The role of superconductivity in the development of cyclotrons

By Luciano Calabretta, INFN-LNS, Catania

The role of superconductivity in the development of cyclotrons

Henry Blosser
a father of the superconducting cyclotrons.
He was founder and longtime Director of the Cyclotron Laboratory at Michigan State University.
Henry passed away on past 20 March!

AIP Conference Proceedings
No. 9

Cyclotrons - 1972

18 -21 July, Vancouver, Canada

Henry Blosser

FUTURE CYCLOTRONS*

what does the future hold in terms of developments of this type?

An immediate first thought in this direction is superconductivity, a technology under intensive study by our linac and synchroton brethern. The virtues of using superconducting elements in cyclotrons are however much less clear than in either of these other applications. Synchroton interest in superconductivity for example is for the purpose of making the machine smaller since the size of the new large synchrotrons has reached the proportions of a critical problem. The size of cyclotrons is however much less of a problem and the virtues of making cyclotrons smaller are at best mixed. On the positive side there would be savings in building and

United States Patent [19]

Bigham et al.

[11] 3,868,522

[45] Feb. 25, 1975

[54] SUPERCONDUCTING CYCLOTRON

[75] Inventors: Clifford B. Bigham; Harvey R. Schneider, both of Deep River, Ontario, Canada

[73] Assignee: Atomic Energy of Canada Limited, Ottawa, Ontario, Canada

[22] Filed: Nov. 26, 1973

[21] Appl. No.: 419,034

[30] Foreign Application Priority Data

June 19, 1973 Canada 174422

[52] U.S. Cl. 313/62, 328/234, 335/216
[51] Int. Cl. H05h 13/00
[58] Field of Search 313/62; 328/234; 335/216

[56] References Cited

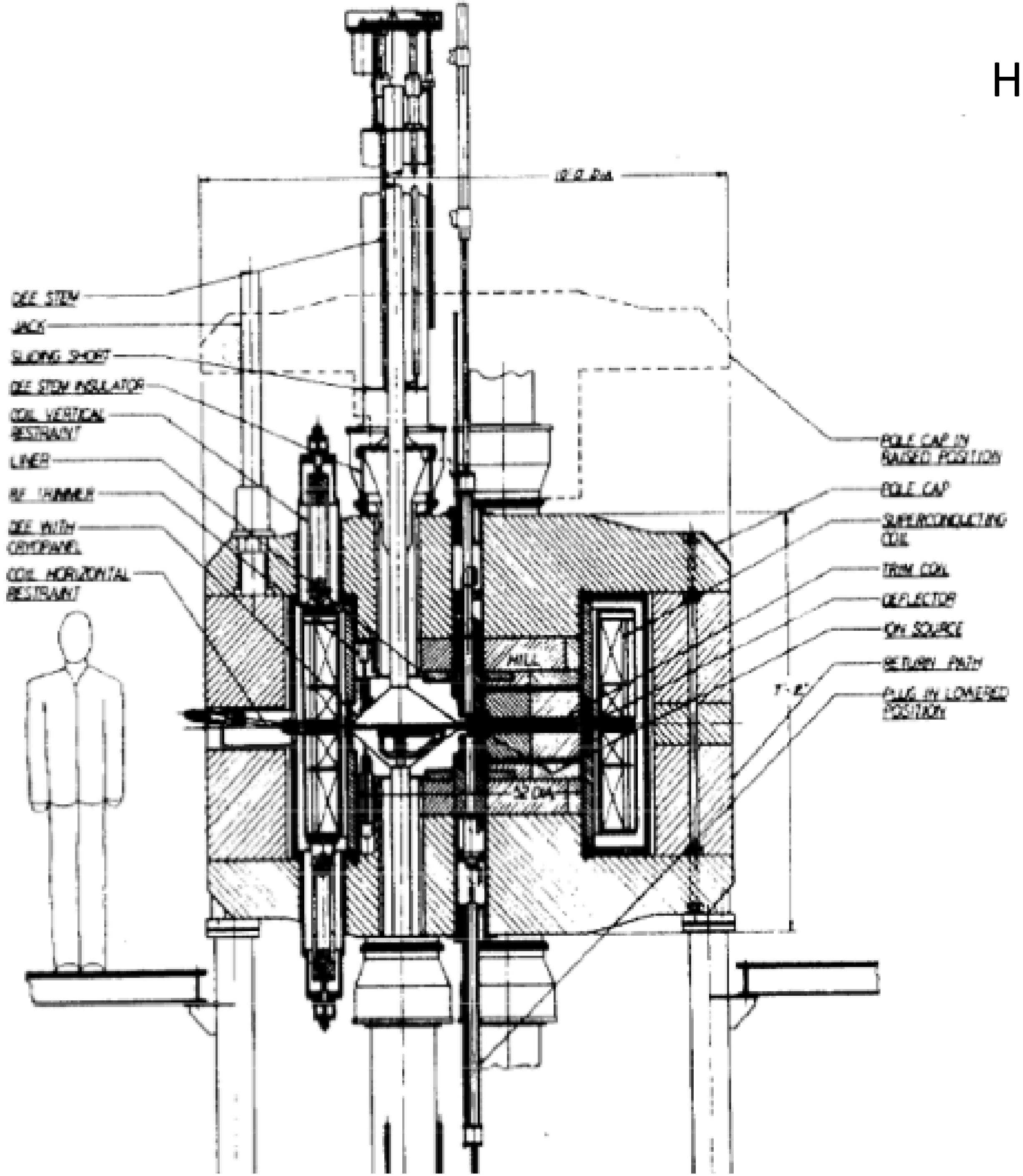
UNITED STATES PATENTS

3,175,131	3/1965	Burleigh et al.	313/62 X
3,427,557	2/1969	Speciale	328/234
3,613,006	10/1971	Kantrowitz et al.	335/216
3,641,446	2/1972	Gordon	328/234 X

Primary Examiner—Paul L. Gensler
Attorney, Agent, or Firm—James R. Hughes

[57] ABSTRACT

Isochronous cyclotron using an air core superconducting magnet to provide high intensity magnetic fields. To provide an axial focussing field, iron sectors with spiral edges acting as flutter poles positioned in the magnetic field such that saturation of the iron in the sectors gives an increased field between the sectors and a slightly decreased field outside.



