativistic particle is independent of the particle velocity

Successive acceleration occurs.
Particles reach periphery.

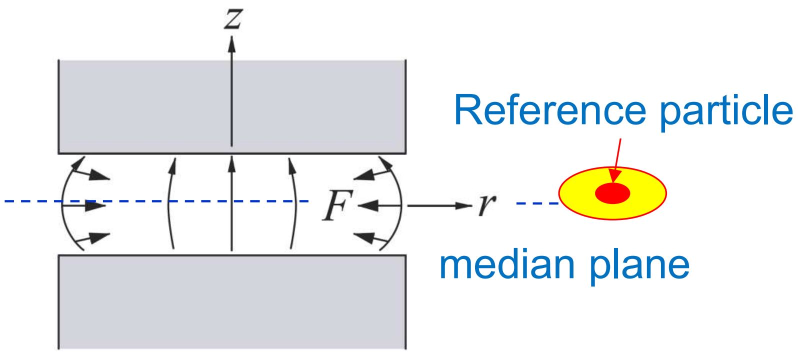
Taken from “Beam Dynamics in Cyclotrons”, A. Goto (1998)

Acceleration in the cyclotron



ほうきで掃くような加速

Cyclotron: weak convergence



Vertical Focusing

$$
\begin{aligned}
F_z &= q v_\theta B_r \\
&= q v_\theta \frac{\partial B_r}{\partial z} z = q v_\theta \frac{\partial B_z}{\partial r} z \qquad \left(\Leftarrow \nabla \times \vec{B} = 0 \right) \\
&= q \omega r \frac{\partial B_z}{\partial r} z = m \omega^2 \frac{r}{B_z} \frac{\partial B_z}{\partial r} z \\
&= m \omega^2 \mu' z
\end{aligned}
$$

a new parameter μ'

$$\mu' \equiv \frac{r}{B_z} \frac{\partial B_z}{\partial r} = -n$$

→simple harmonic mortion

Equation of motion in z direction

$$\frac{d^2 z}{d t^2} - \mu' \omega^2 z = \frac{d^2 z}{d t^2} + \omega_z^2 z = 0$$

z→azimuthal angle θ transformation

$$\boxed{\frac{d^2 z}{d\theta^2} - \mu' z = \frac{d^2 z}{d\theta^2} + \nu_z^2 z = 0}$$

a new parameter ν_z

$$\nu_z = \frac{\omega_z}{\omega} = \sqrt{-\mu'}$$

→ betatron oscillation

$$\boxed{\mu' < 0 \qquad \left(\frac{\partial B_z}{\partial r} < 0 \right)}$$

Cyclotron: weak convergence

Equation of motion in radial direction

$$-qv_\theta B_z = m\left(-\frac{v^2}{r} + \frac{d^2 r}{dt^2}\right)$$

$$\left\{\begin{array}{l} B_z(r) = B_z(R) + \dfrac{\partial B_z}{\partial r}x + \cdots \\ X << R \end{array}\right.$$

$$-qv_\theta \frac{\partial B_z}{\partial r}x = \frac{mv^2 x}{R^2} + m\frac{d^2 x}{dt^2}$$

Thus, we obtain

$$\frac{d^2 x}{d\theta^2} + (1+\mu')x = \frac{d^2 x}{d\theta^2} + \nu_r^2 x = 0$$

betatron oscillation is:

$$\nu_r = \frac{\omega_r}{\omega} = \sqrt{1+\mu'}$$

$$\mu' > -1 \qquad \left(\frac{r}{B_z}\frac{\partial B_z}{\partial r} > -1\right)$$

Weak convergence condition

$$-1 < \mu' < 0$$

Z方向、R方向ともに収束

Cyclotron principle

Isochronism

- phase stability of beam acceleration

Beam convergence

- vertical focusing

Classical cyclotrons - weak convergence

relativistic effect
→ Increasing radially magnetic field
→ causes the axial defocusing

a new parameter μ'

$$\mu' \equiv \frac{r}{B_z}\frac{\partial B_z}{\partial r} = -n$$

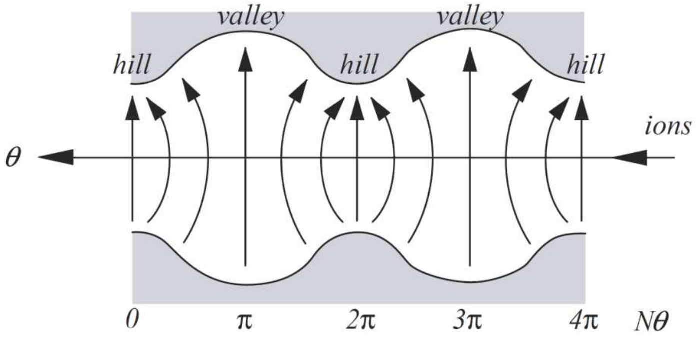
z→azimuthal angle θ transformation

$$\frac{d^2 z}{d\theta^2} - \mu' z = \frac{d^2 z}{d\theta^2} + \nu_z^2 z = 0$$

Limitations: relativistic effects break the isochronism
→ $E_{pmax} \approx 12\ MeV$

Cyclotron: strong convergence

Increasing radially magnetic field causes the axial defocusing. It is solved by provided magnetic field **Azimuthally Varying Field (AVF)**



radial velocity & B as azimuth angle

$$v_r = \omega \frac{dx}{d\theta} = -\frac{\omega f R}{N} \sin N\theta$$

$$B_\theta = \frac{\partial B_\theta}{\partial z} z = \frac{\partial B_z}{R \partial \theta} z = -z \frac{\bar{B} f N}{R} \sin N\theta$$

$$(\because \nabla \times \vec{B} = 0)$$

Incident angle

focusing force in z direction

$$F_z = -q v_r B_\theta = -m \omega^2 f^2 z \sin^2 N\theta$$

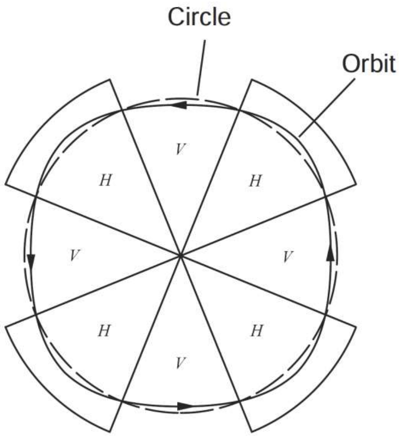
Azimuthally Varying Field

$$B_z = \bar{B}(1 + f \cos N\theta)$$

particle motion at x_f from R

$$-qv\bar{B} f \cos N\theta = m \ddot{x}_f$$

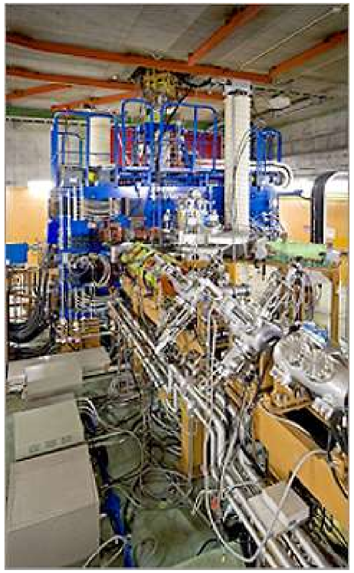
$$\rightarrow \quad x_f = \frac{fR}{N^2} \cos N\theta$$



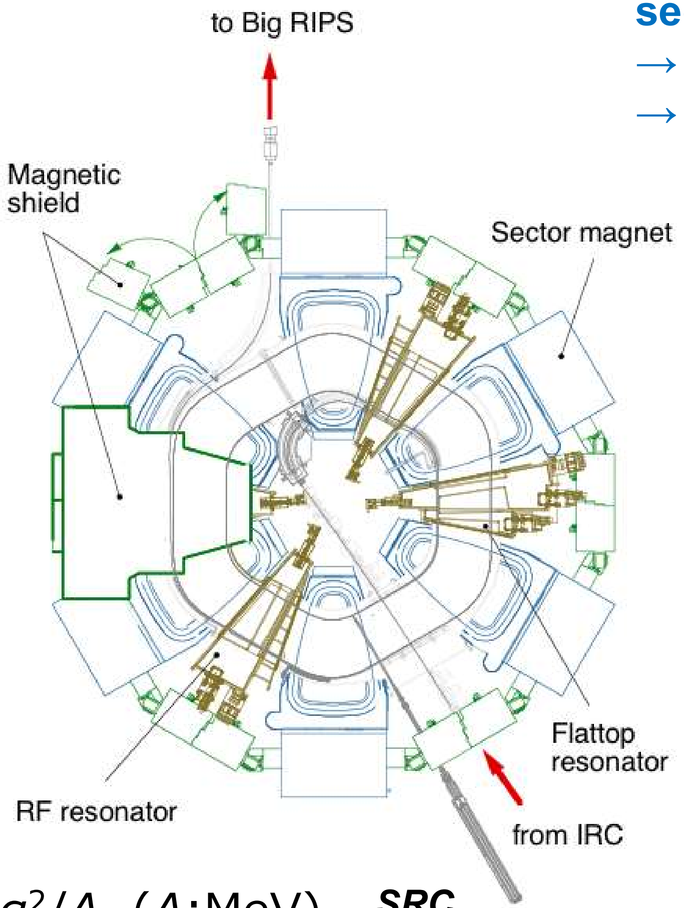
- **always makes strong focusing**
- **Edge focusing**

サイクロトロンの進化

Classical Cyclotron → **AVFCyclotron** → **Higher energies – Ring Cyclotron**



sector magnet structure
→ deep hill/valley
→ stronger edge focusing



SRC

K-value	2,600 MeV
No. of sectors	6
Extraction radius	5.36 m
Max. mag. field	3.8 T
No. of resonators	4
Magnet weight	8,100 t

Superconducting

サイクロトロンの超伝導化

AVFサイクロトロン
MSU K00 から始まった。

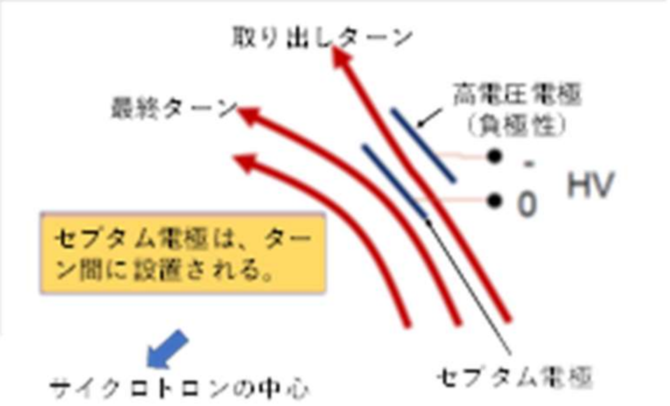
Ring Cyclotron
理研のSRCが唯一の適応例

K value

$$E = K \cdot q^2/A \quad (A \cdot \mathrm{MeV})$$

最初の超伝導サイクロトロン

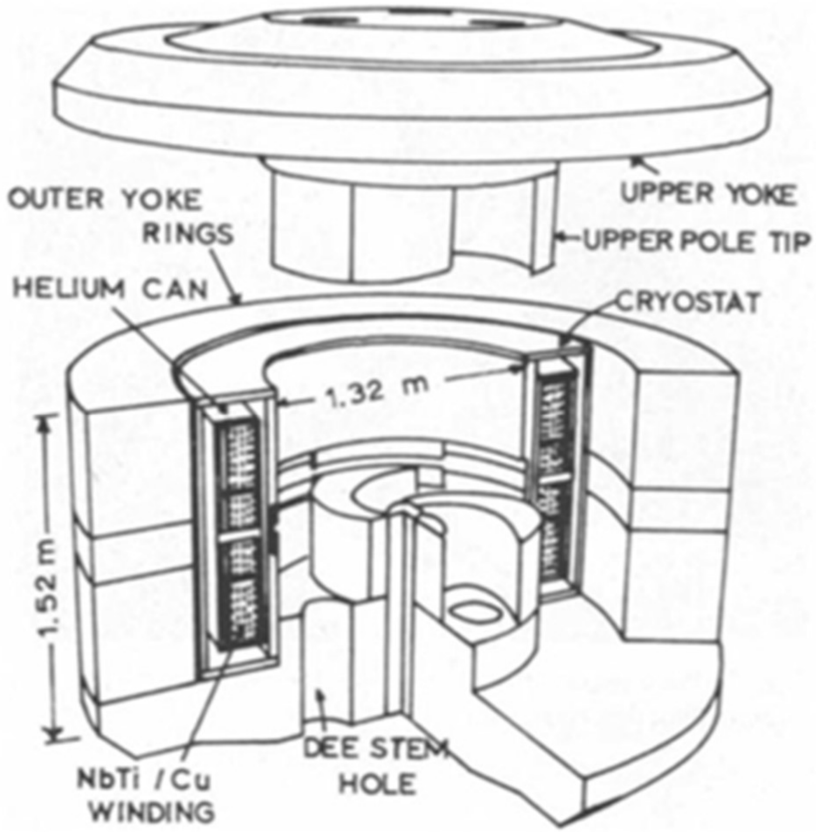
- 最初に超伝導コイルを用いたサイクロトロンのコンセプトを打ち出したのは、カナダChalkriver原子核研究所のBighamだった。
- 超伝導サイクロトロンを最初に作ったMSUのBlossorは、1972年にバンクーバーで行われたサイクロトロン国際会議で、このコンセプトに対して次の様に反論している。
- **“Superconductivity then seems unlikely to make a contribution to cyclotrons in the foreseeable future, primarily because there is no overriding problem which would thereby be solved such as it is the case for synchrotrons and linacs.”**
- Blossorの主な心配は、超伝導磁石によりサイクロトロンが小さくなる事により、ビームの質や取り出しに問題が出てくるのでは無いかという事である。しかし、程なく、Blossorは、その考えを改め、1973年に超伝導サイクロトロンの超伝導磁石の実証機の検討を始めることを決定し、1974年には超伝導サイクロトロンの設計を発表した。