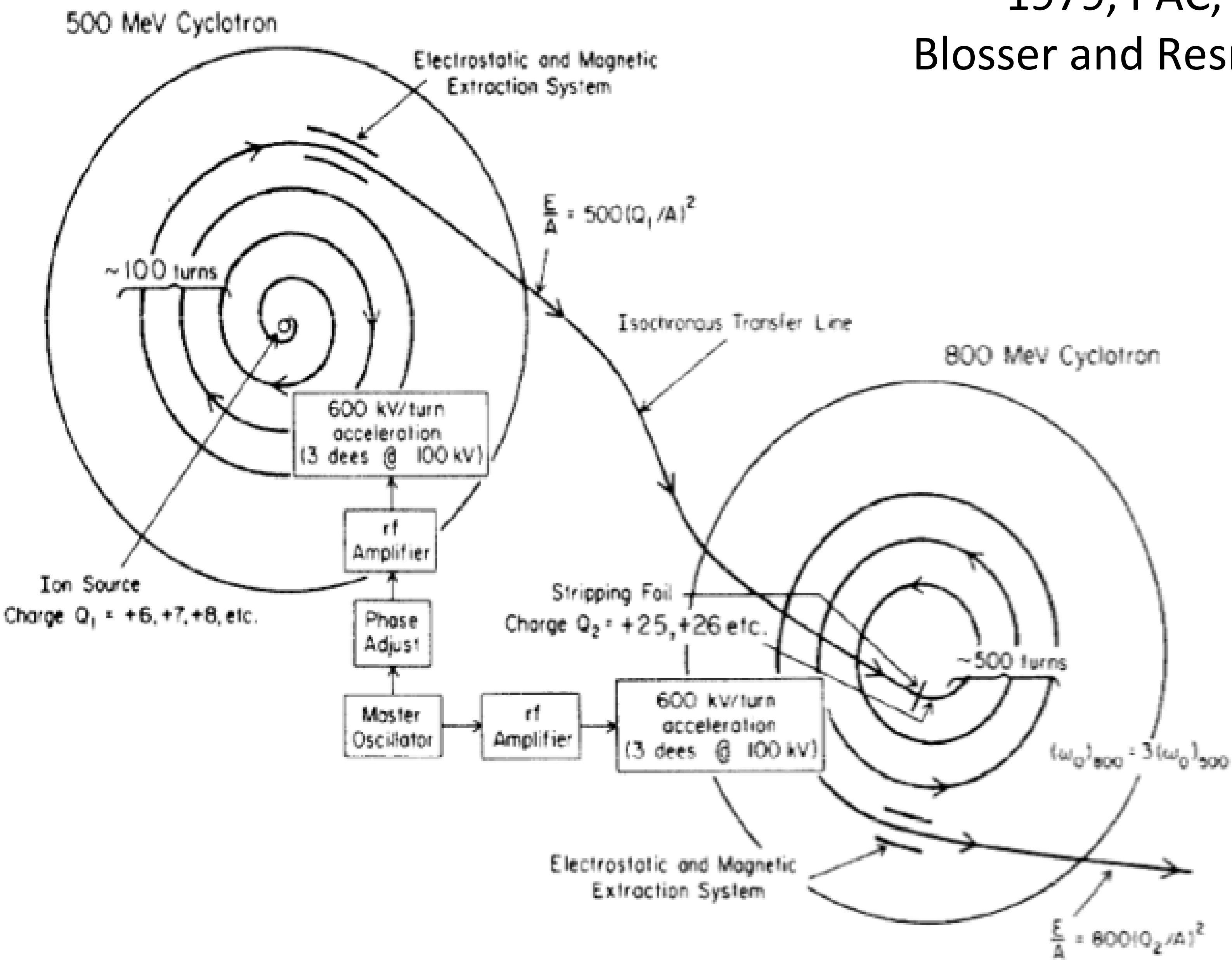
1979, PAC, H. Blosser and F. Resmini present the design of K500

The research cyclotrons were designed to accelerate ions beams from proton to uranium! This goal complicated greatly the job!

The cryostat has to host two pairs of superconducting coils.

The RF cavities escapes!

1979, PAC,
Blosser and Resmini



COUPLED SUPERCONDUCTING CYCLOTRON SYSTEM

1980, K500 MSU

Compact superconducting cyclotron for Nuclear research In the world:

K500 MSU (USA)

K520 Chalk River (C)

K1200 MSU (USA)

K800 Milano (I)

K500 Texas AM (USA)

K600 AGOR (NL)

K500 Calcutta (IN)

Superconducting cable Nb-Ti

In Liquid He bath

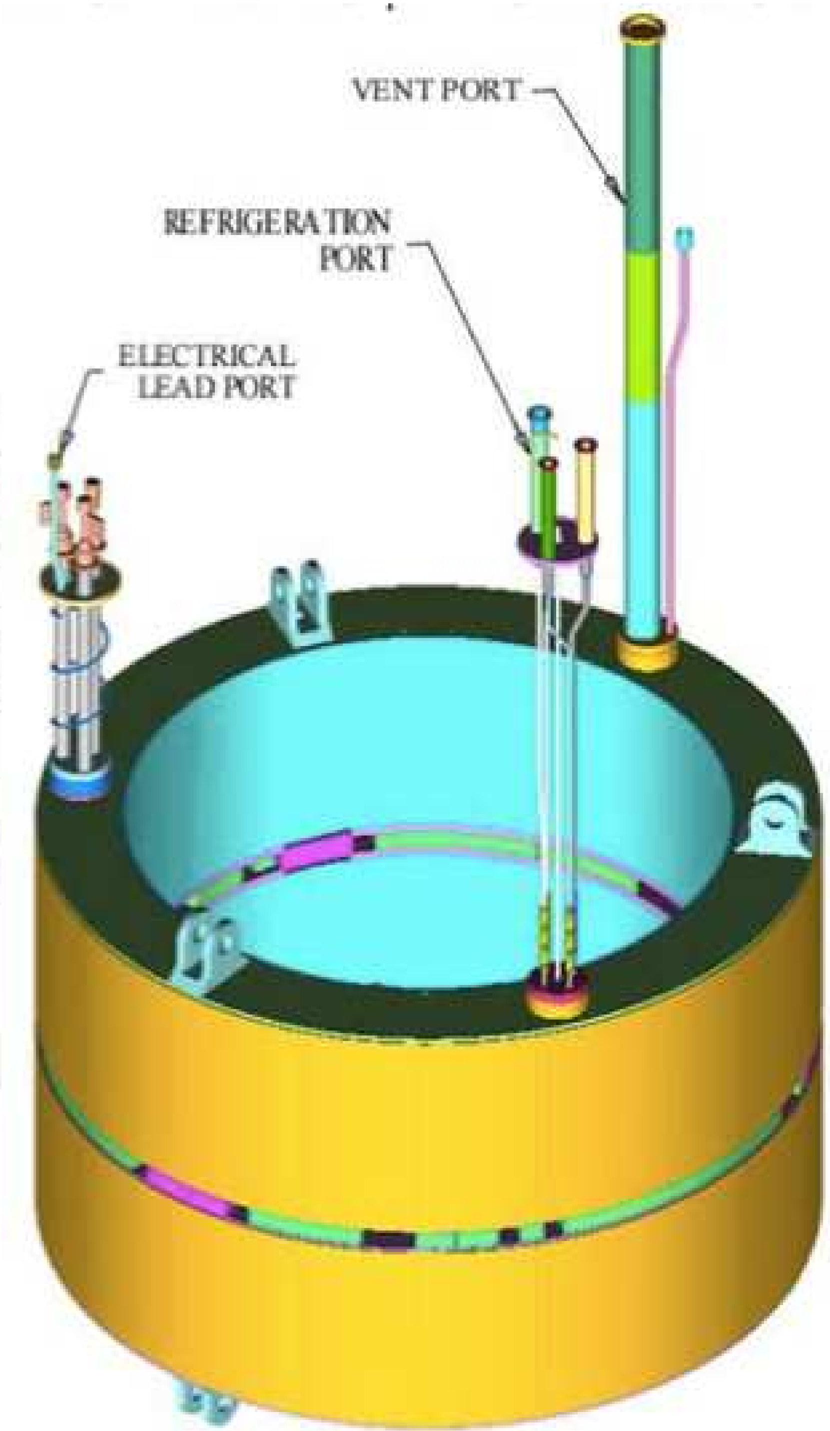
Superconducting winding

To minimize the risk of quench, the coils of Milan's cyclotron, like for Chalk River, were built joining together a set of double pancake coils

The MSU people chose the solenoid winding style

Both solutions worked well!

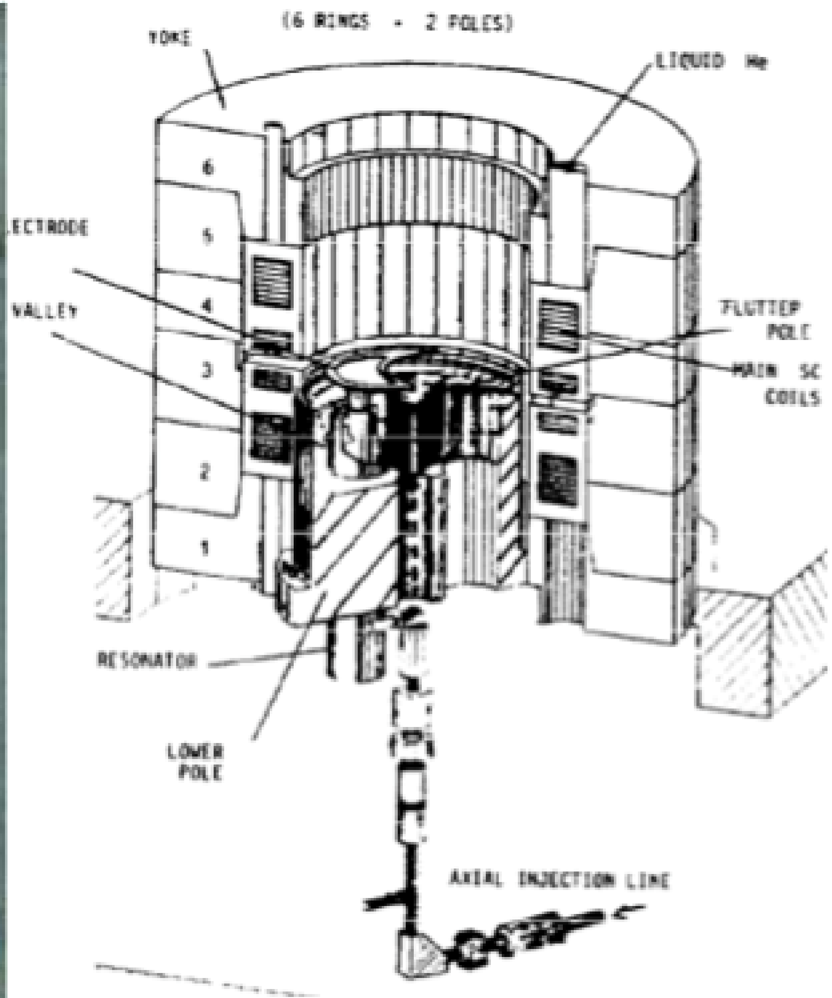
Kolkata
superconducting cyclotron
MSU K500 like