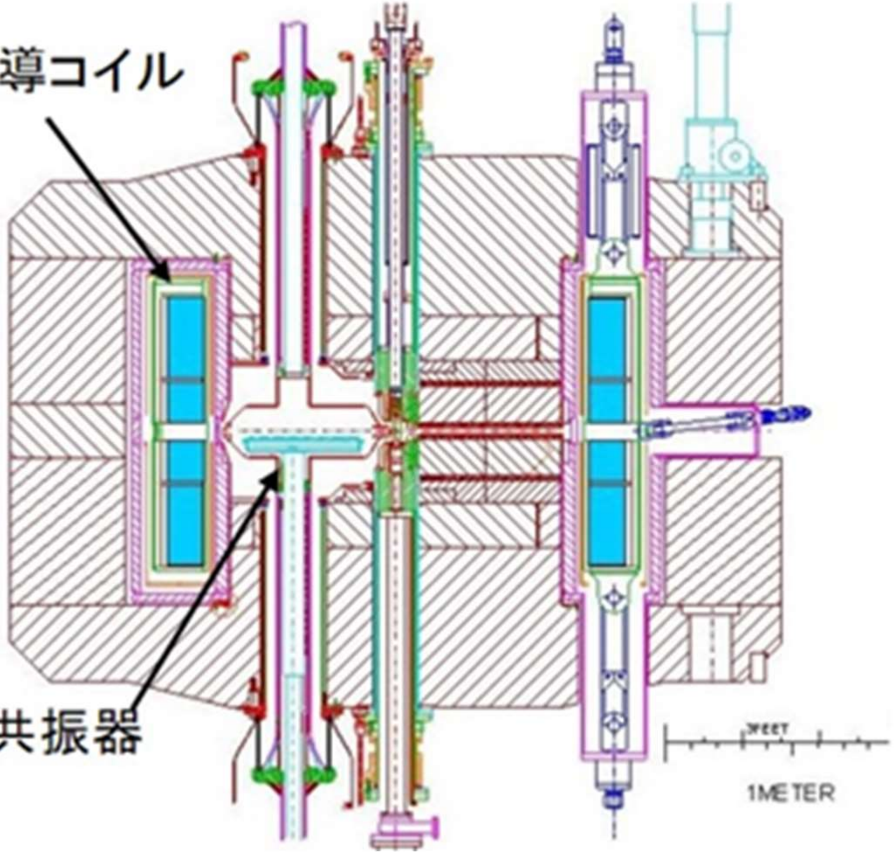


Henry Blosser, 1928-2013

https://snf.ieeecsc.org/obituary/henry-blosser

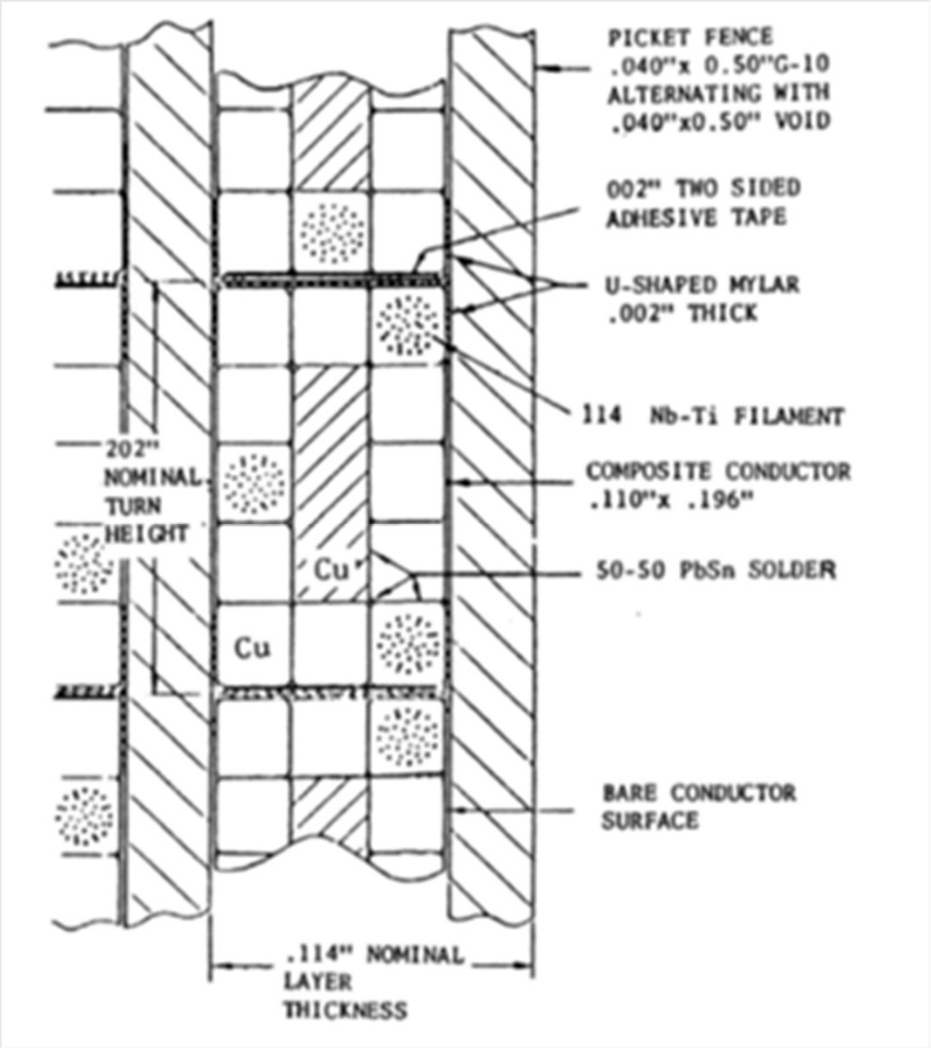
MSU K500




超伝導コイル

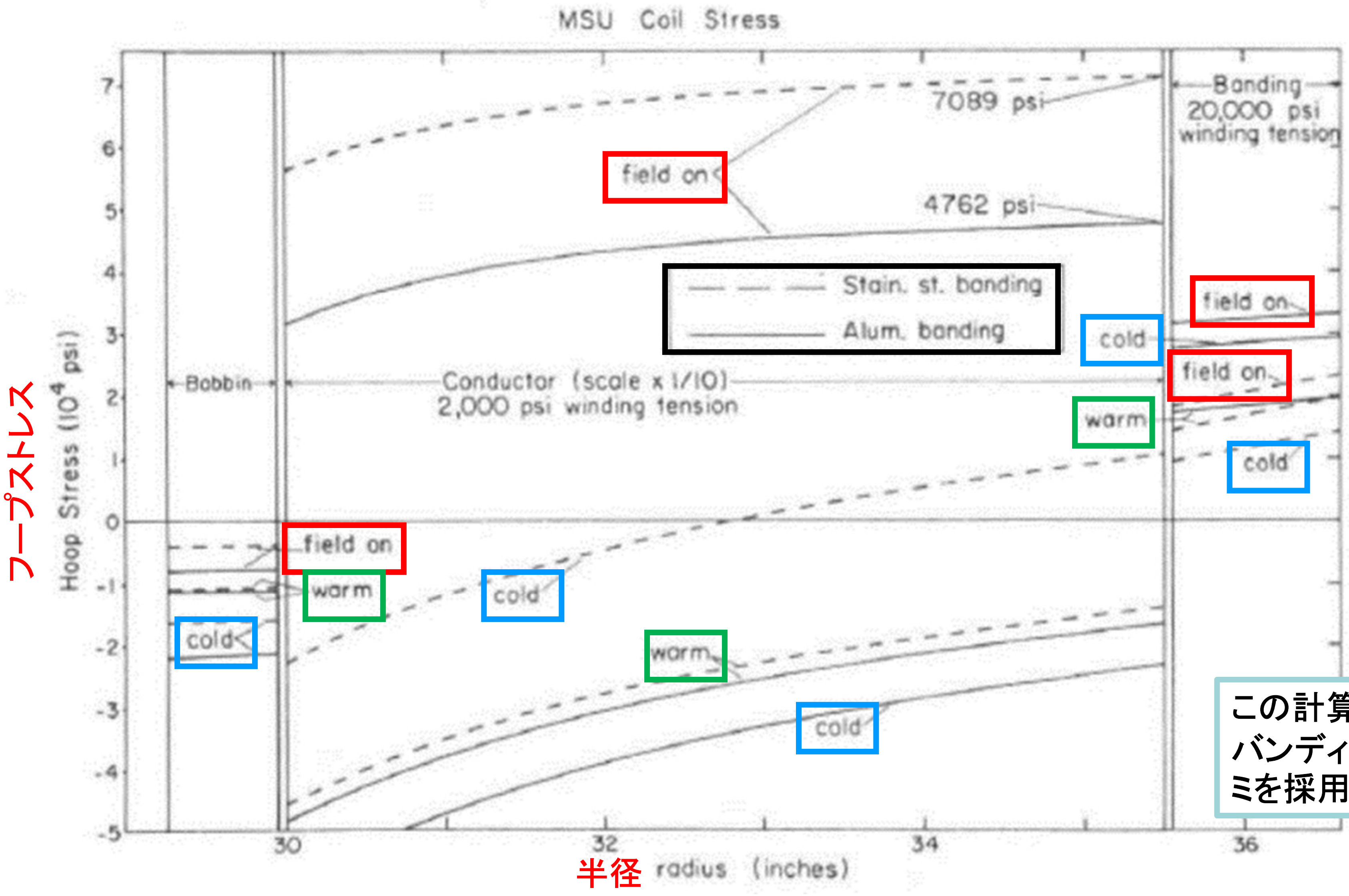
加速共振器

K500用の超伝導導体



Size: 0.110 inch x 0.196 inch

コイル内の応力の履歴



この計算結果から
バンディングはアル
ミを採用

K500のトラブル

（1）コイル容器内の液体ヘリウム低で最大励磁からのクエンチ（空焚き）

（2）断熱真空の破れ

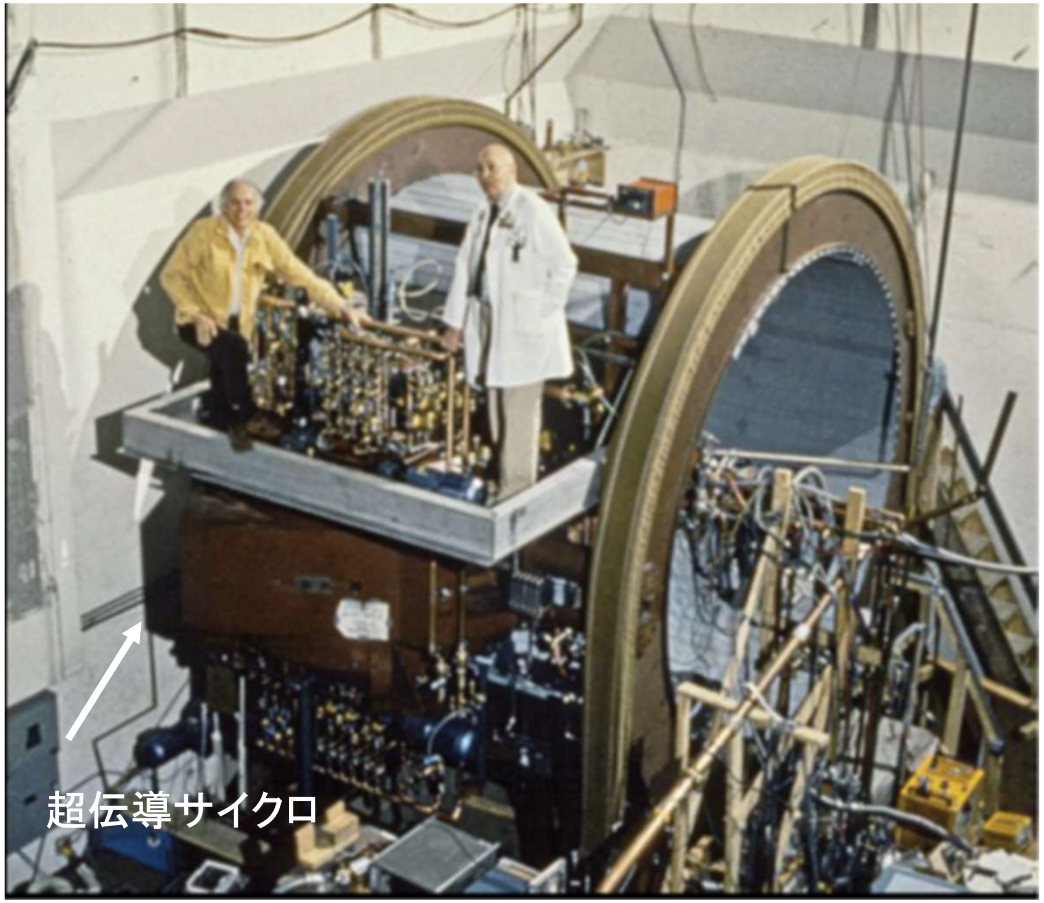
（3）断熱支持棒の損傷。

（4）コイル内には小さな切子がある様で、ショートがあり、定常状態では問題にならないが、励磁や減磁の際には“ミニクエンチ“という興味深い現象が起きていた。

（3）に関連して、

ビーム軌道面を挟む形で設置されている一対のコイルは互いに引き合うが、コイル全体は不安定な位置に置かれているという事である。つまり、コイル全体の位置の微小なずれに対して復元力が働くわけではなく、そのずれを助長するような向きに力が働くという事である。そのため、鉛直方向の支持棒は、その負のばね定数より十分大きいばね定数を持っている必要がある。この設計を誤るとコイルを損傷することになるため、気を付ける必要がある。（Superferic磁石の落とし穴）

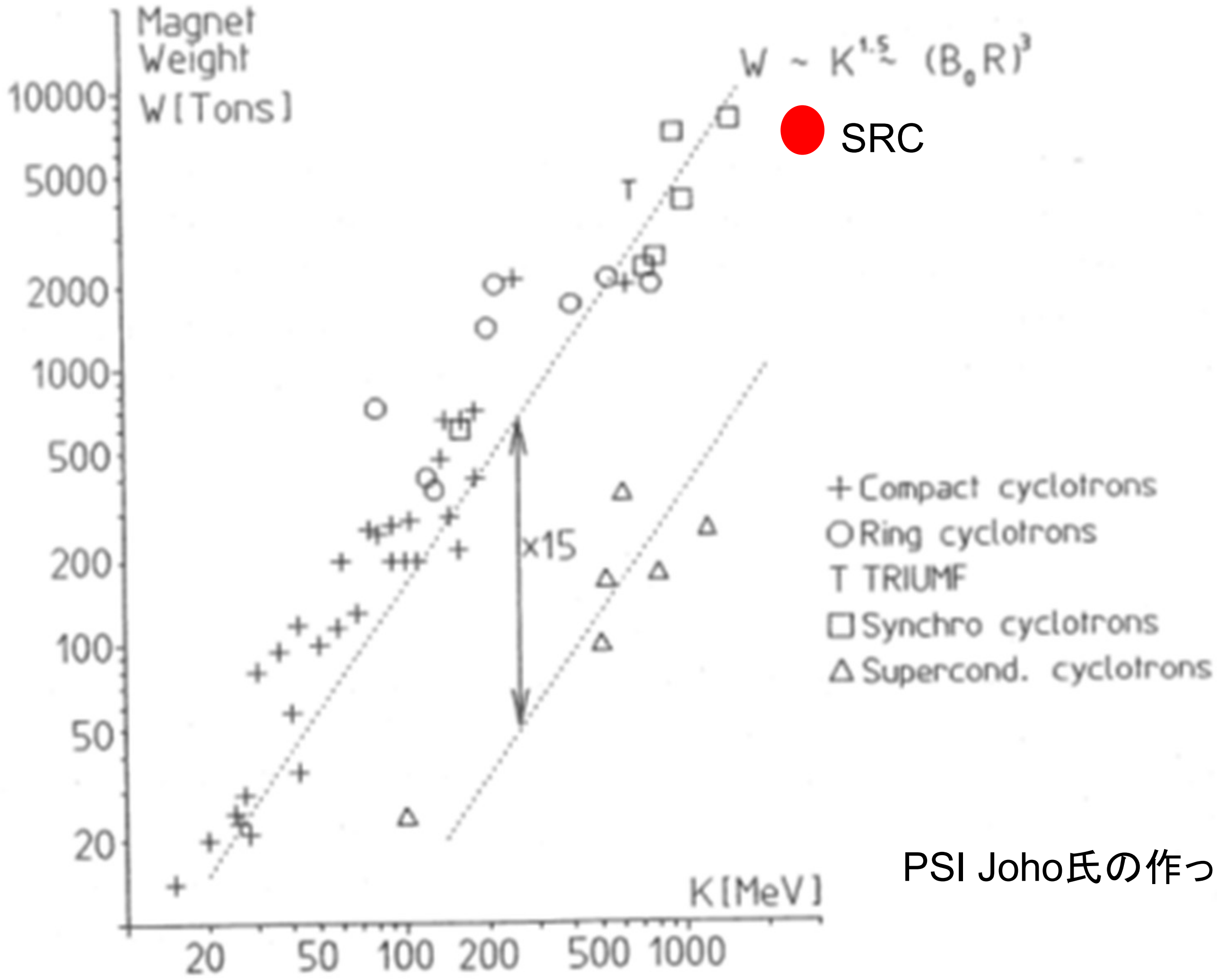
K500後の超伝導サイクロトロン



K500 MSU (USA)
K520 Chalk River (Canada)
K1200 MSU (USA)
K800 Milano (Italy)
K500 Texas AM (USA)
K600 AGOR (Netherland)
K500 Calcutta (India)

デトロイト病院に納められた中性子がん治療用の回転可能な超伝導サイクロトロン（軽量化のためにできる事）

超伝導サイクロトロンの重さ



サイクロトロンを超伝導化することにより15倍軽くなる。

SRCの重さは常伝導サイクロ並み

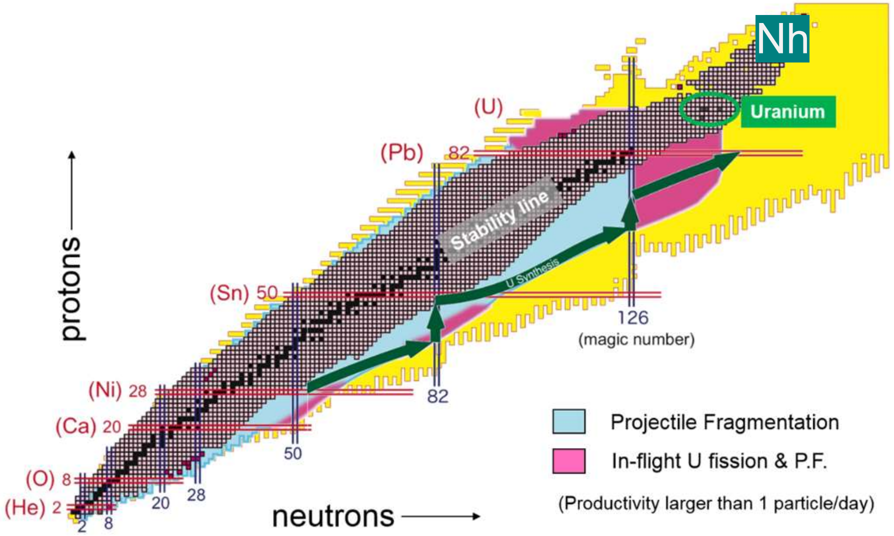
PSI Joho氏の作ったグラフ

超伝導リングサイクロトロン@RIビームファクトリー

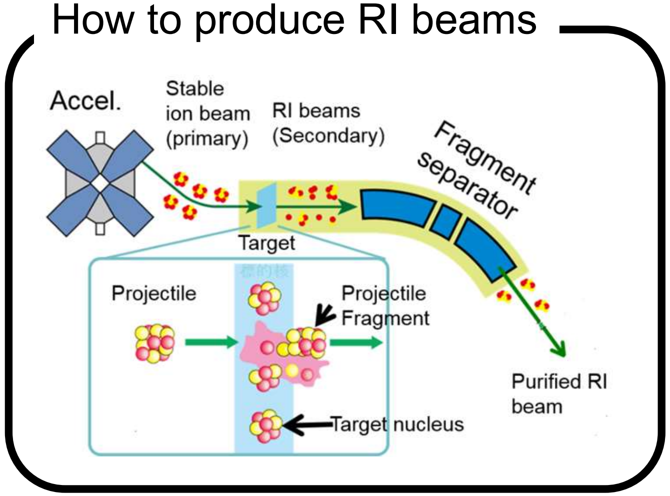
項目	MSU	SRC
重さ	AVFサイクロトロン	リングサイクロトロン
重さ	100ton	8300ton
蓄積エネルギー	18MJ	245MJ
コイル	円形コイル	非円形コイルの組み合わせ
コイル冷却	浸漬冷却	浸漬冷却
鉄の使用	Superferic	Superferic
その後の適用例	多数	ゼロ

Goal of RIBF

- Great expansion of the nuclear chart (new 1000 kinds of isotope, exotic nuclei)
- Challenge to solve the big puzzle of element genesis (r-prosess = U-synthesis)
- Promotion of industrial and biological applications



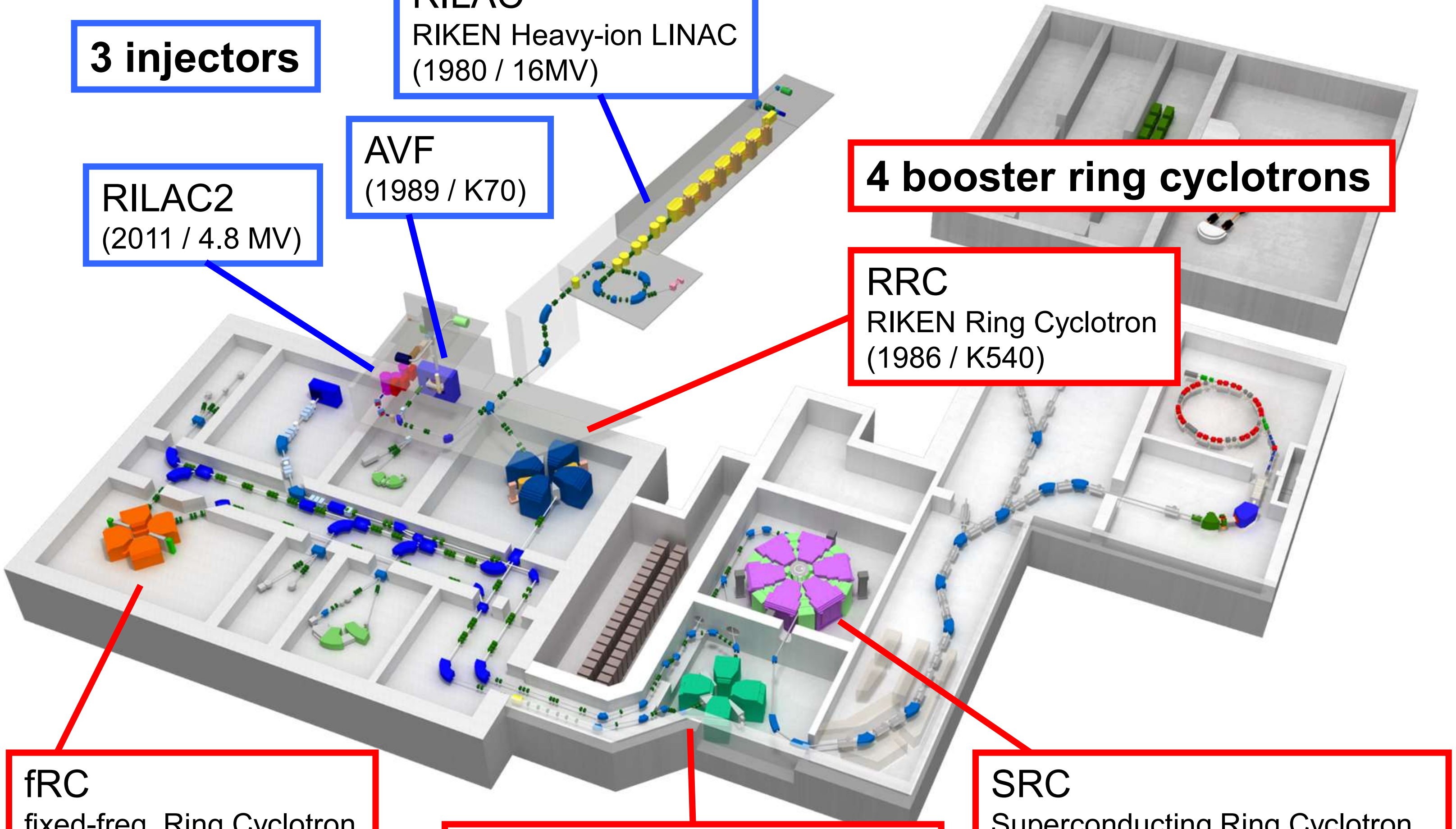
Tetra neutron


How to produce RI beams

- RI beams are generated by fragmentation or fission of high-speed heavy ion beams.
- Accelerator complex is required to produce high speed heavy ion beams with high intensity.