On courtesy of R. Bandary

AGOR SUPERCONDUCTING CYCLOTRON

Lower module of welded mechanical structure

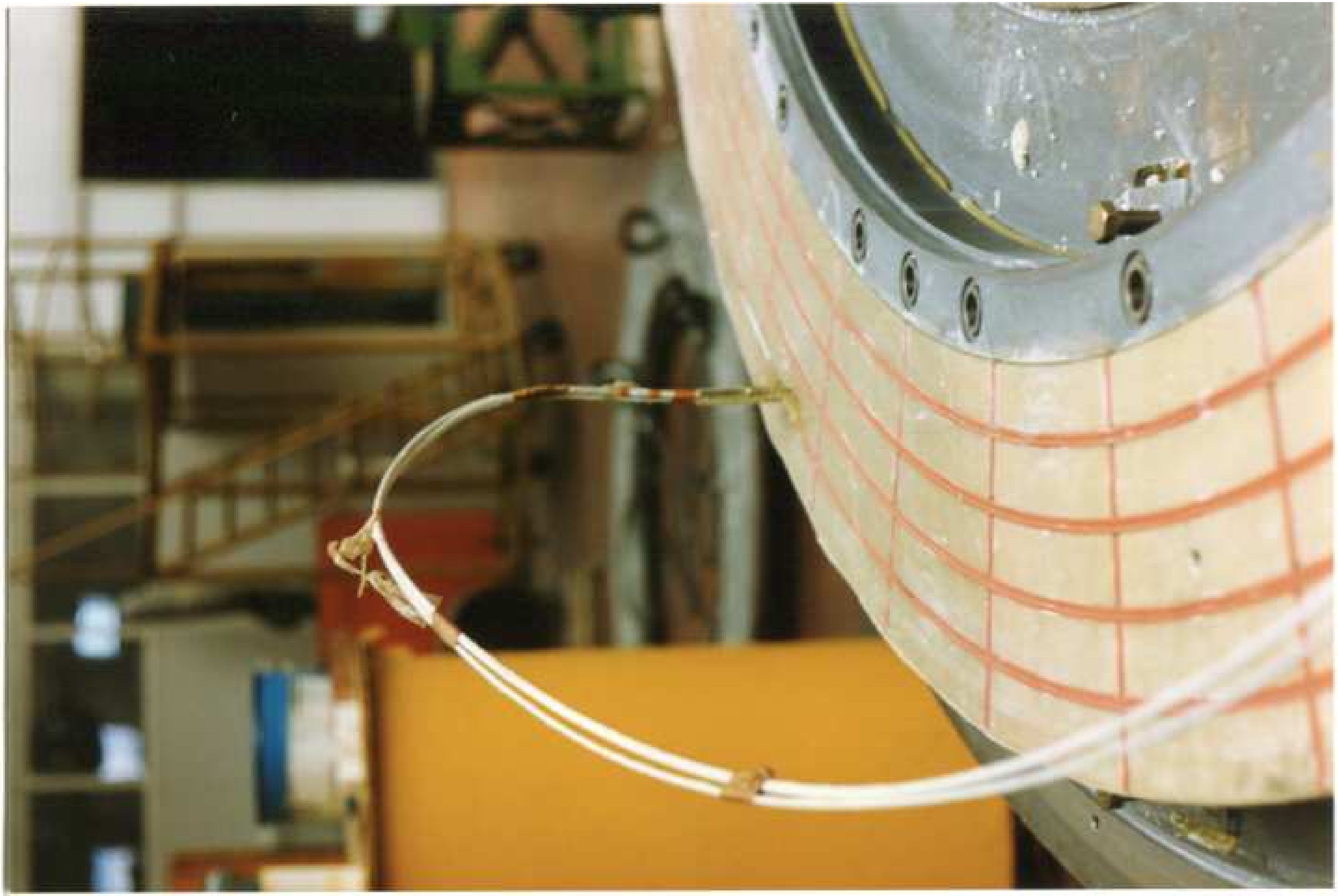


AGOR used the first superconducting extraction magnetic channel

Each laboratory developed in house a lot of the technique necessary to the cable winding!

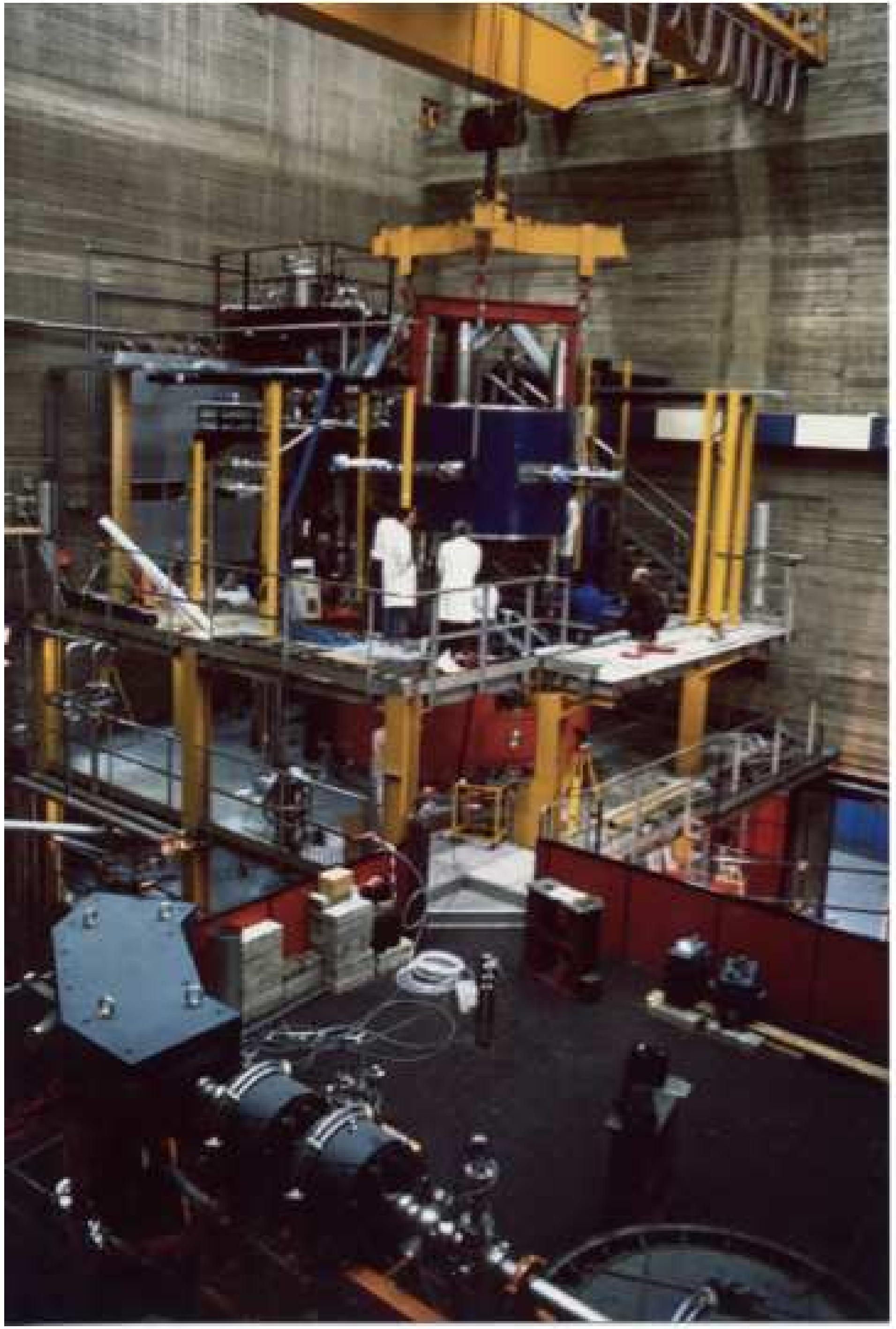
On courtesy of S. Brandenbourg


On courtesy of S. Brandenbourg



On courtesy of S. Brandenbourg

Cryostat of the K800 cyclotron installed at Catania site 1992



A serious advantage of superconducting cyclotrons is their significant reduction of electrical power!

K800 cyclotron power consumption 1.6 - 2 MW

GANIL(F) 6-8 MW!

Liquid Helium plants, need room!


He
compressor

Superconducting Isochronous Cyclotrons-- in their 3rd decade of use

- MSU K500 – 1982
  - Solved field design problem
  - Solved 3-phase RF
  - Solved beam extraction
- MSU K1200 – 1988
  - highest energy CW accelerator
- TAMU K500 – 1988
  - improved RF mech. design
- MSU K100 – 1989
  - Solved gantry rotation with pool boiling cryogens
  - C.R. w/ separated cathode PIG
- Milan/Catania K800 - 1994
- Orsay/Groningen K600 - 1996
- Accel/MSU K250s- PBRT 2005-6
  - two built and commissioned simultan.

These machines have:

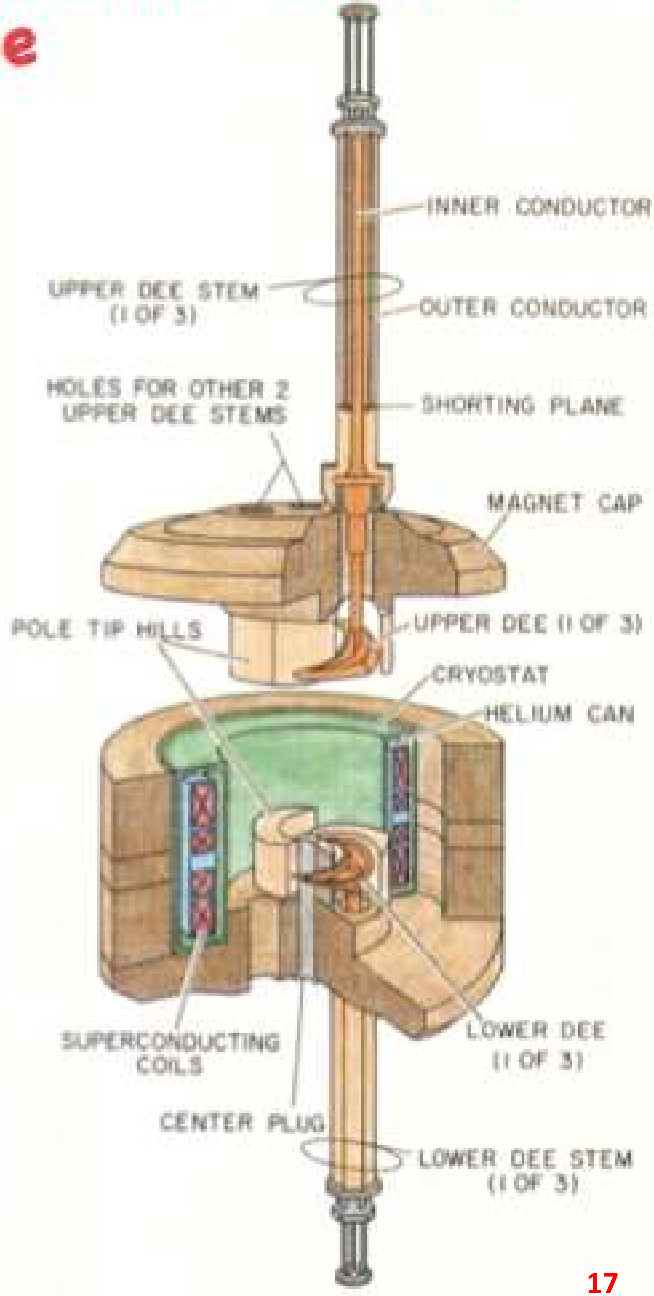
Establish important technol. limits @4-6T