RIBF accelerators

Y. Yano, NIM B261 (2007) 1009.



3 injectors

RILAC
RIKEN Heavy-ion LINAC
(1980 / 16MV)

AVF
(1989 / K70)

RILAC2
(2011 / 4.8 MV)

4 booster ring cyclotrons

RRC
RIKEN Ring Cyclotron
(1986 / K540)

fRC
fixed-freq. Ring Cyclotron
(2006 / K570 => K700)

IRC
Intermediate-stage Ring Cyclotron
(2006 / K980)

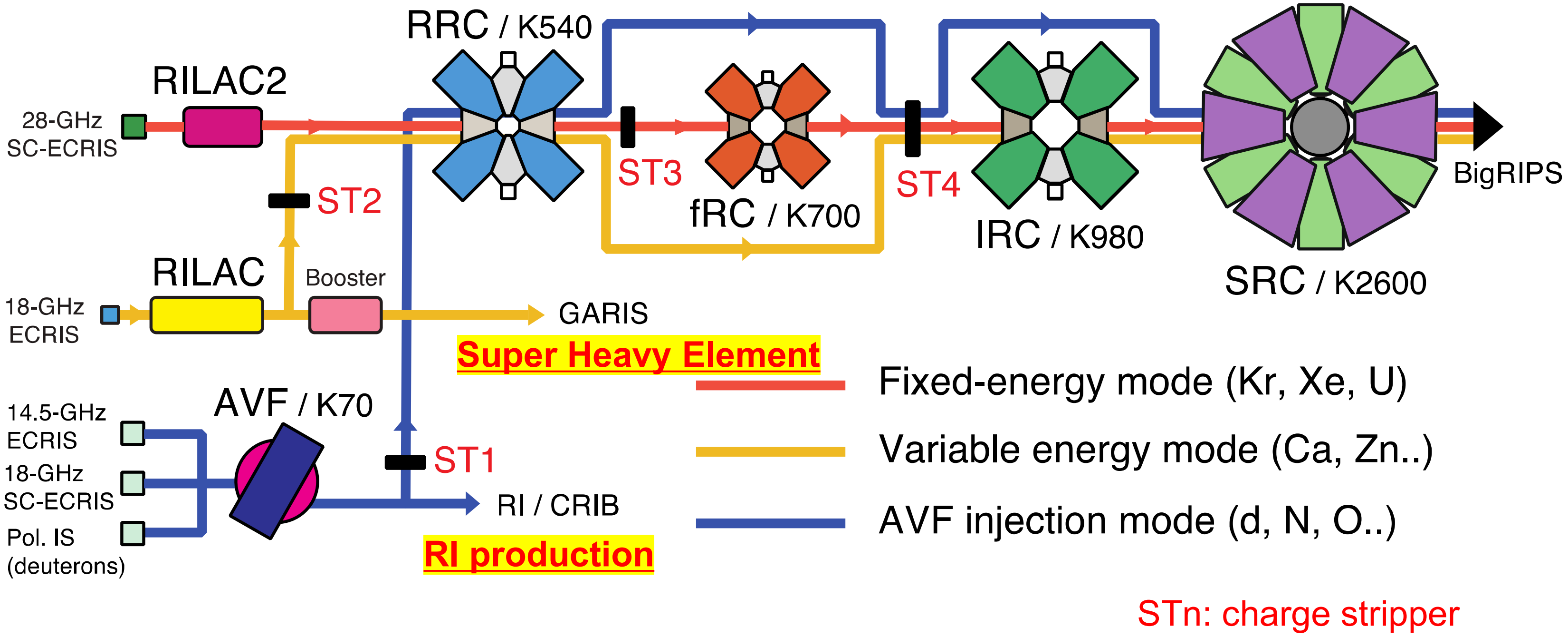
SRC
Superconducting Ring Cyclotron
(2006 / K2600)

Acceleration modes

Accelerate ALL ions (from H_2^+ to U), up to 70% of the light speed, in CW mode

3 injectors + 4 booster ring cyclotrons

1) AVF-injection mode (< 440 MeV/u) : d, He, O, …
2) Variable-energy mode (< 400 MeV/u) : Ar, Ca, Zn, Kr, …
3) Fixed-energy mode (345 MeV/u) : Xe, U …



STn: charge stripper

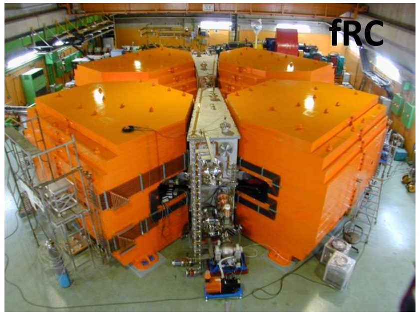
Specifications of RIBF ring cyclotrons

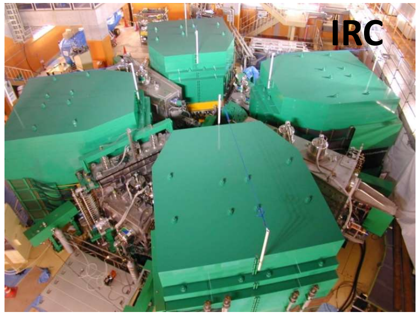
Challenging

	RRC (1986~)	fRC	IRC	SRC
K-number (MeV)	540	700	980	2600
R_{inj} (cm)	89	156	277	356
R_{ext} (cm)	356	330	415	536
Weight (tons)	2400	1300	2900	8300
Sector magnets	4	4	4	6
Number of trim coils (/ main coil)	26	10	20	4 (SC) 22 (NC)
Trim coil currents (A)	600	200	600	3000 (SC) 1200 (NC)
RF resonators	2	2+FT	2+FT	4+FT
Frequency range (MHz)	18～38	54.75	18～38	18～38
Acceleration voltage (MV)*	0.28	0.8	1.1	2.0
Turn separation (cm)*	0.7	1.3	1.3	1.8

*uranium acceleration

SC : superconducting, NC : normal conducting, FT : flattop resonator





SRC:ギネス世界記録®に登録。何が世界一なのか？

□ビームエネルギー最大値のサイクロトロン(Highest beam energy cyclotron) 82400MeV

□(マニアックすぎる）K値：K=2600 MeV（加速粒子の磁気剛性）

238 X 346.2 MeV/u

□(重さが測るのが大変）重いサイクロトロン (8300 トン)

□大きさ(直径）は2番目（1位はTriumf）

□昔欧米の研究者は製作不能と言う結論を出した（幻のサイクロトロン）←日本の技術力

2022年4月11日登録
(埼玉県和光市)

2022年3月28日エネルギー測定（KEK下村先生、QST羽島先生立ち合いの元）

東京スカイツリー
40000 ton

SRC
8300ton
↑
x2
↑
東京タワー
4000 ton

SRC: 超伝導リングサイクロトロン

K = 2,600 MeV
最大磁場: 3.8T (235 MJ)
Rf **周波数**: 18-38 MHz
重さ: 8,300 tons
直径: 19m **高さ**: 8m

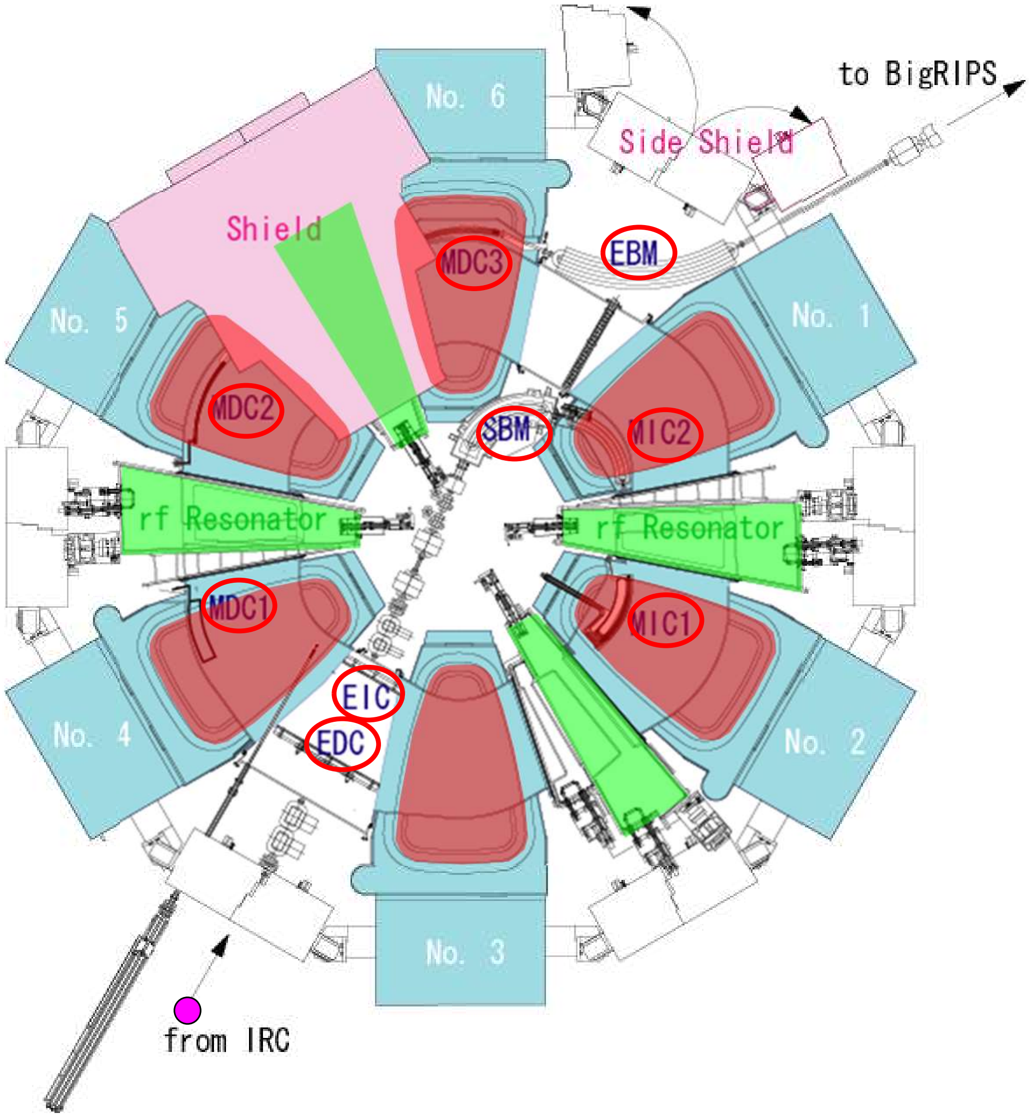
セクター電磁石 :6
Rf **共振器** :4
入射機器:
取り出し機器:

自己磁気遮蔽
自己放射線遮蔽

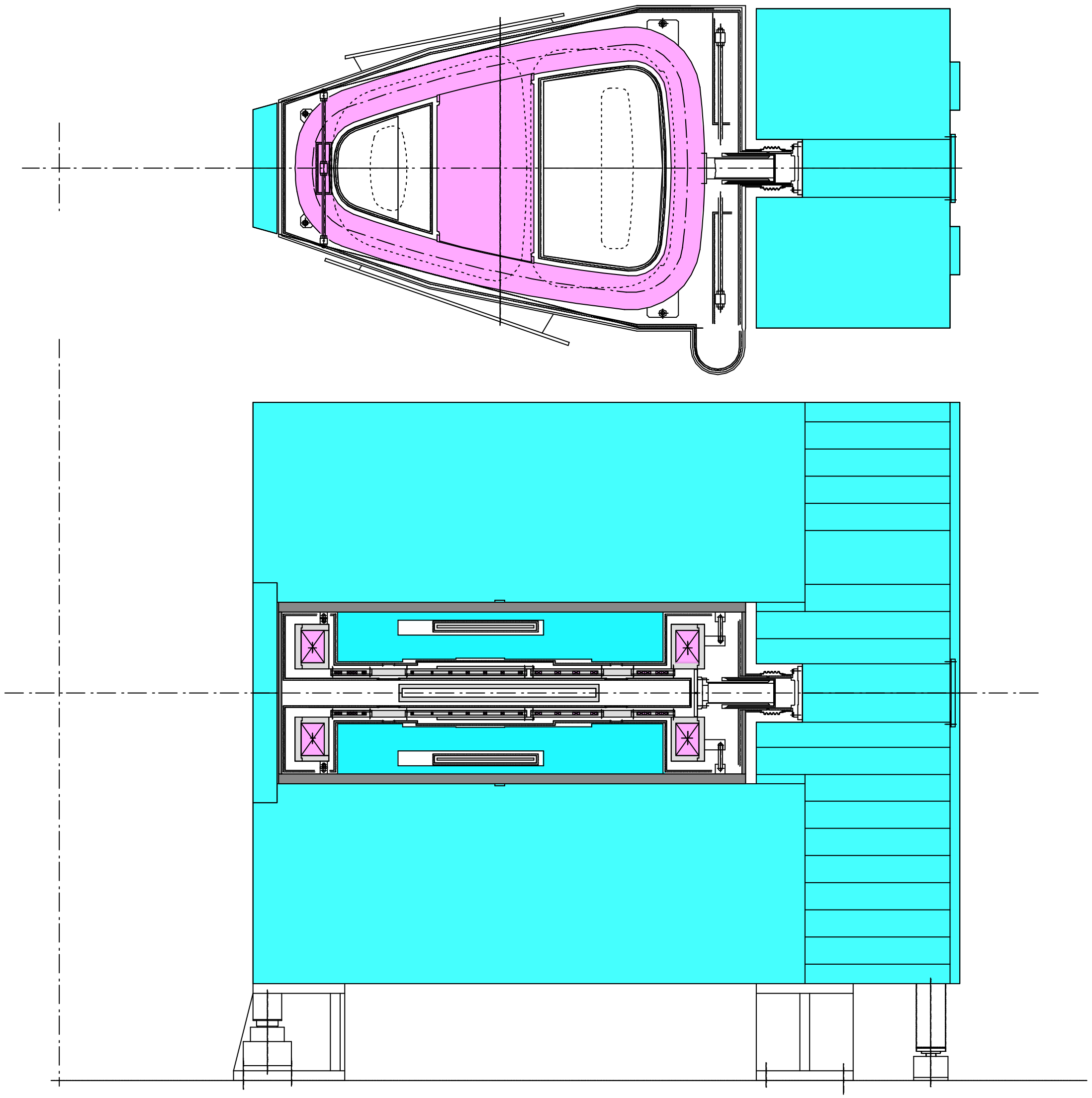
SRCの中の超伝導磁石

1) セクター磁石

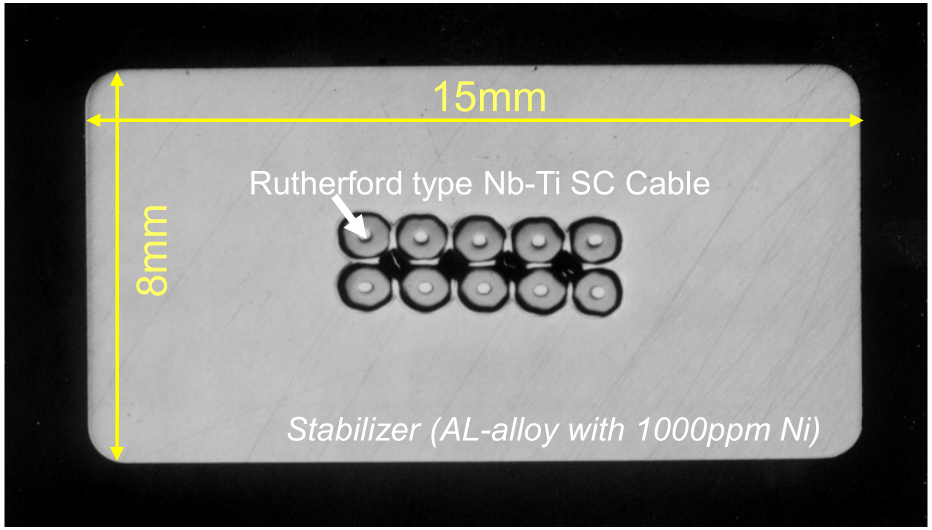
2) 入射用超伝導偏向磁石

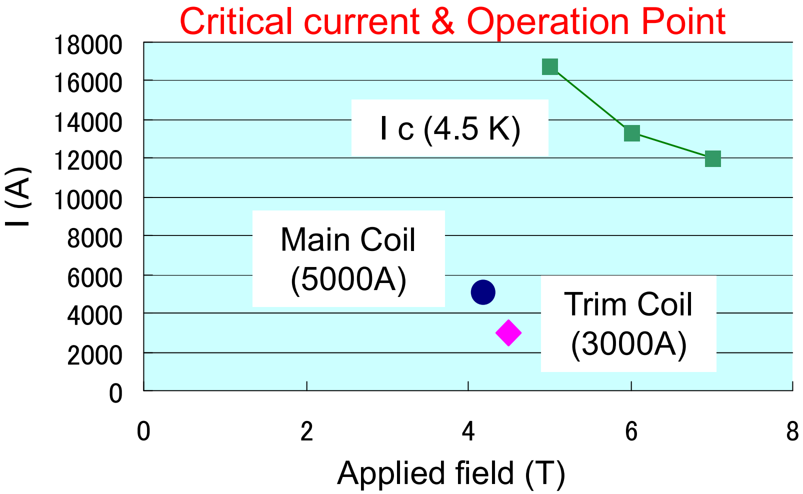


セクター磁石



Superconductor(Al安定化導体)





Yield Strength > 56.2 MPa

(cf. 40 MPa for pure Al)

RRR of Al > 803

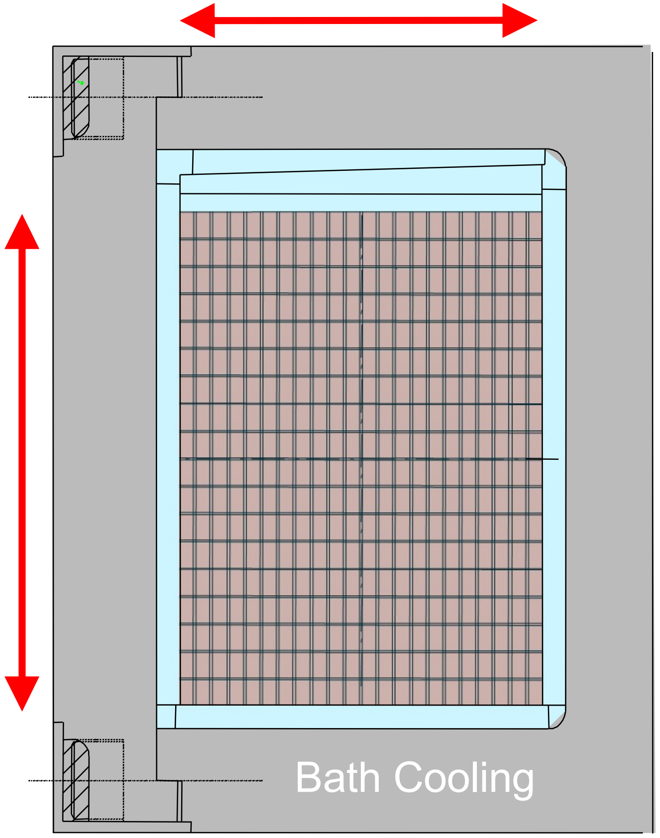
Structure of the Main Coil Block

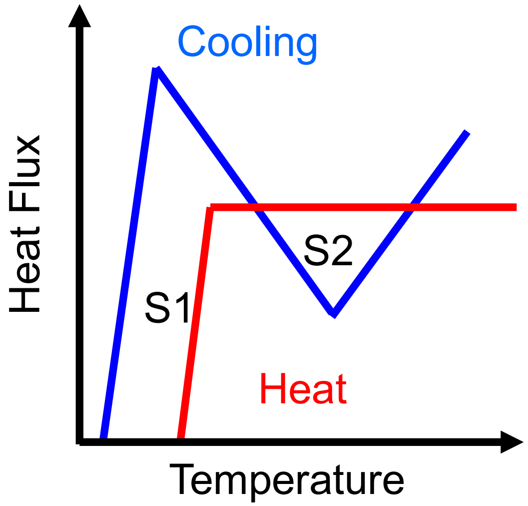
Solenoid winding with 396 turns

18 layers (Vertical gap: 1.5 mm)

Cooling Channel (50 %)

22 turns (Horizontal gap: 0.8 mm)

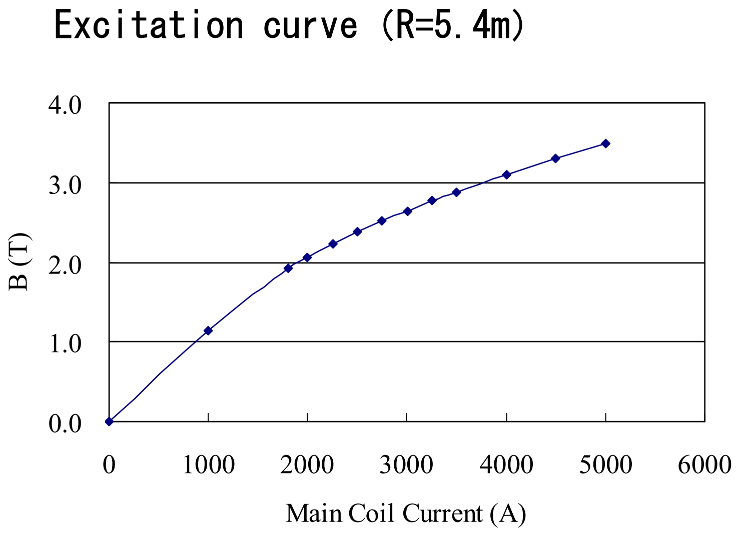




S1=S2 →

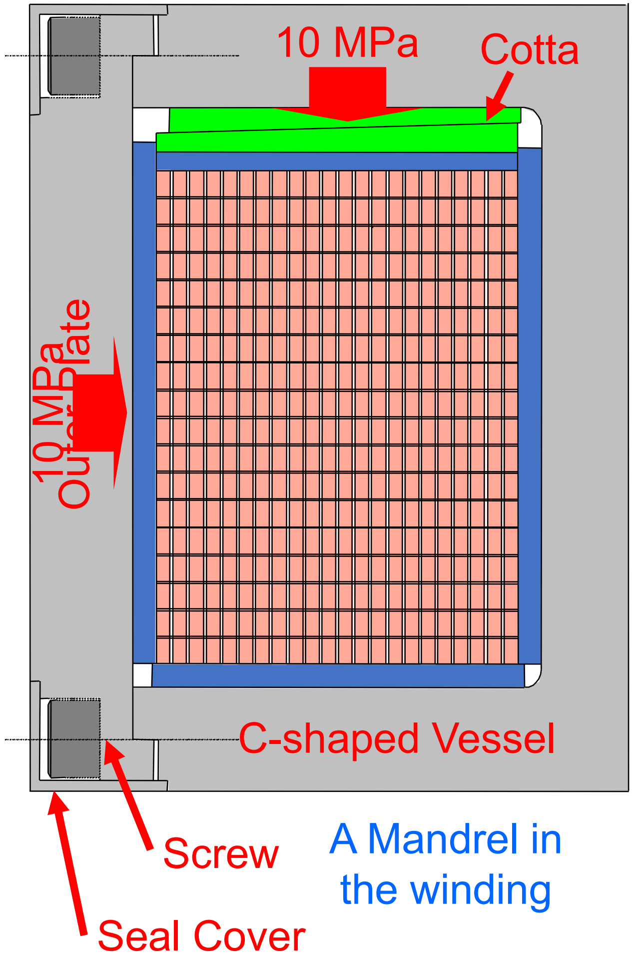
Madock Stabilization current:6300A

> Operational Cuurent:5000 A


Excitation curve (R=5.4m)

Fabrication of the Main Coil

Accuracy of the Center of the Coil < ±1 mm



10 MPa

Cotta

10 MPa

Outer Plate

C-shaped Vessel

Screw

Seal Cover

A Mandrel in the winding

Completion of the Main Coil

Tension of 20 MPa

Superconducting trim coil

#Four sets of coils

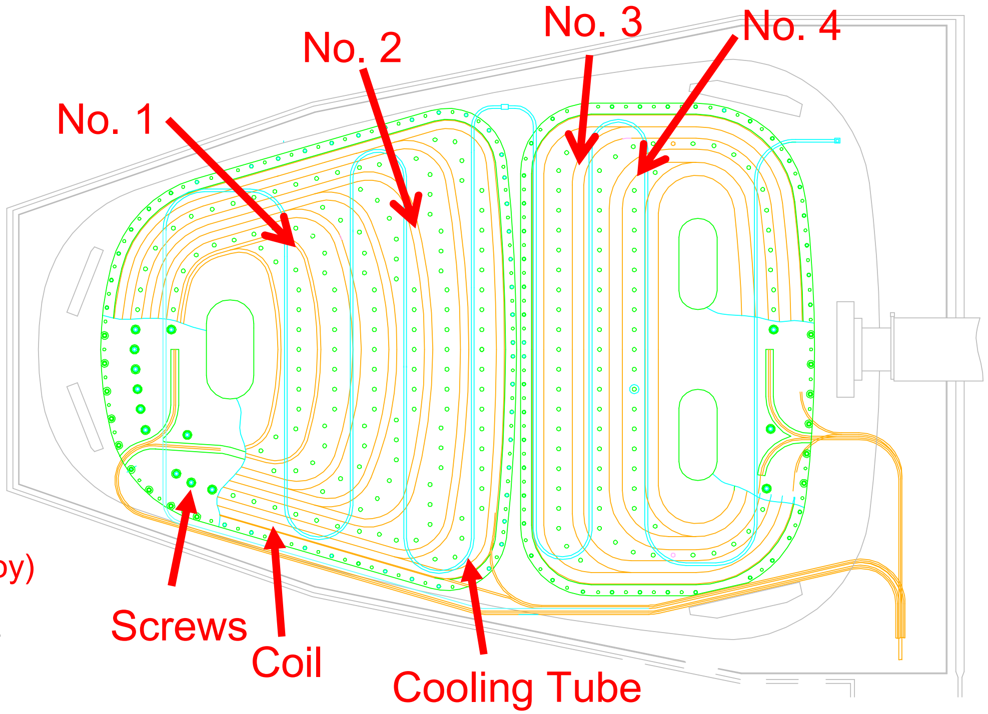
I max = 3000 A

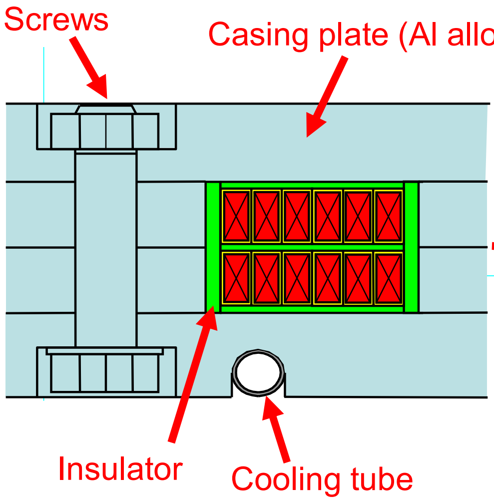
#Double pancake winding

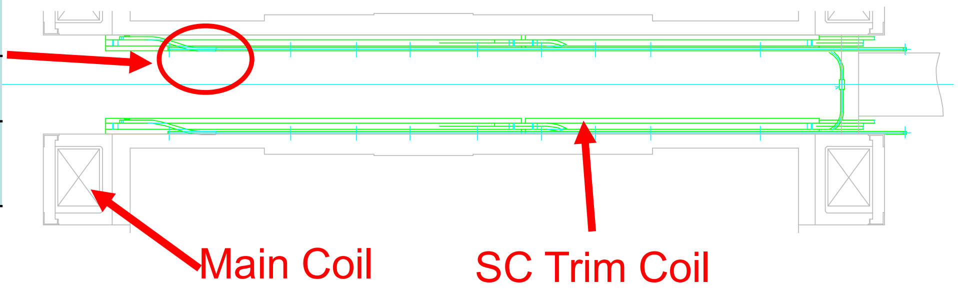
#Indirect cooling

by forced 2 phase helium

#Temp. margin ~2.1K

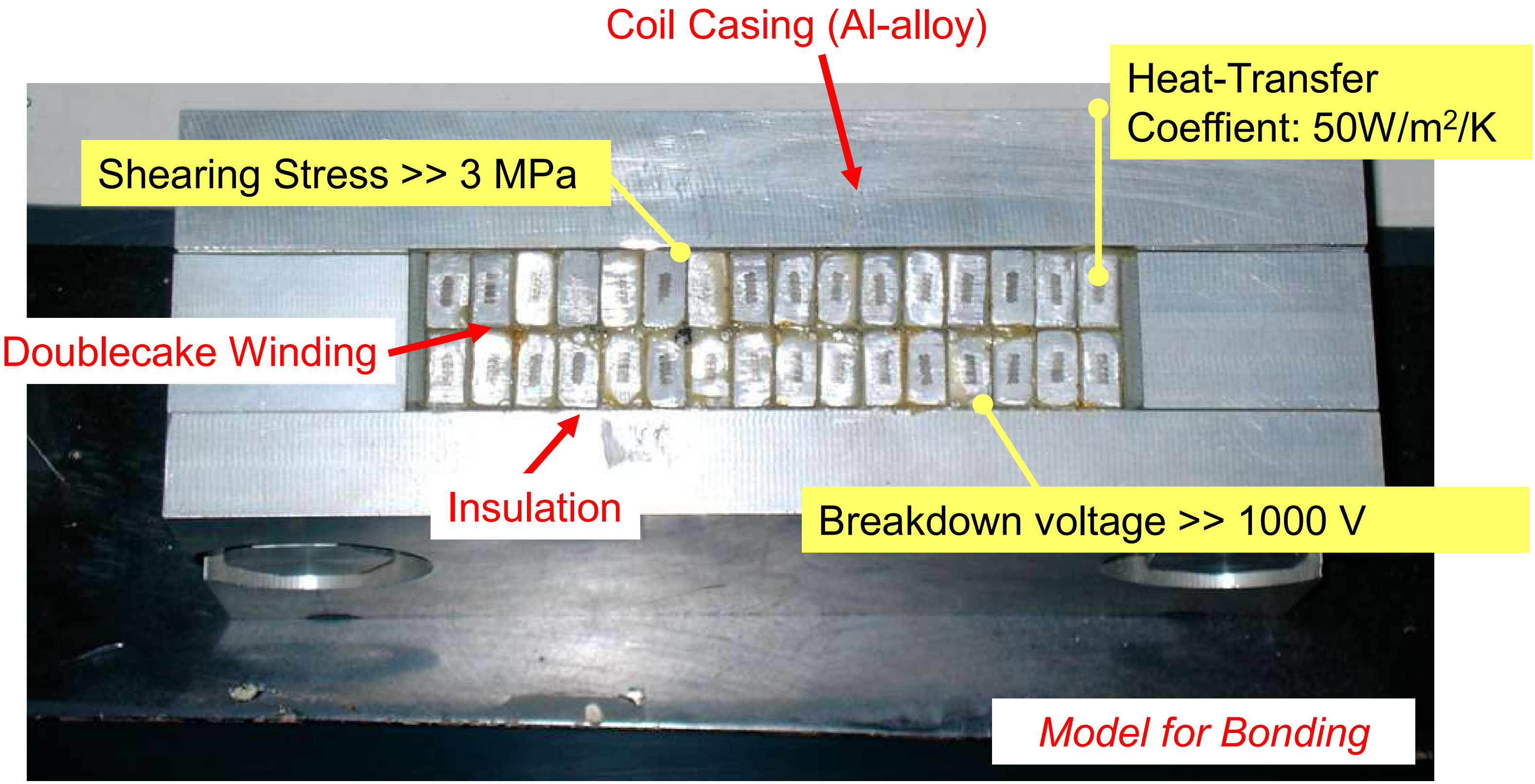






Structure of the SC Trim coil

Bonding of the coils and casing, which satisfied the following three condition, was studied.



Coil Casing (Al-alloy)

Heat-Transfer Coeffient: 50W/m^2/K

Shearing Stress >> 3 MPa

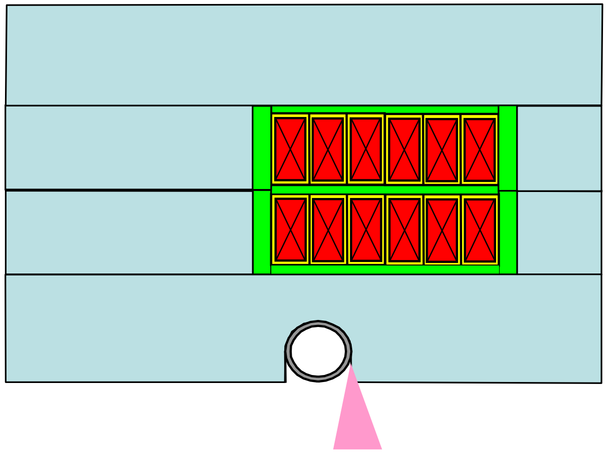
Doublecake Winding

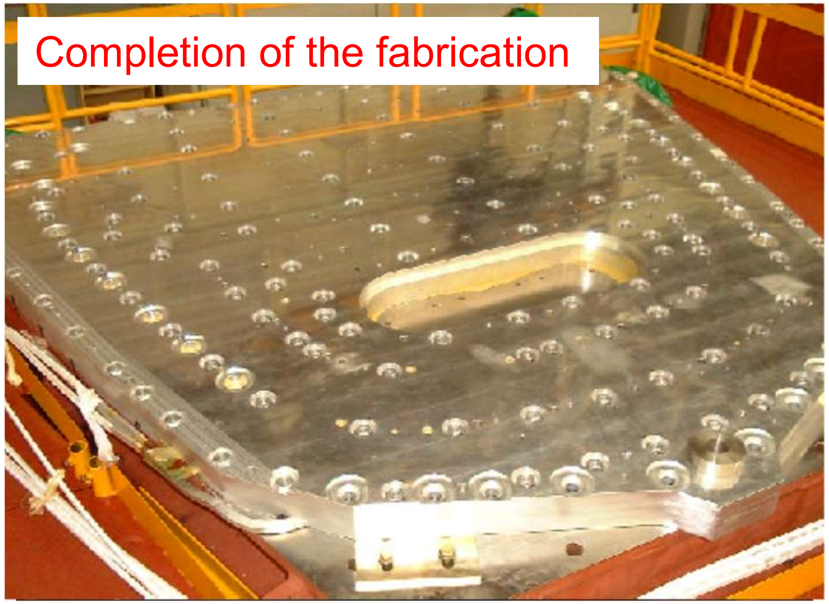
Insulation

Breakdown voltage >> 1000 V

Model for Bonding

Fabrication of the SC Trim Coil

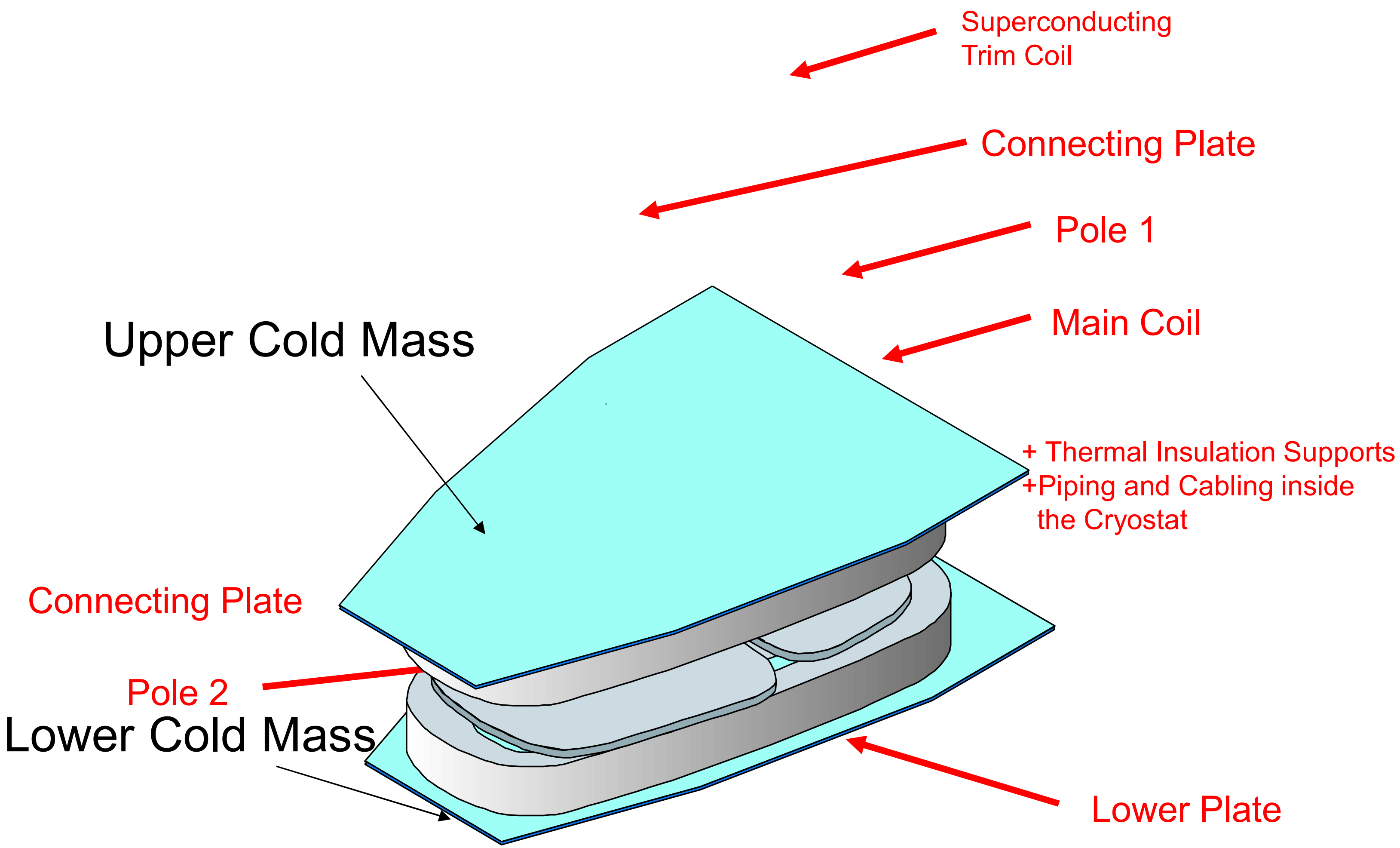




Completion of the fabrication

The coil is cured at about 150 degree with a pressure of 2 MPa.

Structure of the cold mass unit



Superconducting
Trim Coil

Connecting Plate

Pole 1

Main Coil

+ Thermal Insulation Supports
+Piping and Cabling inside
the Cryostat

Upper Cold Mass

Connecting Plate

Pole 2

Lower Cold Mass

Lower Plate

Assembling in R

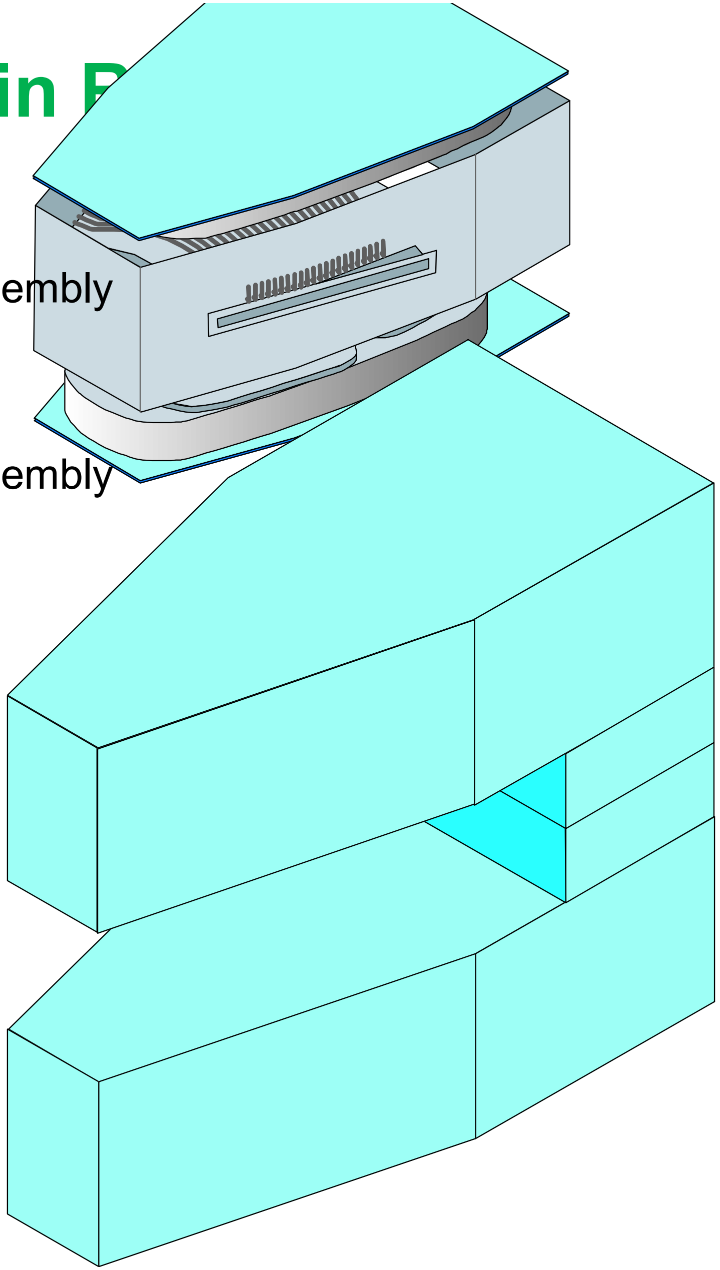
1. Lower Yoke

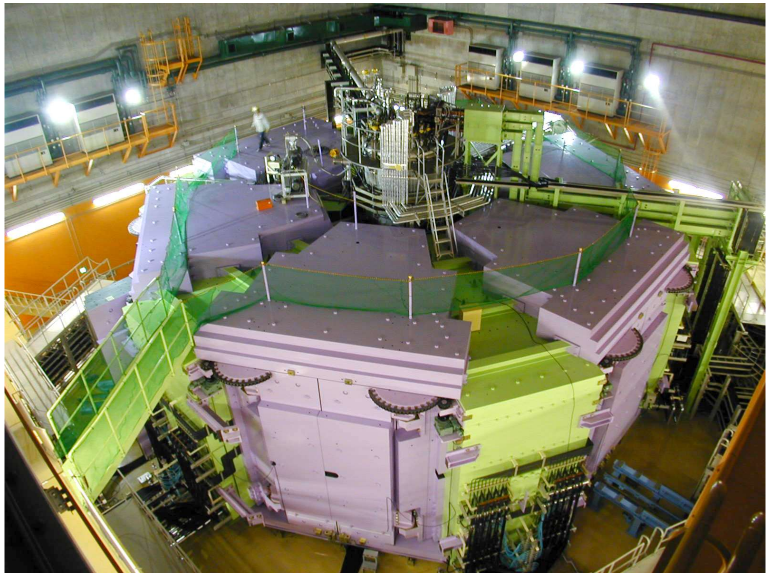
2. Lower Cold Mass Assembly

3. Cryostat

4. Upper Cold Mass Assembly

5. Upper Yoke



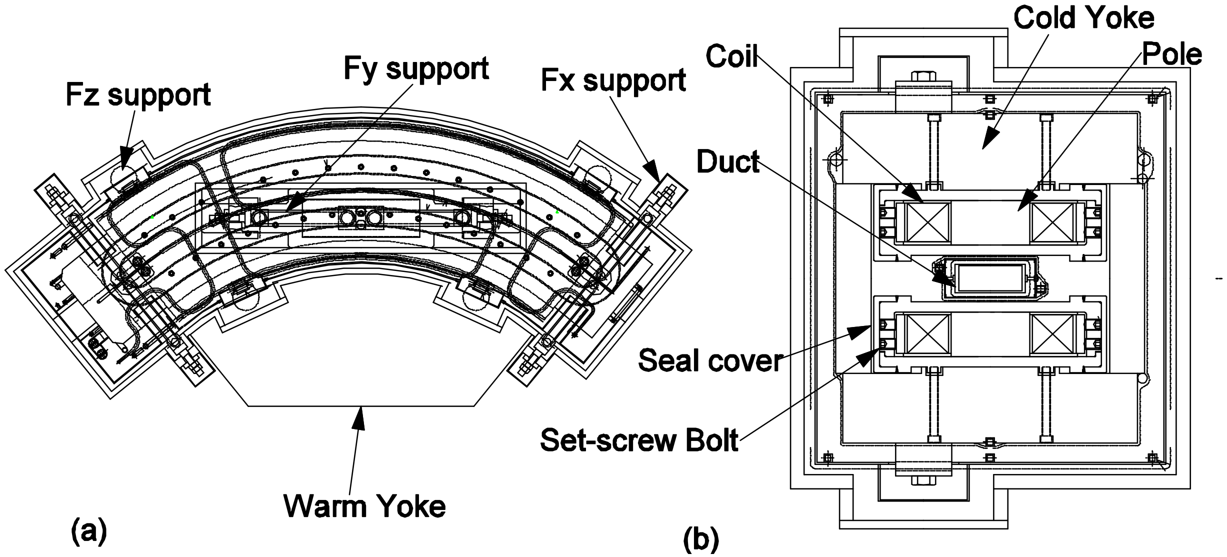


SRCの組み
立ての様子

Specifications of SBM

Plan view

Cross sectional view of the cryostat



Specifications	
Required field :	3.8 T @363 A
Stored Energy:	0.56 MJ
Homogeneity:	few x 10^{-3}
Beam Bore:	40 (H) x 30 (V) mm^2
Radius:	1208mm
Bending Angle:	75.72 deg.
Coil cross section:	55 x 58 mm^2

Trajectory is bended.