Eliminated model magnets and shimming

Lower overall power and size

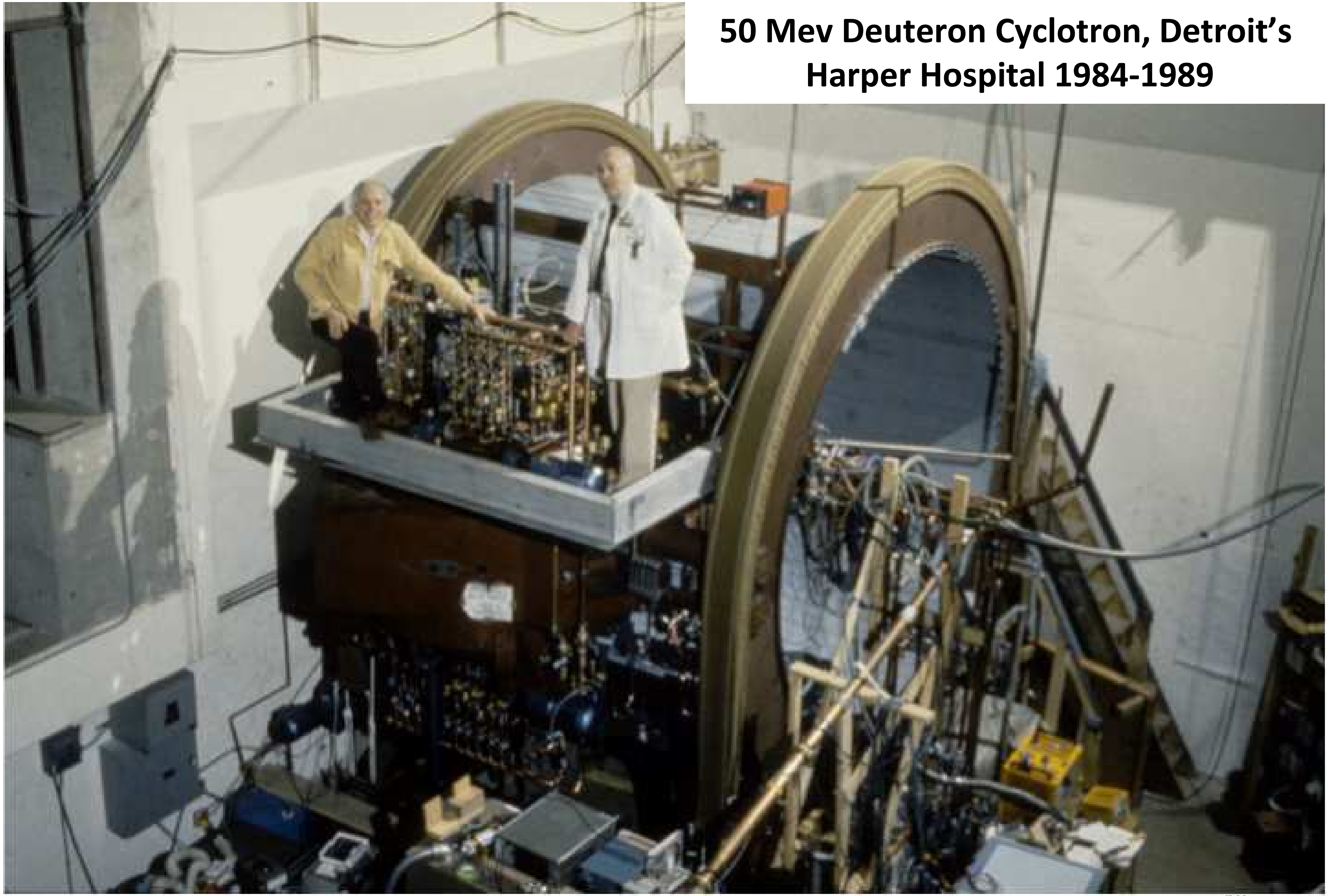
As a class are very robust

Cryogenics- many options



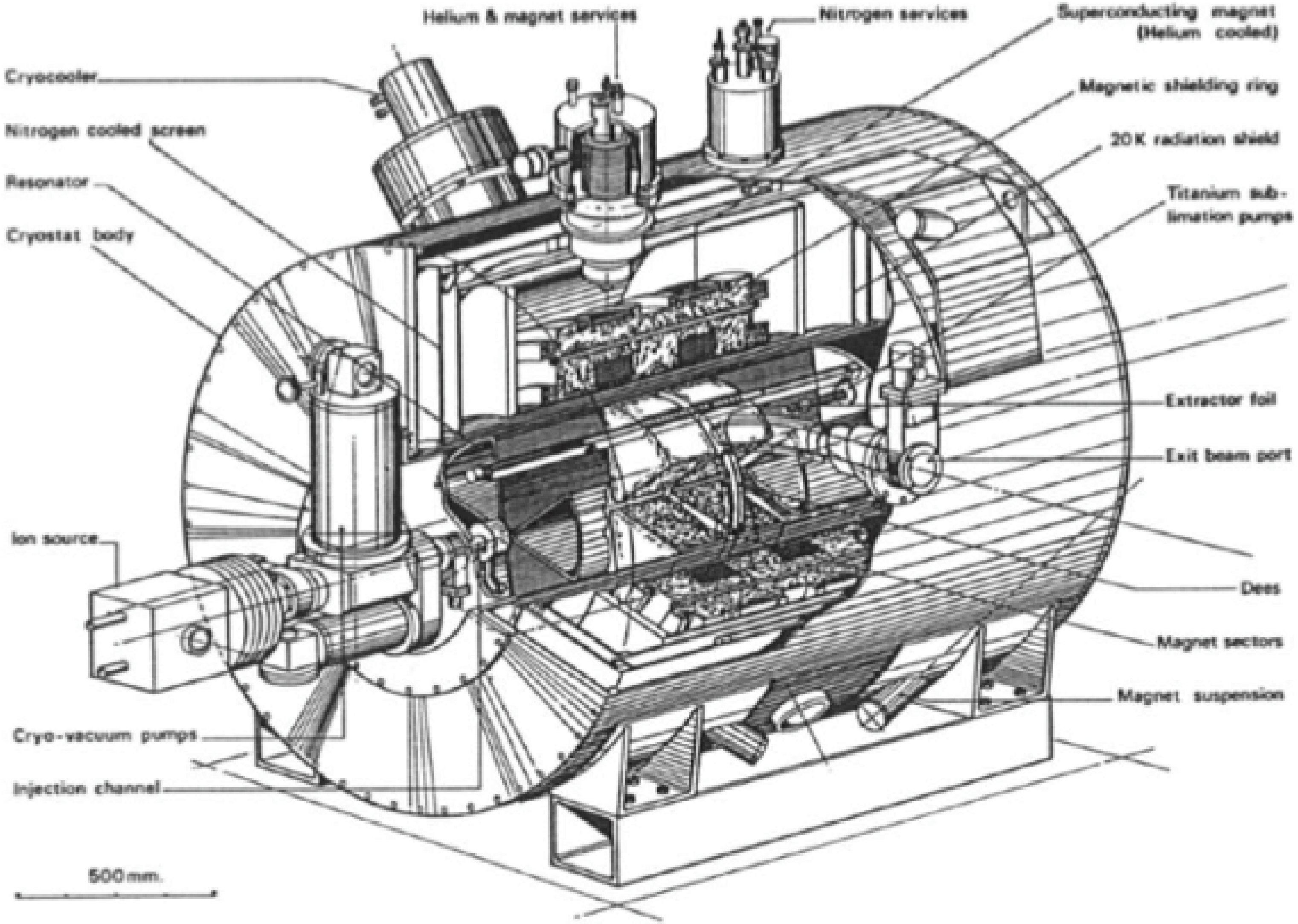
On courtesy of T. Antaya

50 Mev Deuteron Cyclotron, Detroit’s Harper Hospital 1984-1989



On courtesy of F. Marti

Oxford cyclotron (EuroMeV), 12 MeV, 200 μA, R. Griffiths (1989?), radioisotope production



On courtesy of H. Roecken, Varian

2002-2004

ACCEL builds the first superconducting cyclotron for proton therapy!
90 tons!
Closed cycle for LHe system!