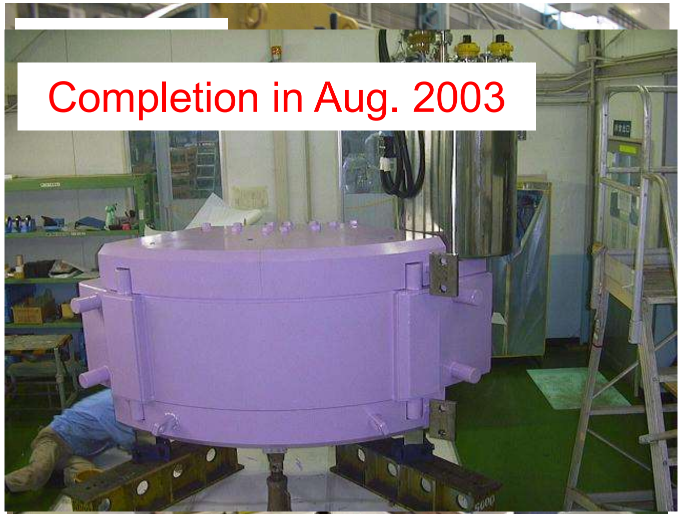
→The coil should be bended.

→Coil winding is the key issue.

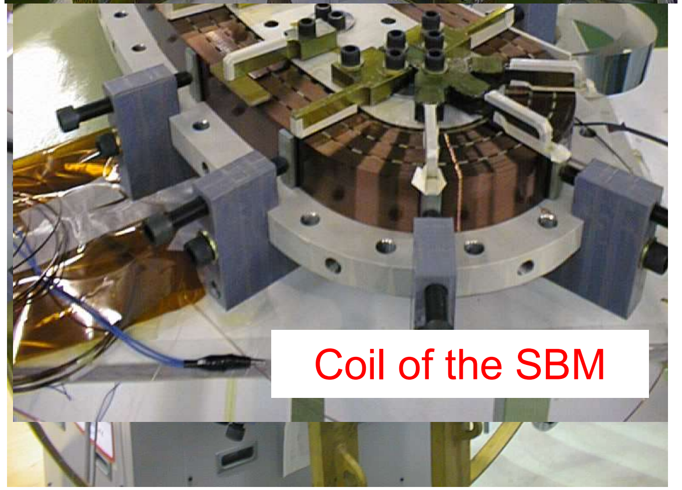
(Negative curvature)

Coil Winding & First Excitation of SBM

Cabling of Superconducting Wires

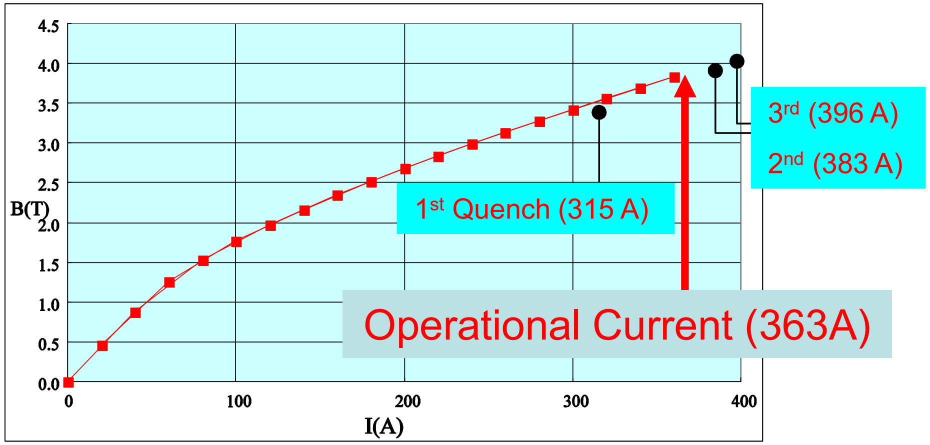


Completion in Aug. 2003



Coil of the SBM

Results of the First Excitation

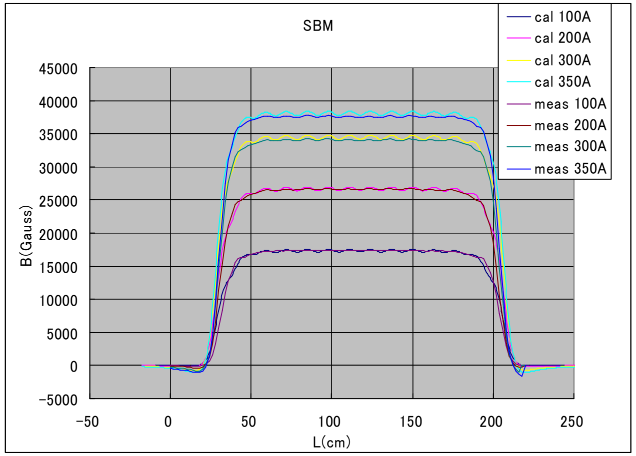


3rd (396 A)

2nd (383 A)

1st Quench (315 A)

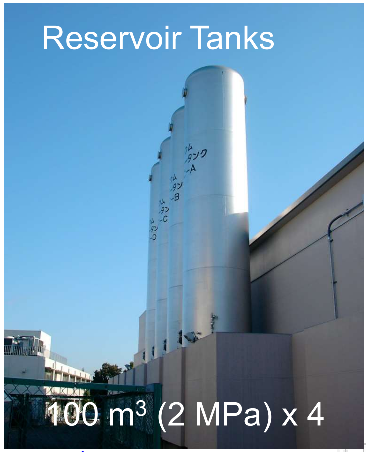
Operational Current (363A)



Cool-down and excitation test of the SRC

Date	Events	Date	Event
05/8/30 – 05/9/17	Purification (N2:< 0.5ppm)	05/11/6	Excitation test (Imain = 5000 A (Max.))
05/9/19	The 1st Cool-down started	05/11/7	Exciation test (Imain = 5000 A, Itrim = 3000 A)
05/10/13 1:00AM	All the main coils transited to superconducting state.	05/11/8	*Trouble due to a He leak*
05/10/16	Level of liquid helium reach up to the operation level.	06/3/16-	The 2nd Cool-down started.
05/10/21	Excitation test started. (Imain =100A)	06/4/15	Full excitation again
05/10/27	Excitation test (Imain=1000 A, Itrim=1000A)	06/4/17-06/6/14	Field measurements
05/10/31	Exciation test (Imain = 3000 A, Itrim = 3200 A (Max.))	06/6/14	Fast shutdown test from full excitation

Cryogenic Cooling System for the SRC


Reservoir Tanks

100 m^3 (2 MPa) x 4

Cooling Capacity

620 W @ 4.5 K

4000 W @ 70 K

4 g/s for cooling of C. L.

Trial run in Dec. 2004

\>>

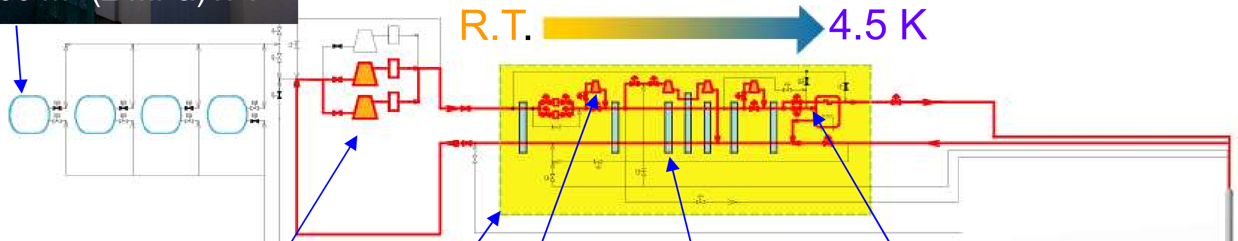
Heat Load

470 W @ 4.5 K

2800 W @70 K

3 g/s for cooling of C.L.

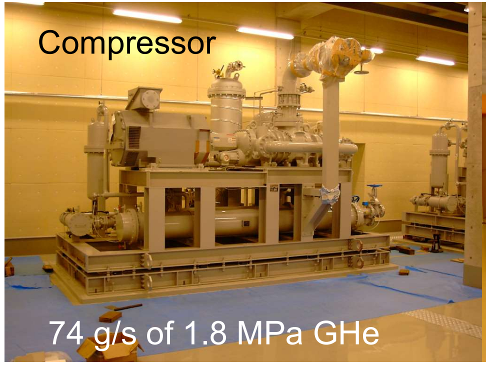
21 days for initial cooling


R.T. → 4.5 K

Turbine

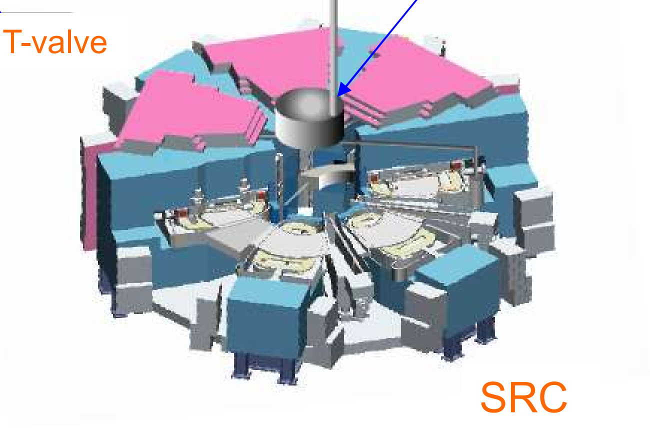
Heat exchanger

JT-valve


Compressor

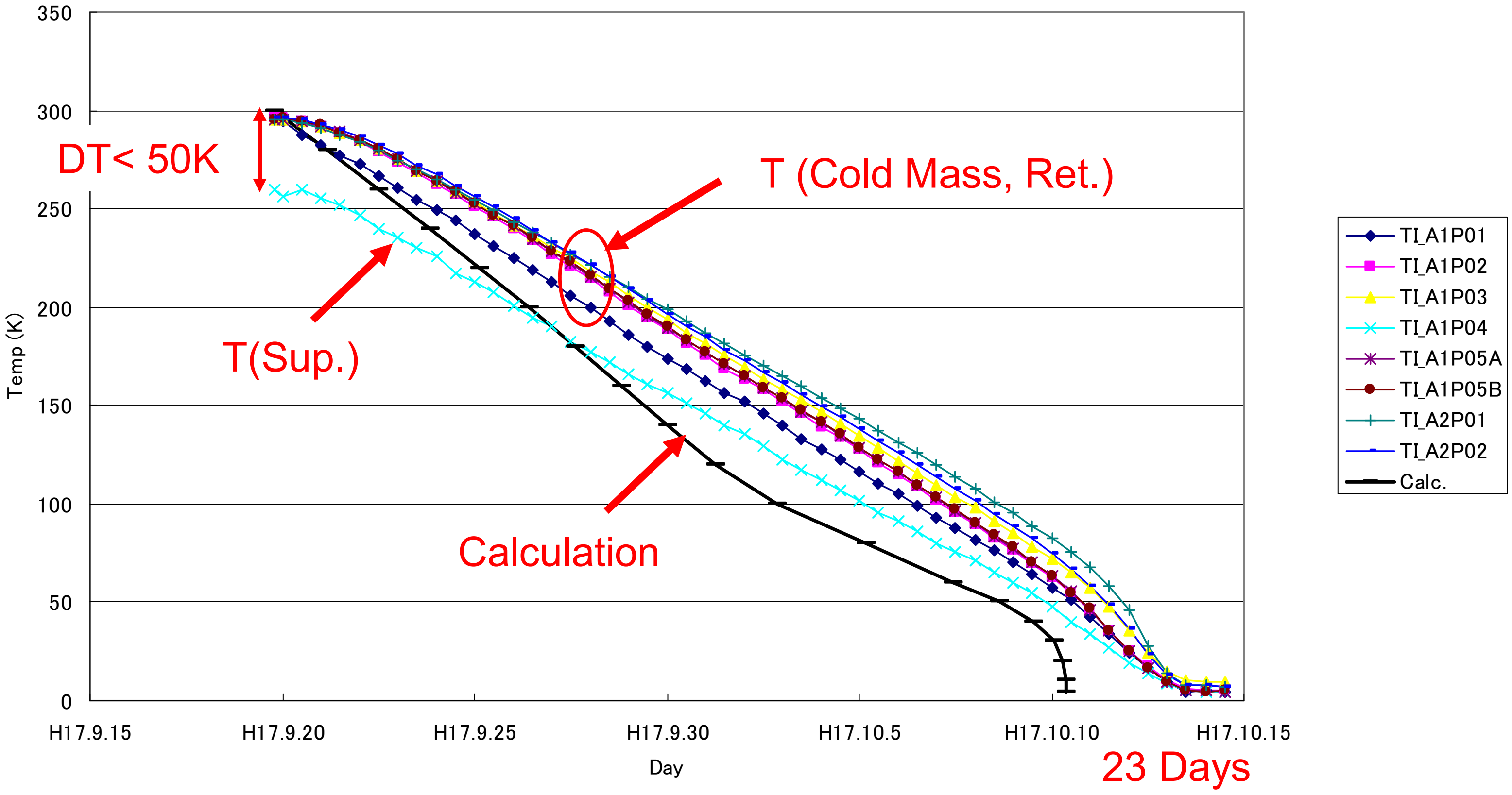
74 g/s of 1.8 MPa GHe


Refrigerator


Control dewar

SRC

Cool-down curve in the first trial



Power supplies and coil protection

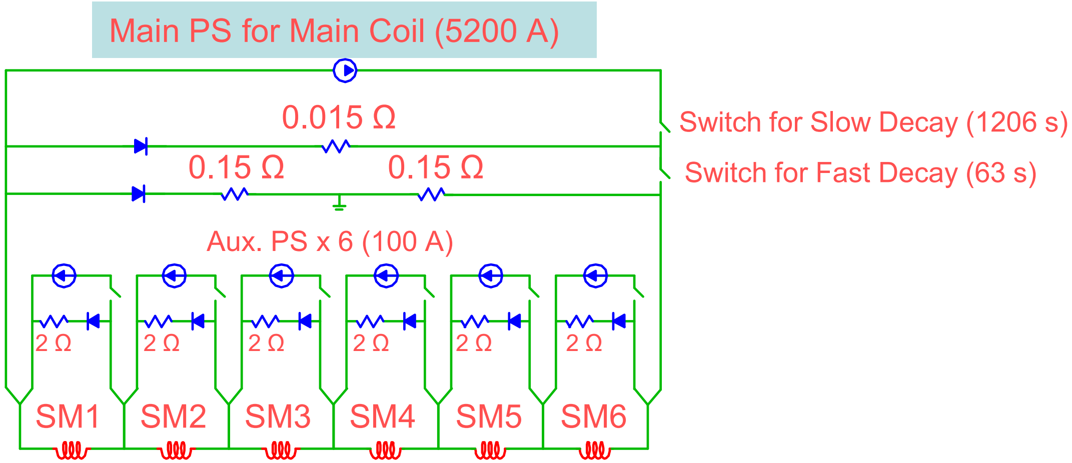
1:Quench characteristic

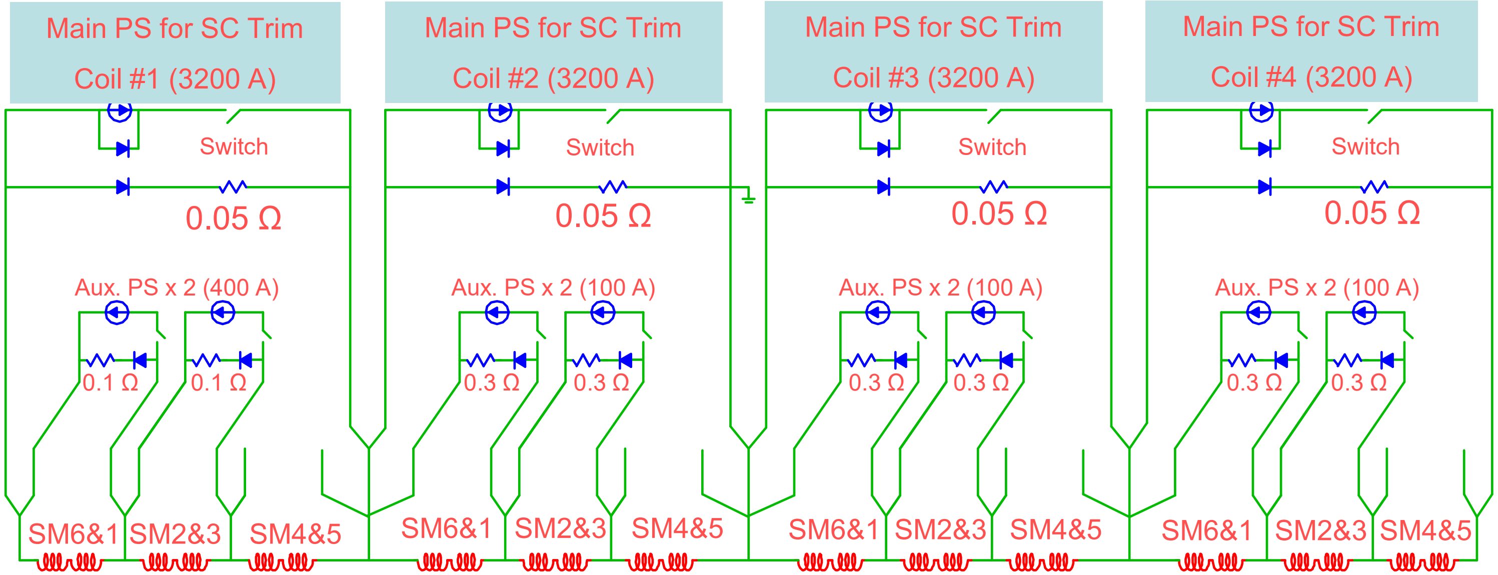
Current decay: 63 s

Temp. rise: 140 K

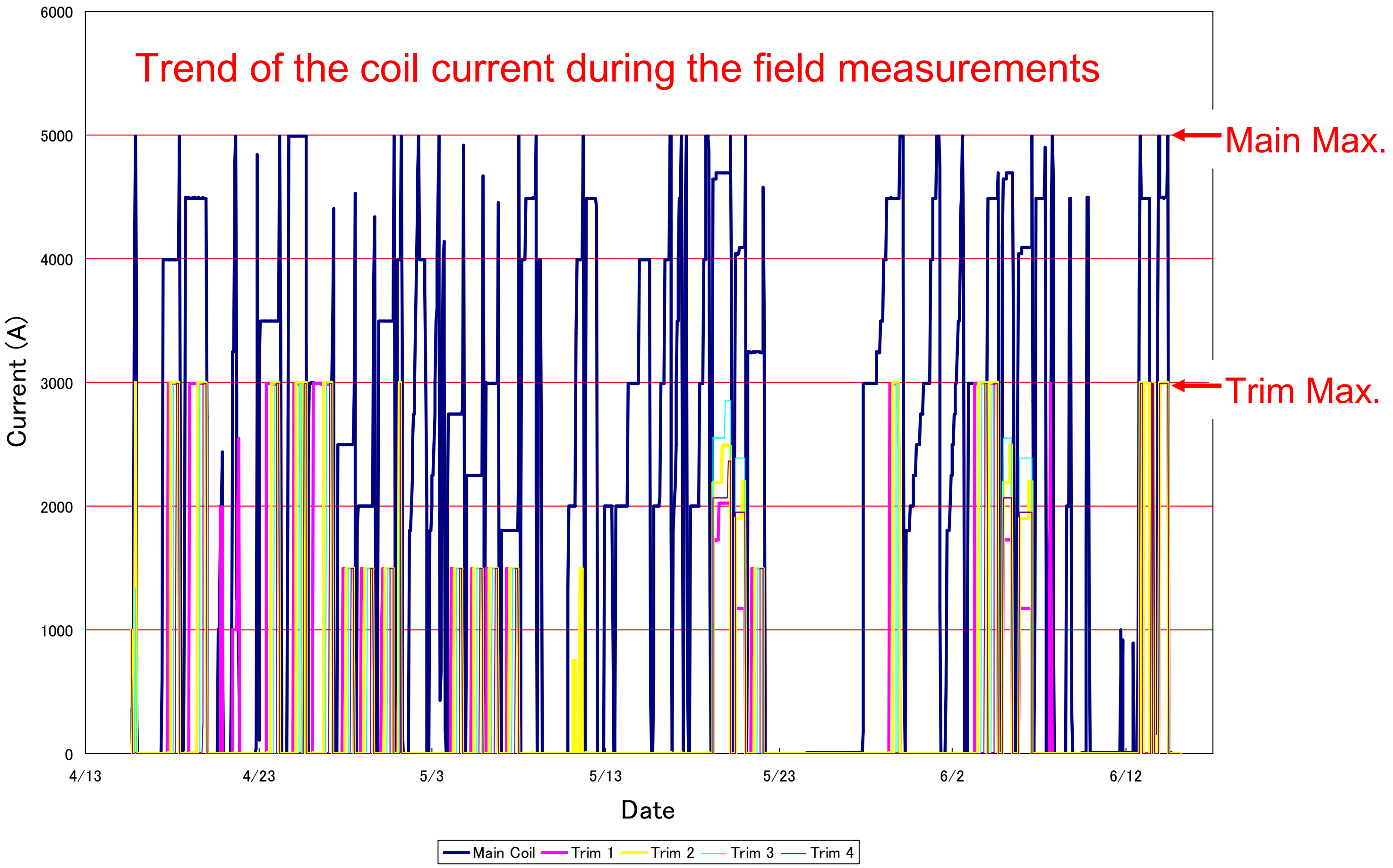
Volt. Development: 1.5 kV/2

2: Strong Coupling between the main coils and S.C. Trim coils

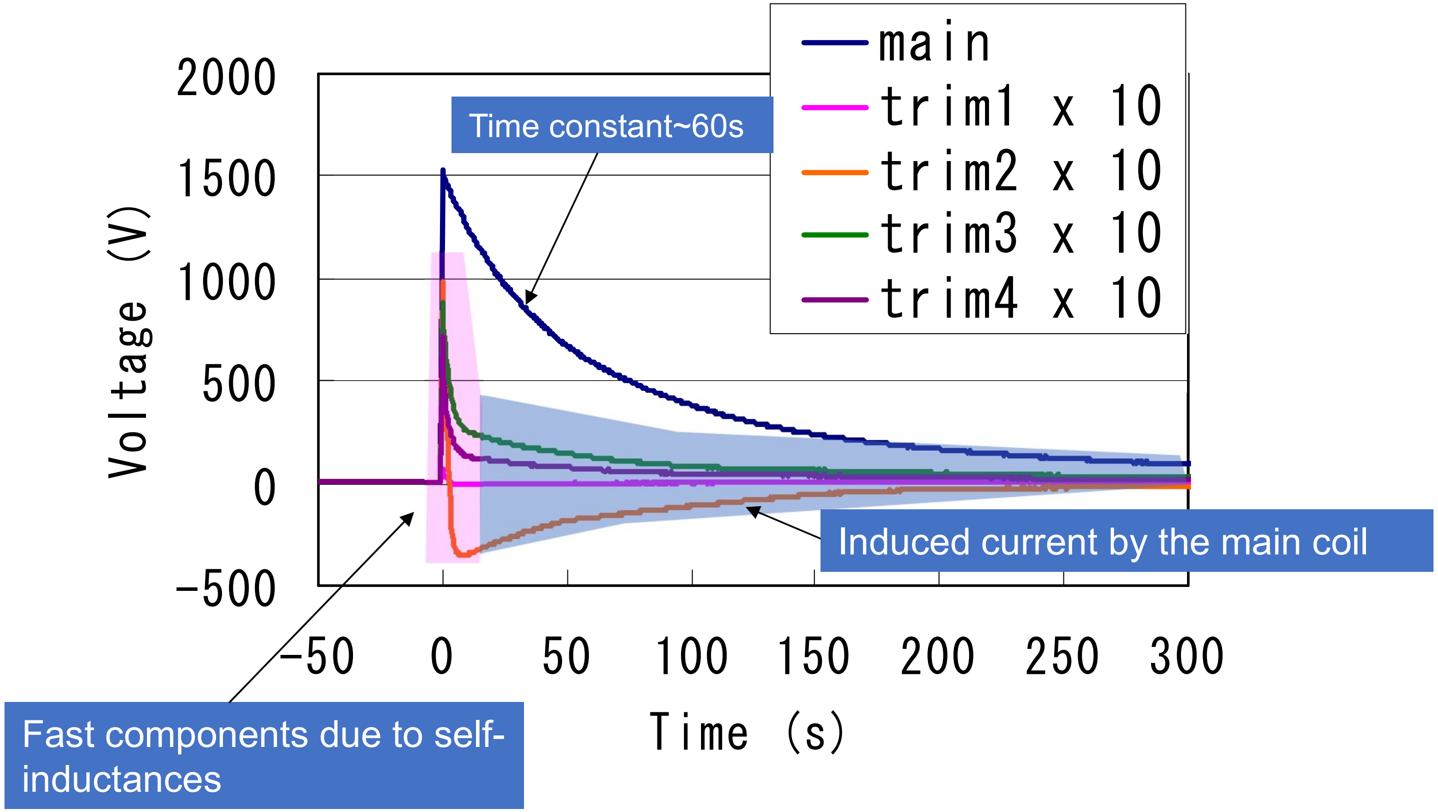




All the coils never quench. *so far..*



Coil voltages in fast shut-down test from full excitation



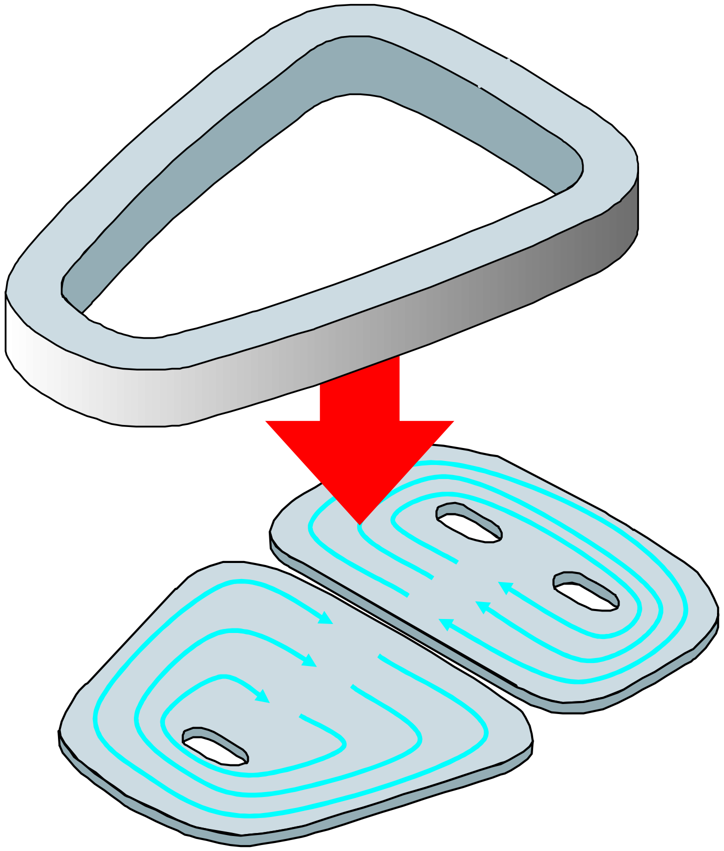
Time constant~60s

Induced current by the main coil

Fast components due to self-inductances

The main and trim coils were safely shutdown even in emergency.

Eddy current loss in shut-down process

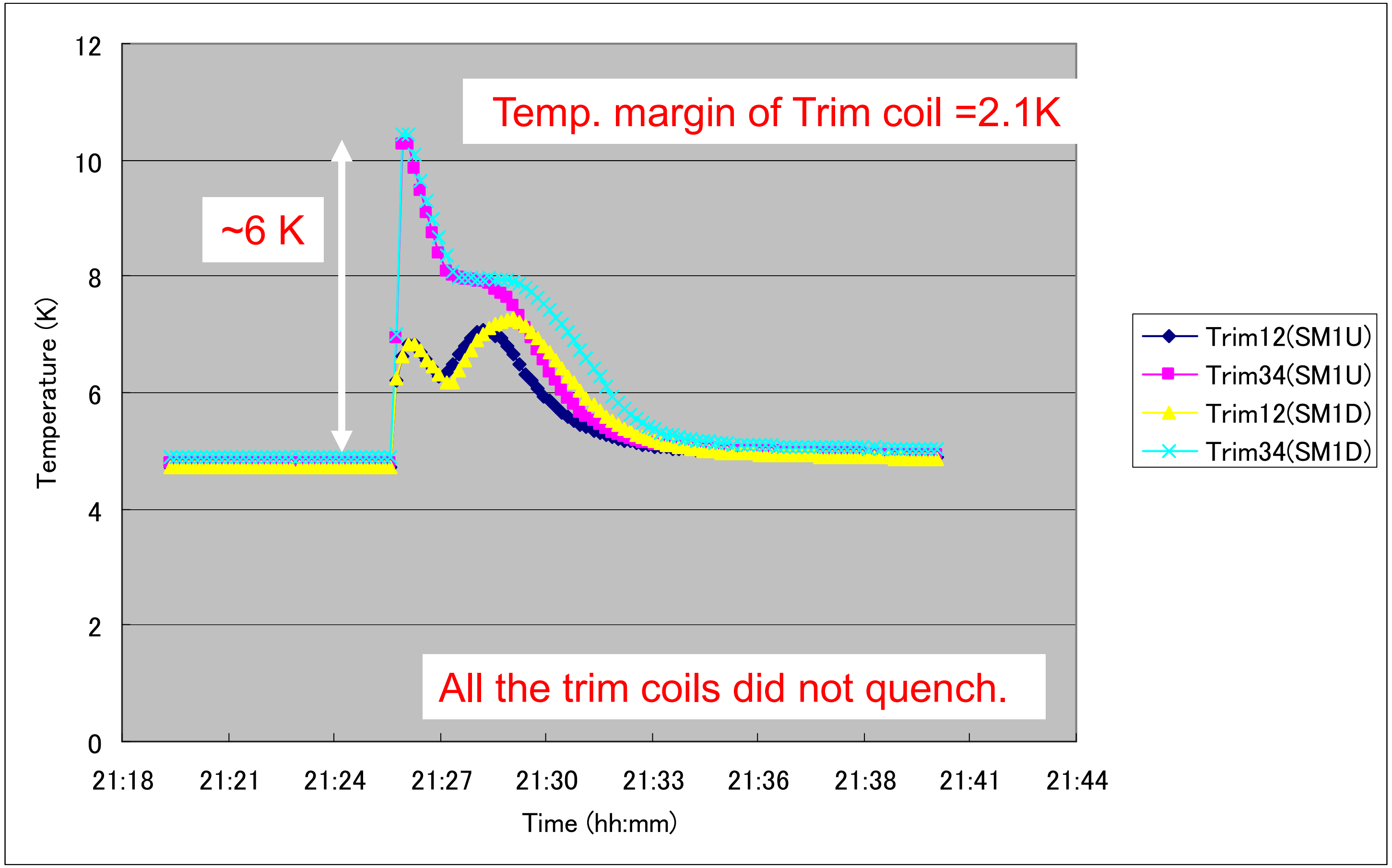


Eddy current loss in the Aluminum supports for the superconducting trim coils

Estimation~ 100W
(slow shutdown from full excitation)

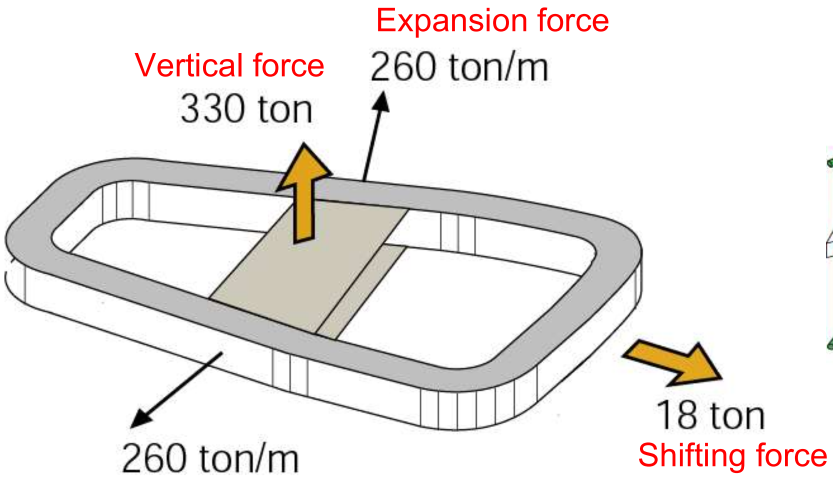
The trim coil quench?
(Temp. Margin~2K)

Temp. rise of the trim coil in slow shut-down from full excitation

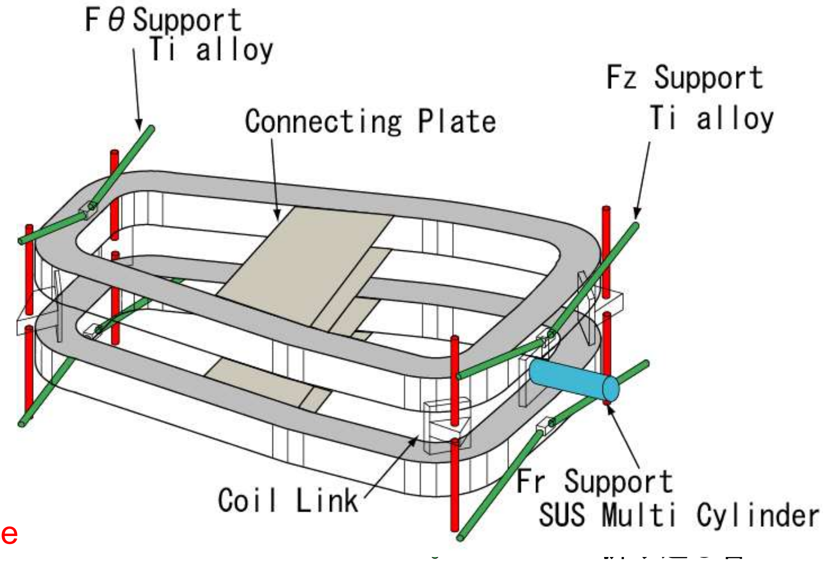


Calculated forces are correct?

Forces on the upper coil (TOSCA calculation)

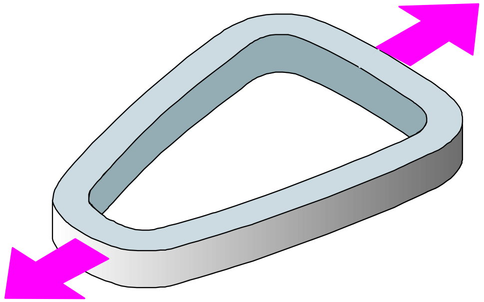


Support system for the cold mass



We continuously measured the forces using the strain gauges attached to all the supports in the excitations.

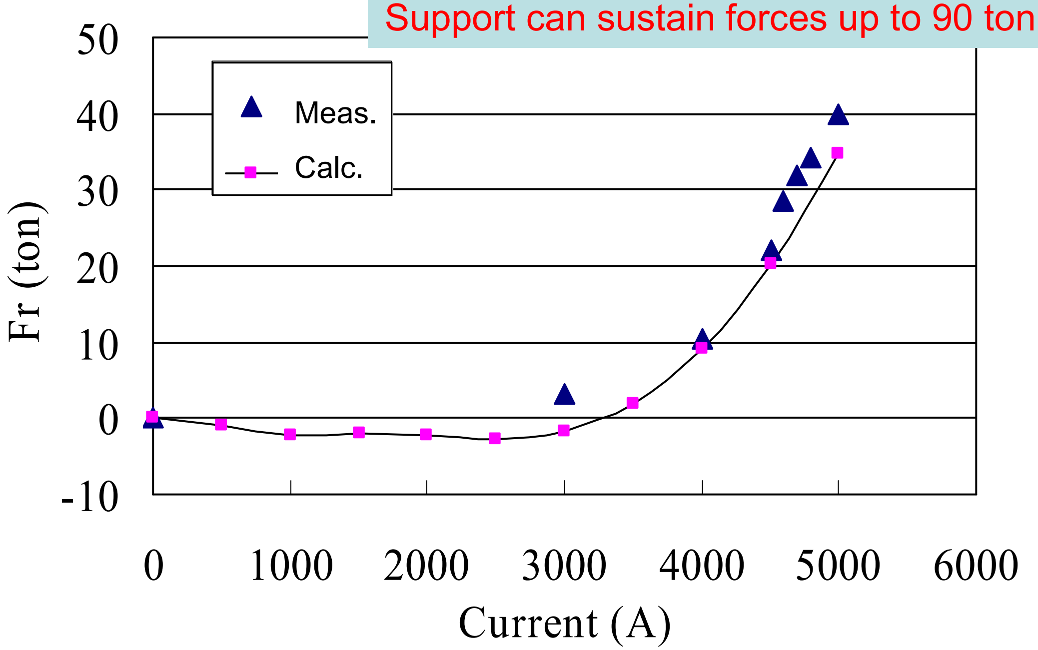
Radial shifting forces are difficult



Fr =(Large Force A)-(Large Force B)

(Large Force A) ~ (Large Force B)

The errors are big?



Support can sustain forces up to 90 ton.

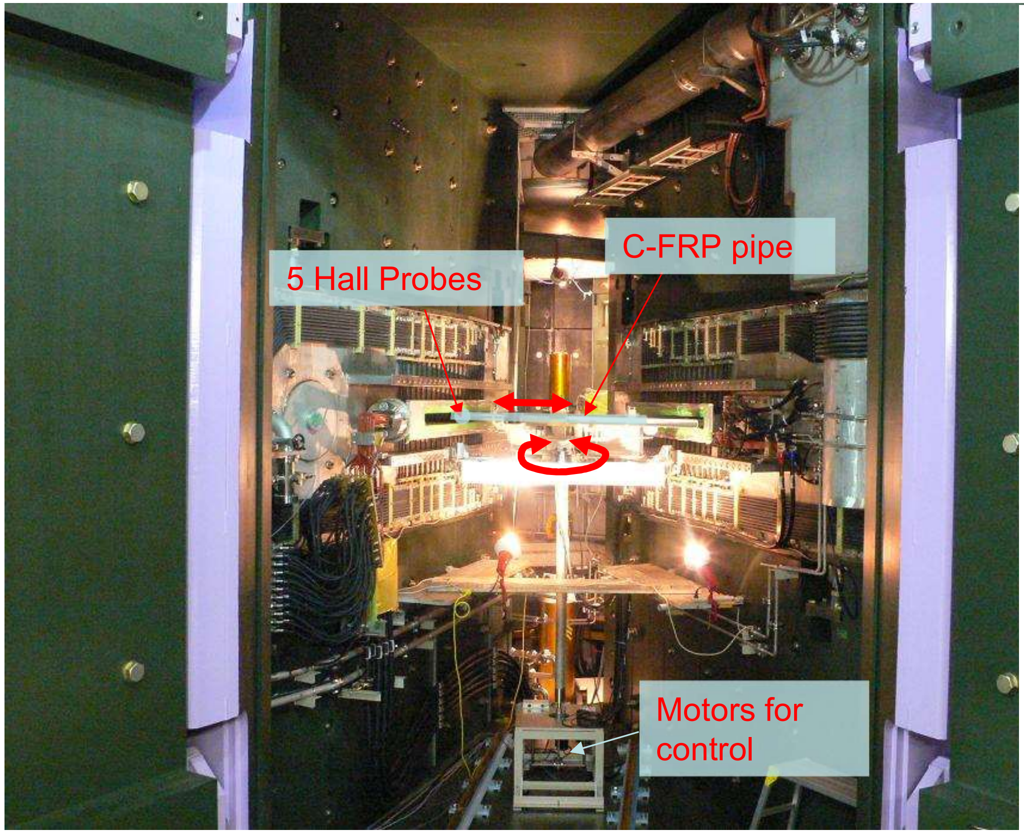
For 3 directions

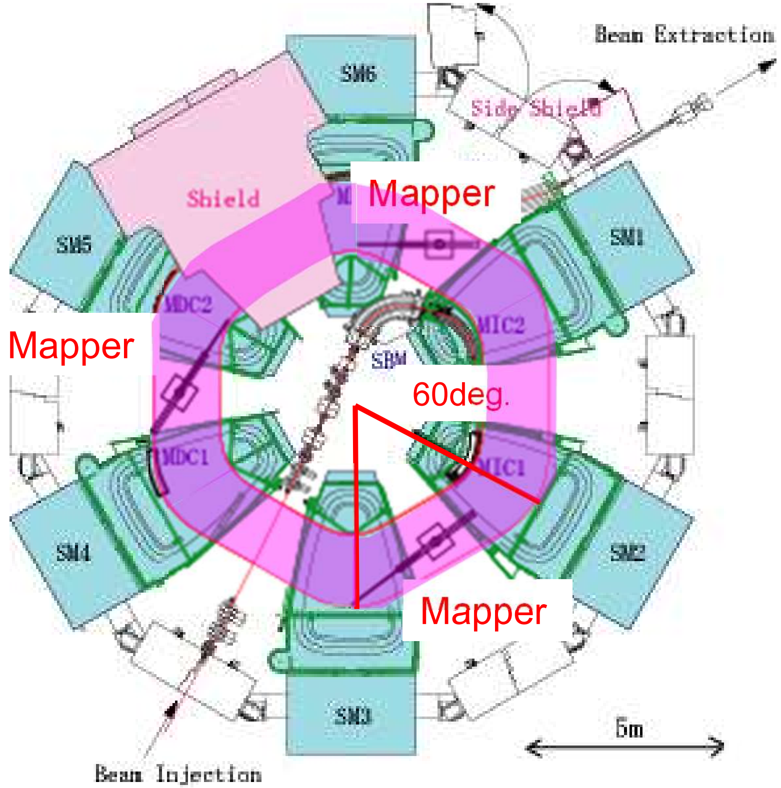
R direct.:compressive 40ton (0.6mm)
θ direct.:compressive and tensile <1ton (<0.1mm)
Z direct.:compressive 7ton (0.5mm)

→ The coil displacement due to excitation is small.