6 W cooling power produced by 4 commercial cryocoolers!

High Tc current leads

On courtesy of H. Roecken, Varian

Still River Monarch 250 (Now MeVion) - smaller than a conventional modern 18 MeV PET Cyclotron

Nb3Sn Coils:

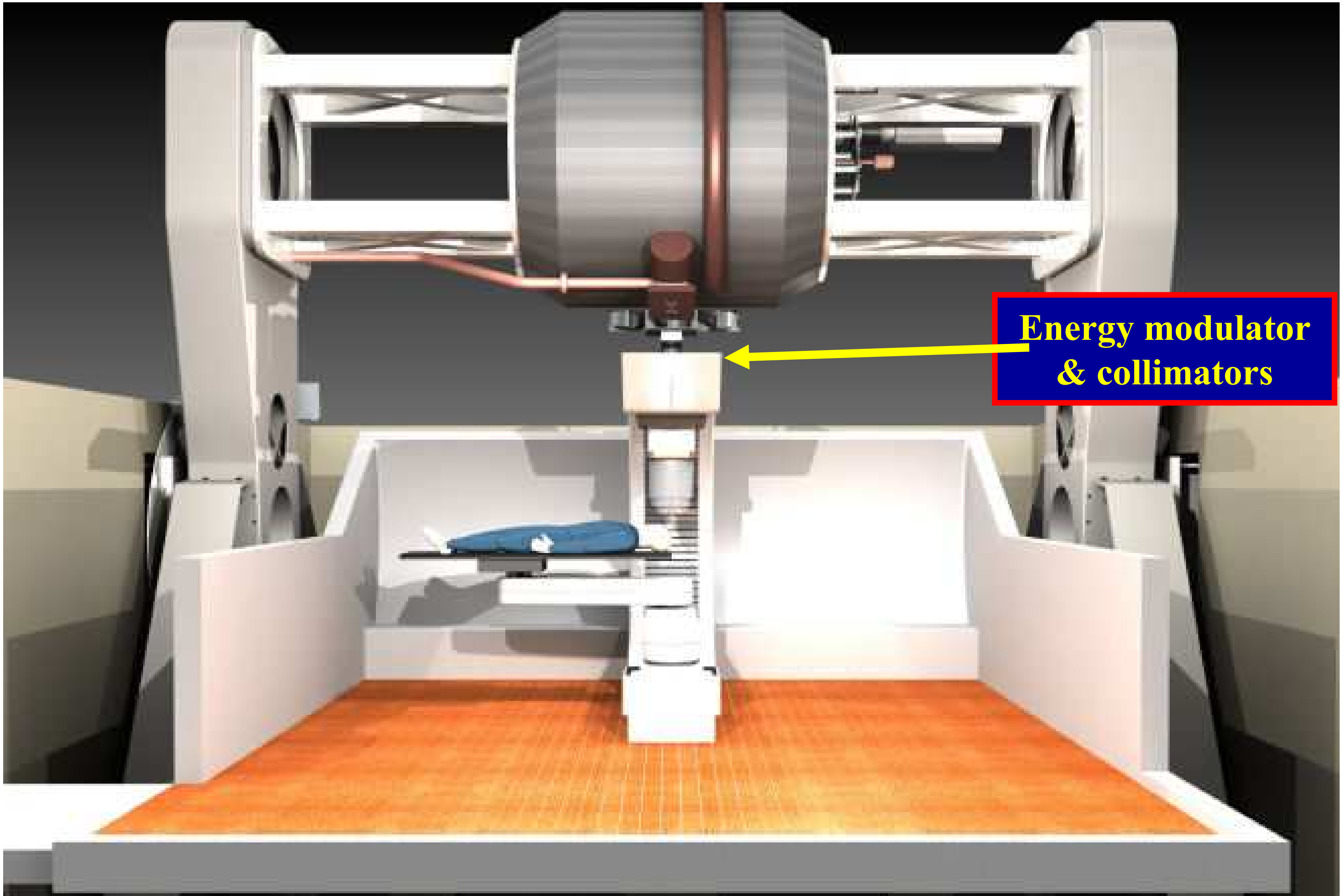
- High Jc strand- ~3000 A/mm^2 (Oxford)

  Conductor is derived from DOE HEP Conductor Development Program extensively vetted by US LARP

  +

- Wind & React, Cable in Channel (Luvata)
  - Follows concept developed for the US DOE OFES Levitated Dipole Experiment (Minervini et al/MIT)