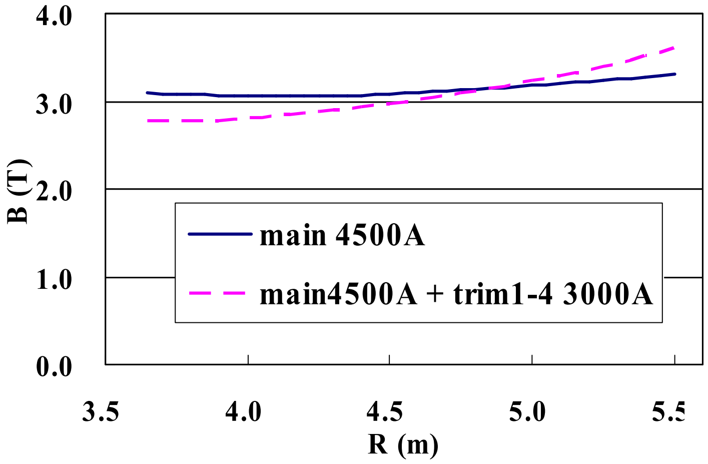
Field mapping over the acceleration region

Field Mapper	**3 (60 deg./each)**
Hall Probe	**5**
Control	**2axis (Rot./Trans.)**
Mesh	**about 5cm**
Meas. Time	**about 3h30m/60deg.**





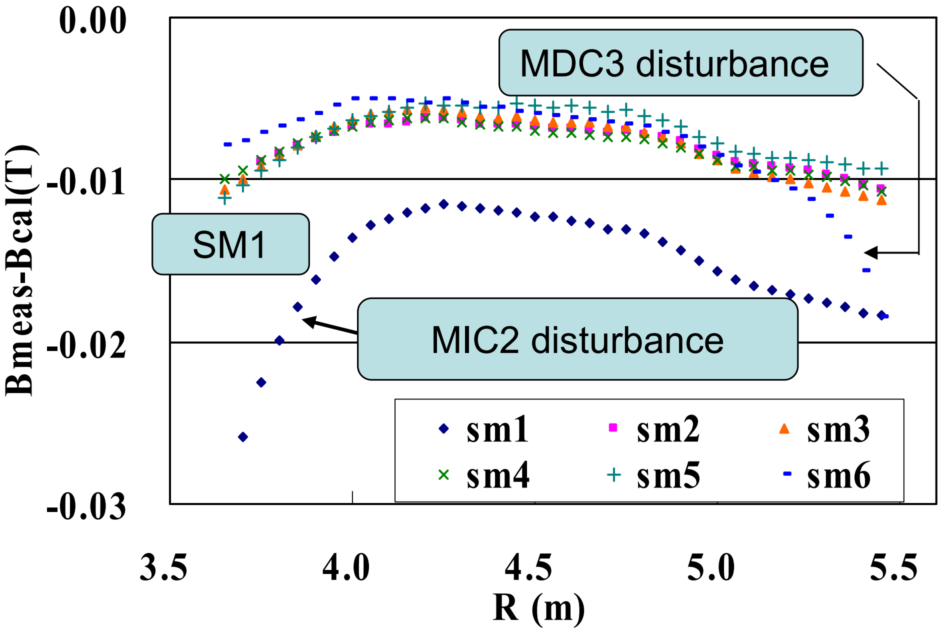
Measured field profiles along the sector-center axis



Main Coil: Bending power during the acceleration

Trim Coil: Isochronous field

Difference between measured and calculated fields



MDC3 disturbance

SM1

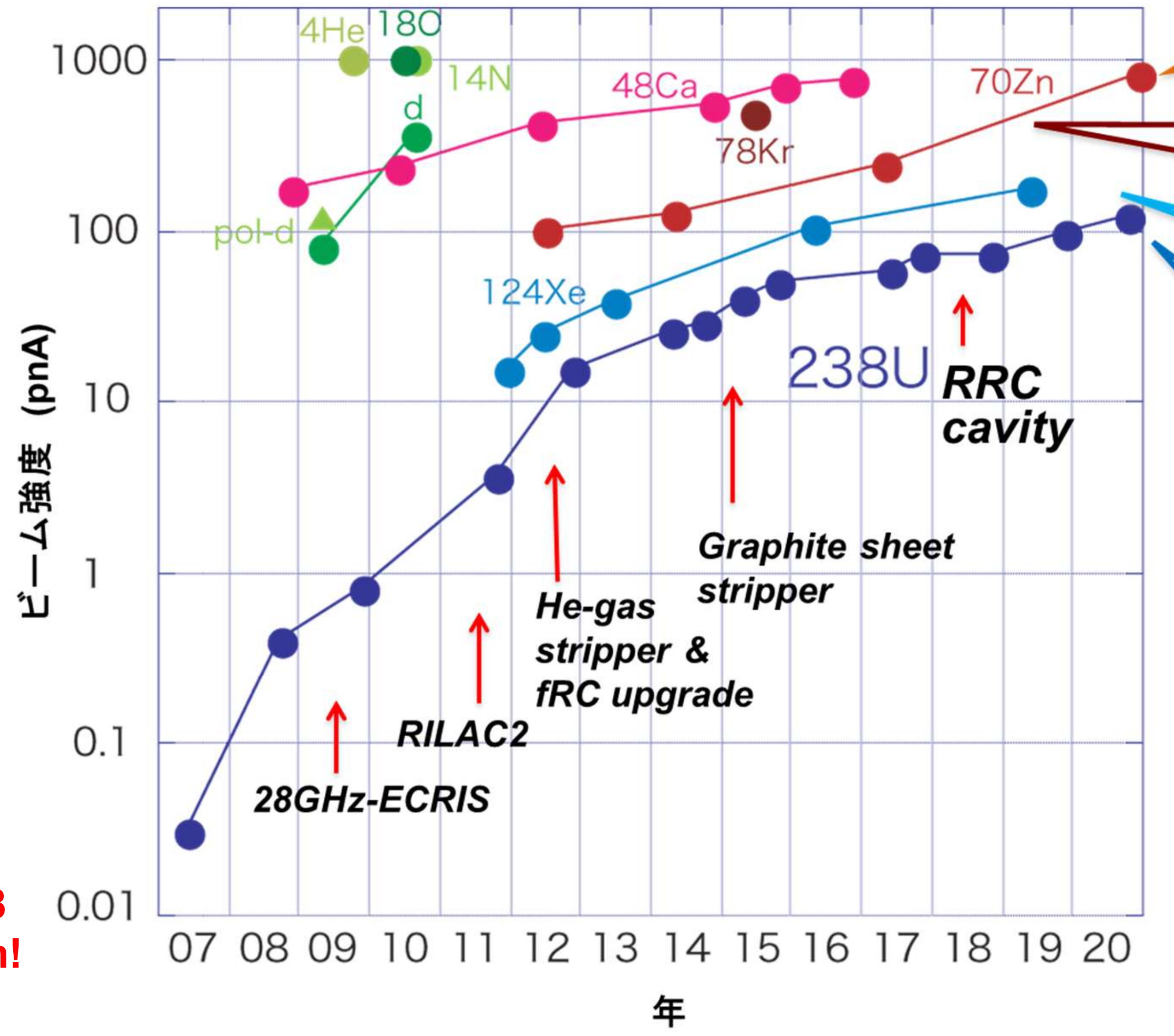
MIC2 disturbance

○ Good agreement (0.16%~0.35%)
○ Small field dispersion among the sectors

Field Disturbances
•SM1 has a slightly different shape.
•Disturbance from MIC2 and MDC3

Small enough to be adjusted by the correction coils in the magnetic channels and aux. power supplies of the main and trim coils.

ファーストビーム(‘06/12/28)後加速されたイオンとビーム強度
目標:全元素で1 pμA（6 x 10^{12} #/s)



^{70}Zn: 788 pnA
=> ***19.0 kW***

^{78}Kr: 486 pnA
=> ***13.1 kW***

^{124}Xe: 173 pnA
=> ***7.4 kW***

^{238}U: 117pnA
=> ***9.6 kW***

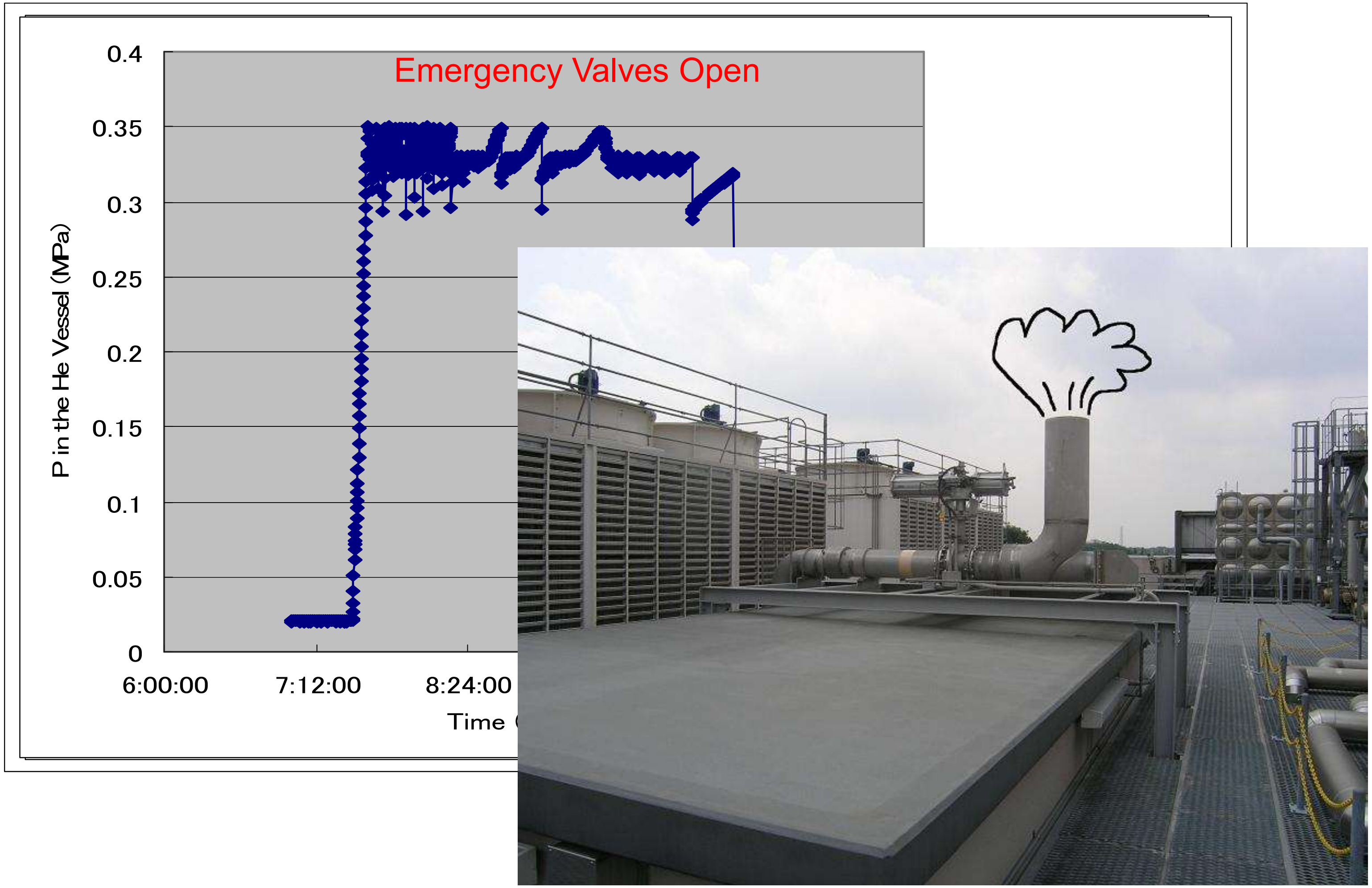
2006.12.28
First beam!

トラブルと反省点

- 幸い超伝導コイルでのトラブルは起きていない。（今のところ）
  - その時に設計上判断したことが正しいかどうかは、10年後にわかることもある。。
  - 柔らかい裸線を巻いたのはショートのリスクをずっと引きずっている。

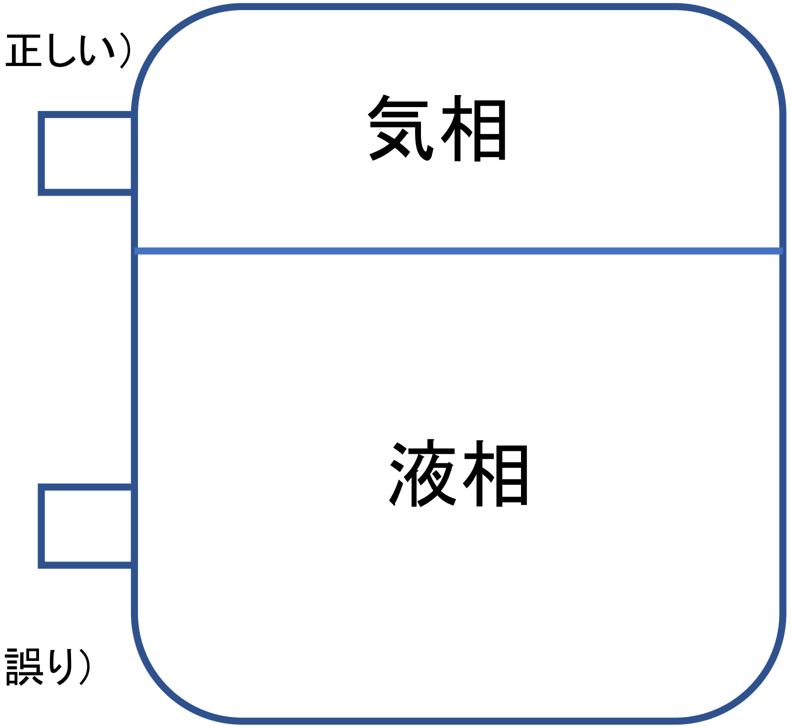
- 2005年11月8日フィードスルーからの漏れ
- ～2008年冷凍機の油問題

What happened on Nov. 8.



A feed through attached the vessel was broken.

フィードスルーの気相に設置



フィードスルー（正しい）

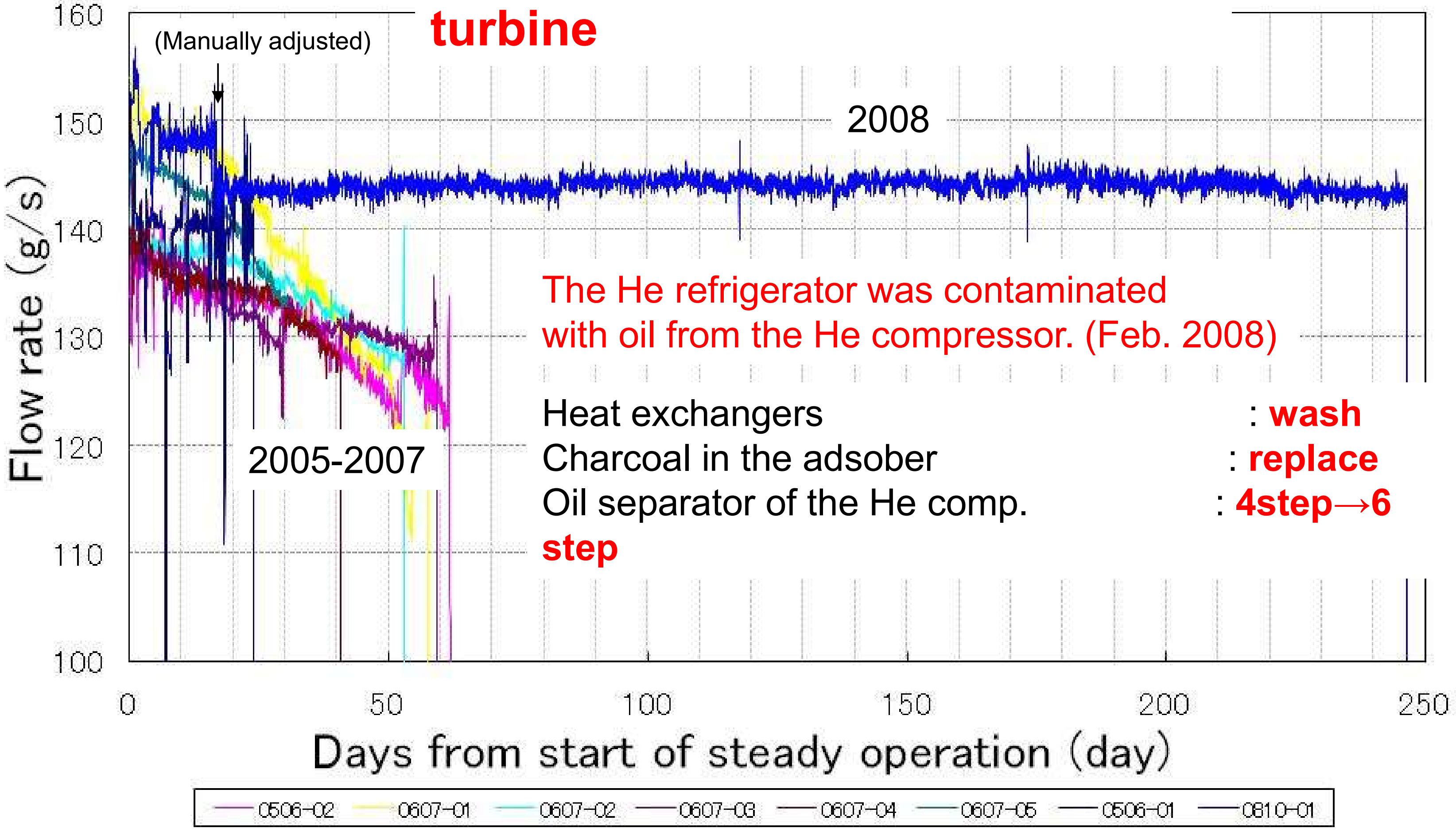
気相

液相

フィードスルー（誤り）

真空漏れの時の影響は1000倍近く違う

Oil contamination in the He refrigerator

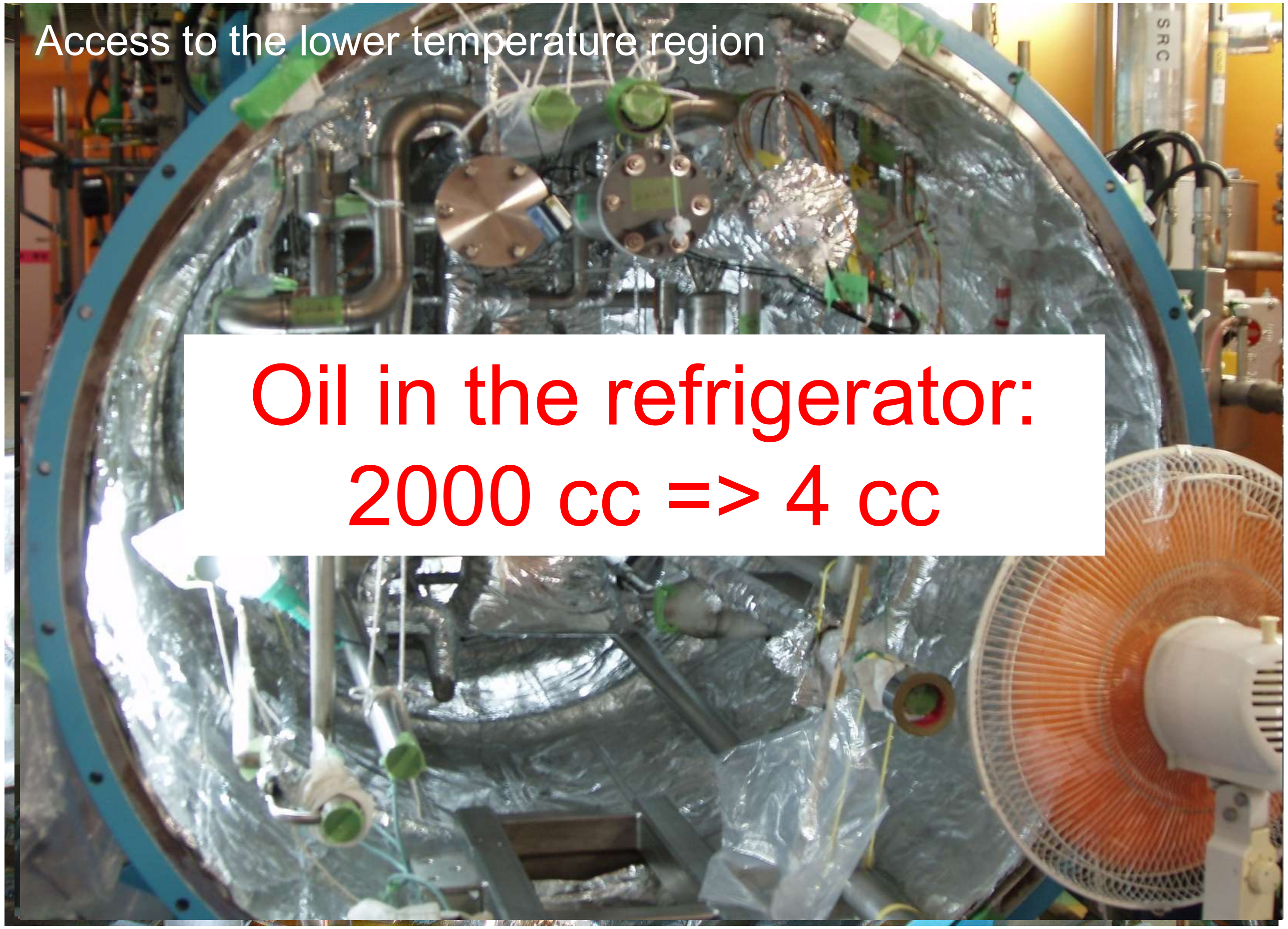


Flow rate through the first turbine

The He refrigerator was contaminated with oil from the He compressor. (Feb. 2008)

Heat exchangers : **wash**
Charcoal in the adsober : **replace**
Oil separator of the He comp. : **4step→6 step**

Battle against the oil in the He refrigerator



Oil in the refrigerator:
2000 cc => 4 cc

油分離機の性能は契約値以上のものを目指すこと。

今後の「サイクロトロンの超伝導化」

- **MSU型（AVFサイクロトロンを超伝導化）**
  - 更なる小型化、高エネルギー化をめざす。
  - 鉄を使わない
  - 高温超電導
  - 用途：RI製造や放射線治療用
- **SRC型（リングサイクロトロンの超伝導化）**
  - MITのニュートリノグループ
  - 用途：基礎科学（ニュートリノ）、ADS用のドライバー
- **フル超伝導化**
  - テキサスA＆Mのグループ

日本での超伝導AVFサイクロトロン

2021年　陽子治療用超伝導サイクロトロンの開発に成功した住友重機

医療機器ニュース

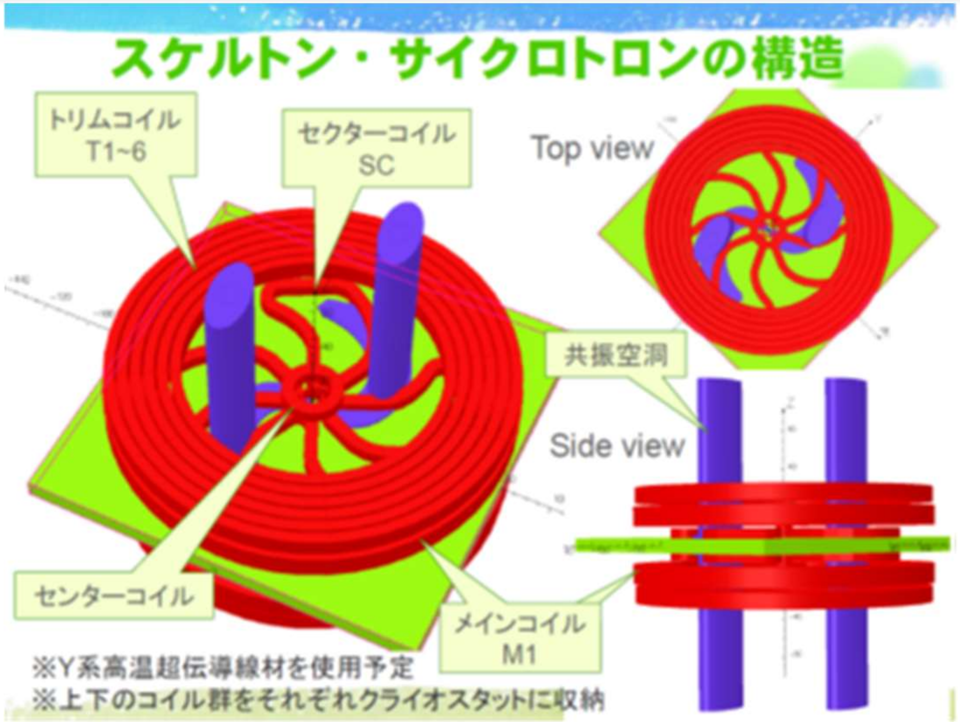
陽子線治療用の超電導サイクロトロンを開発、照射時間3分の1以下

2021年11月08日 15時00分 公開　[MONOist]

住友重機械工業は2021年10月26日、陽子線治療用の超伝導サイクロトロンの開発に成功したと発表した。陽子線の強度を高め、陽子線治療用としては世界最高レベルとなる1000nAの高強度陽子線を発生できる。

超伝導サイクロトロンの陽子線加速試験の様子 出所：住友重機械工業

陽子線治療　200MeV以上
重さはJohoの公式から見ると50－60トン程度と思われる

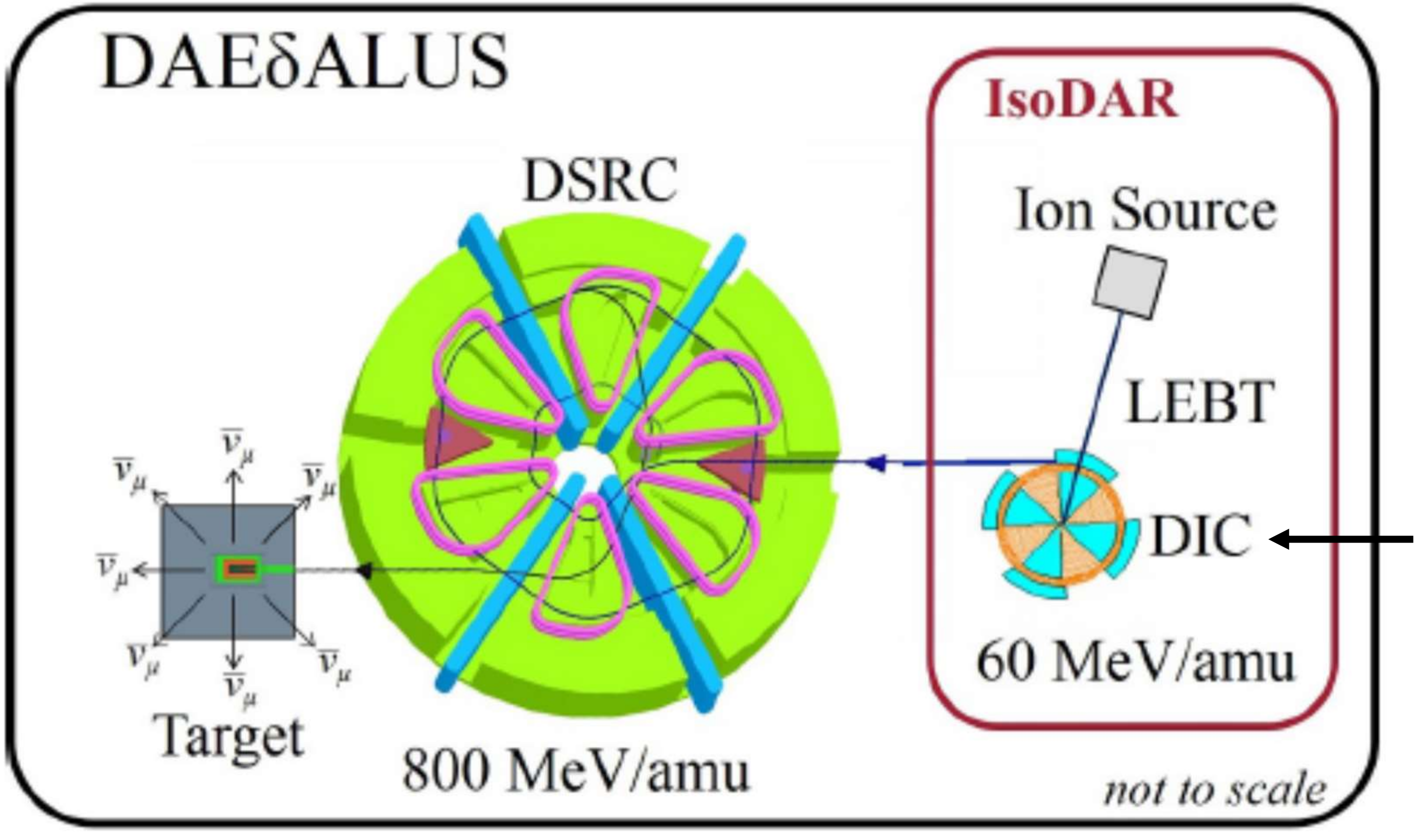


※Y系高温超伝導線材を使用予定
※上下のコイル群をそれぞれクライオスタットに収納

K値：80MeV
最大平均磁場：2.6T
引き出し半径：50㎝
超伝導体：Y系高温超電導線材を使用

MIT J. Conradチームの率いるDaedalusプロジェクト

Superconducting Ring Cyclotron
H2+加速、800MeV, 5mA



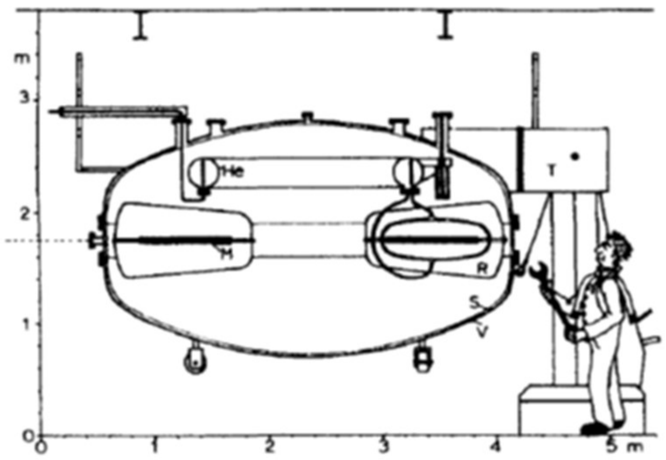
超伝導コイルの設計(2012) by
MIT Joseph Minervini, et al.,

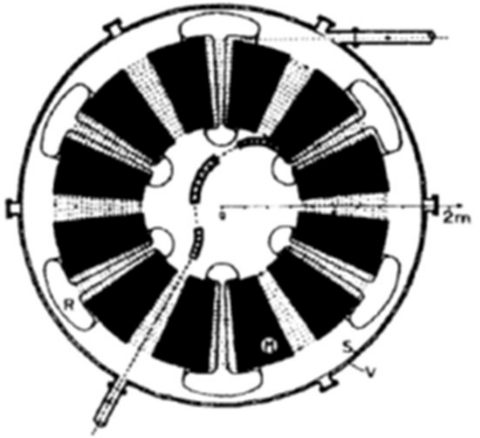
https://arxiv.org/ftp/arxiv/papers/1209/1209.4886.pdf

現在はIsoDARの設計、開発
に集中

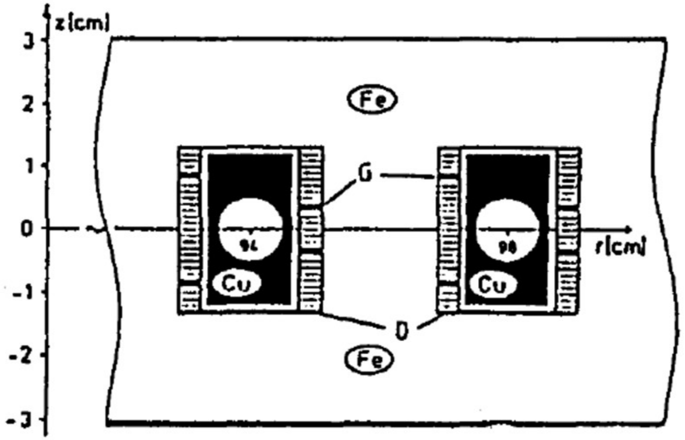
磁石と加速空洞が超伝導のサイクロトロン

Tritron (強収束サイクロトロン）





ビーム輸送チャンネル



超伝導加速空洞

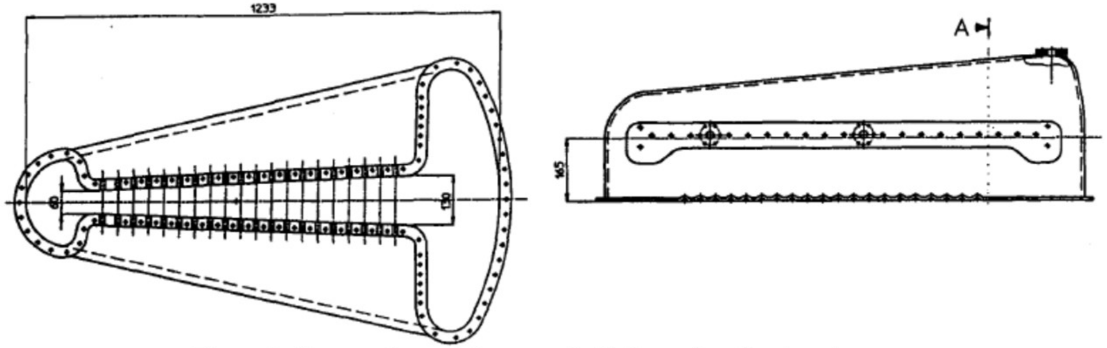


Figure 3: Cross sections of the upper half of a cavity. Numbers in mm.

磁石と加速空洞が超伝導のサイクロトロン

スタックサイクロトロン (強収束サイクロトロン)

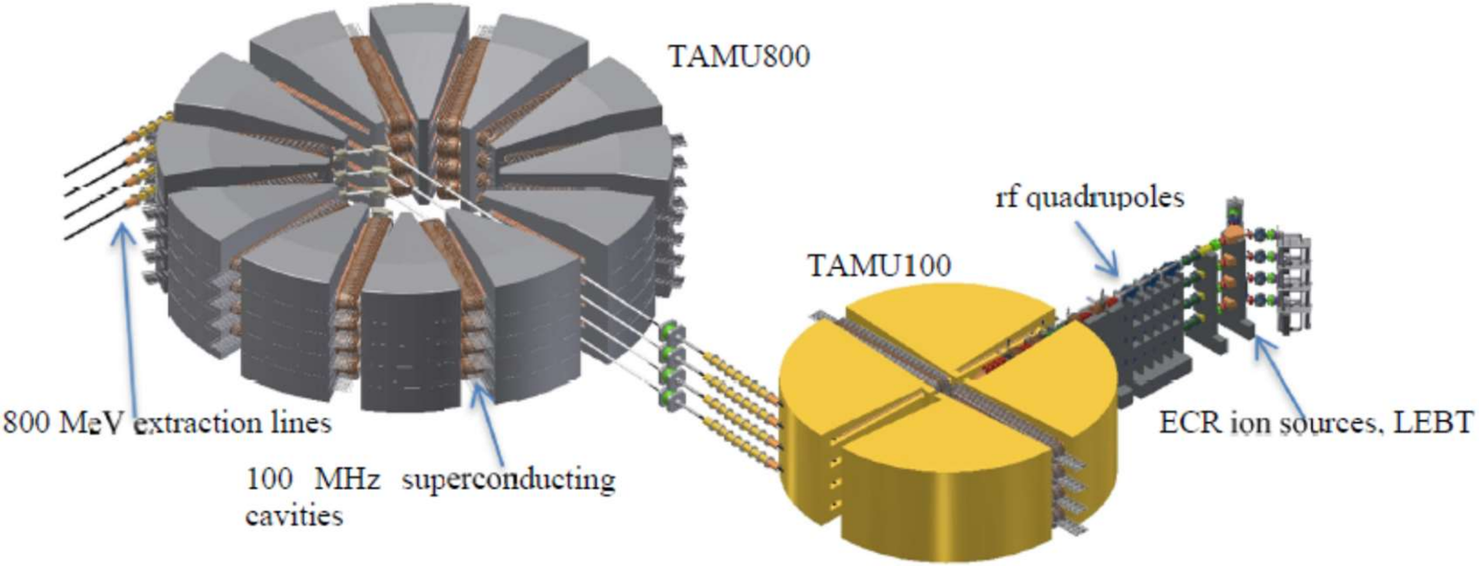
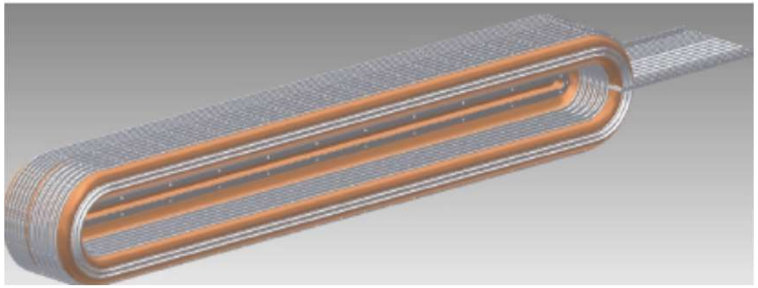


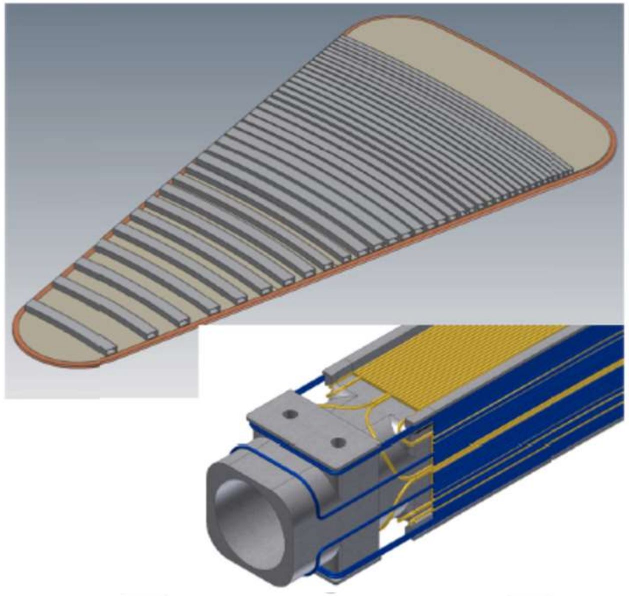
Figure 1: Strong-focusing cyclotron, showing injectors and main ring for a flux-coupled 4-stack.

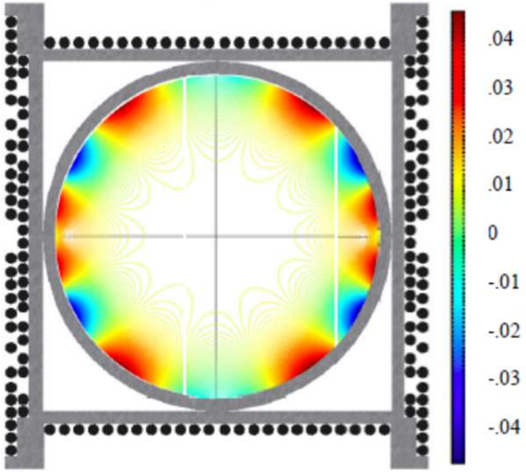
Proton
10mA 800 MeV

超伝導加速空洞(QWR)



ビーム輸送チャンネル





まとめ

- **サイクロトロン概略**
  - Classical →AVF→セクター分離型
- **MSUの超伝導サイクロトロン**
  - AVFサイクロトロンの超伝導化
  - 常伝導サイクロよりも1/15倍軽い
- **理研RIBFの超伝導リングサイクロトロン**
  - 非円形コイルを組み合わせたリングサイクロトロン
  - 力の制御が困難
- **今後の「サイクロトロンの超伝導化」**
  - MSU型→更なる小型化、高エネルギー化、高温超電導
  - RIKEN型→基礎物理用
  - TRITRON型→Stacked Cyclotron (強収束サイクロトロン）