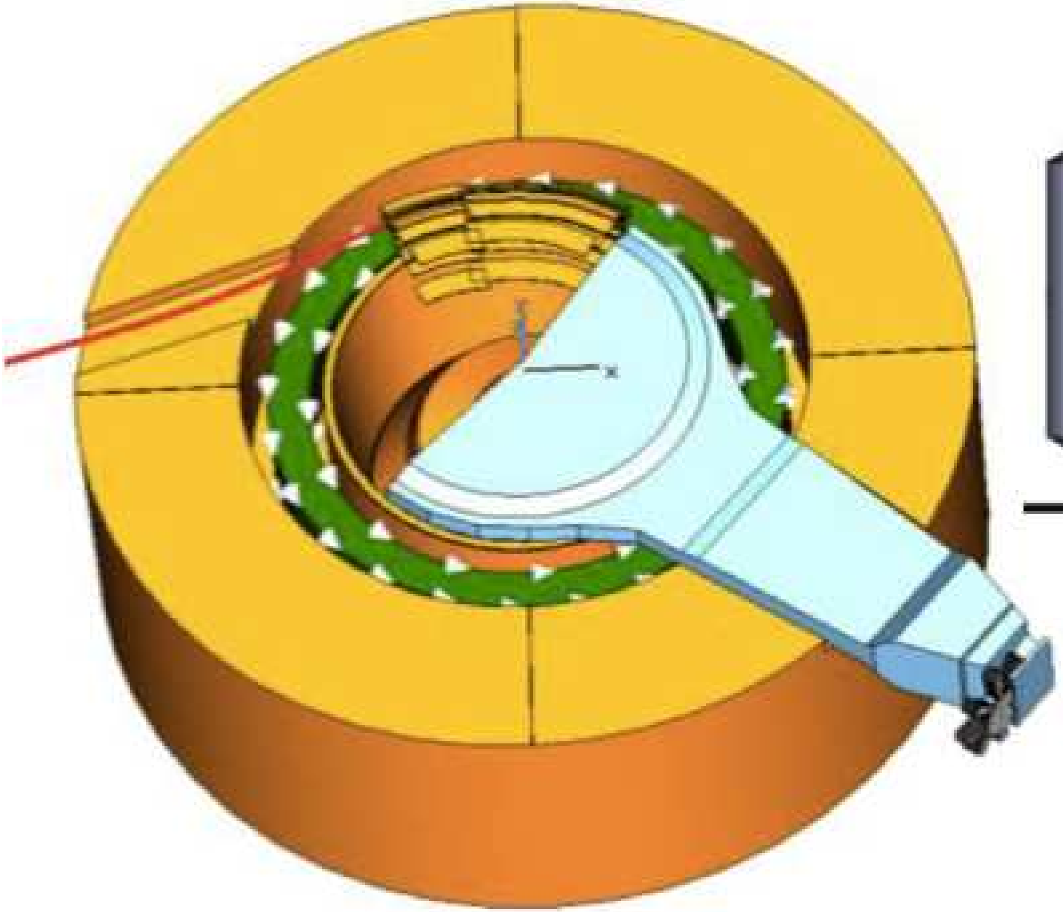
On courtesy of T. Antaya

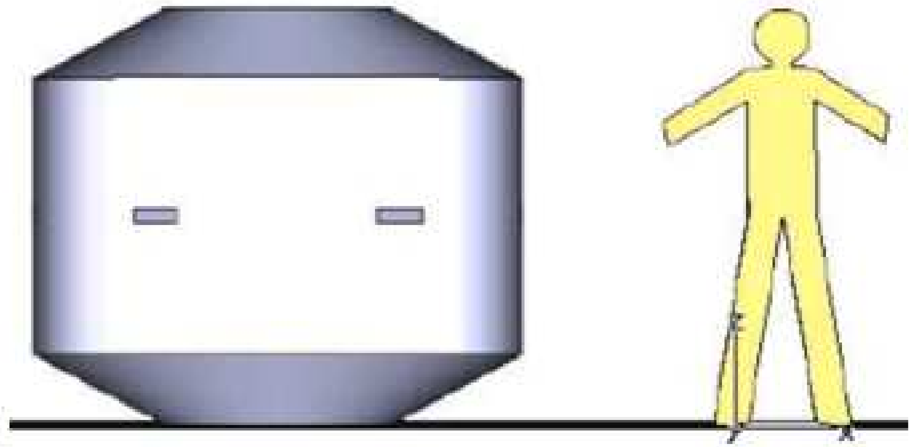


First Beam delivered 2010

The 235 MeV Sinchrocyclotron of IBA

The concept, as imagined back in early 2009.



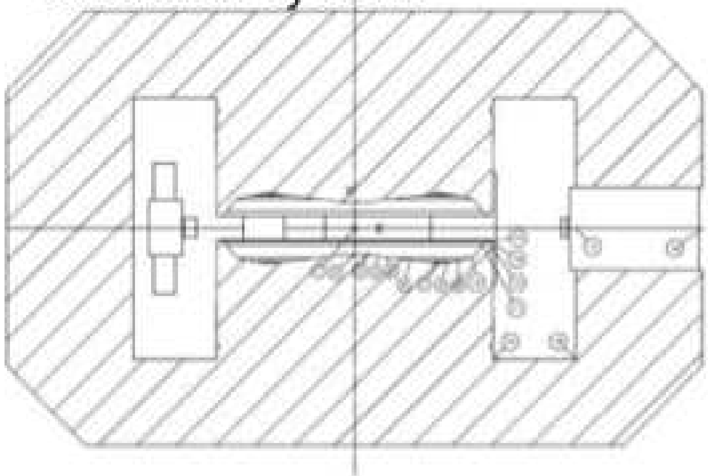


< 50 Tons!

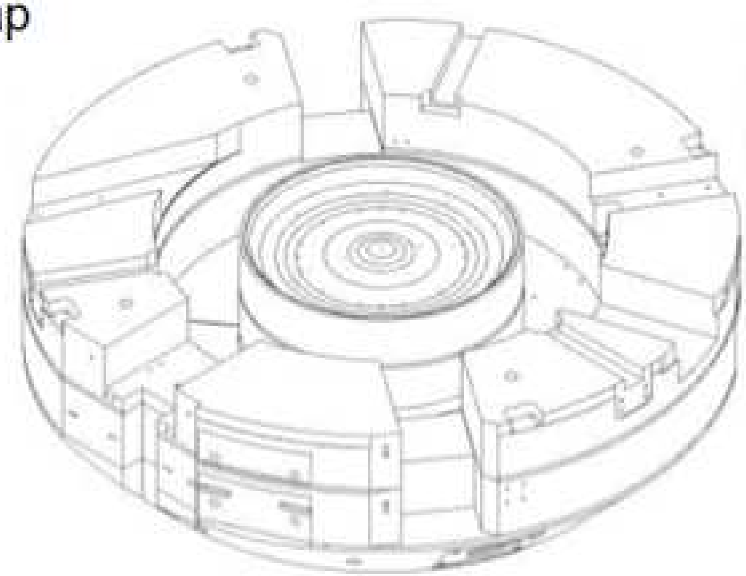
Courtesy of Y. Jongen

The yoke size is a compromise between coil complexity, peak field, stray field and total weight. Also, it allows to stay away from any patents and use cheap and readily available NbTi.

The pole profile is the result of an optimized extraction system.



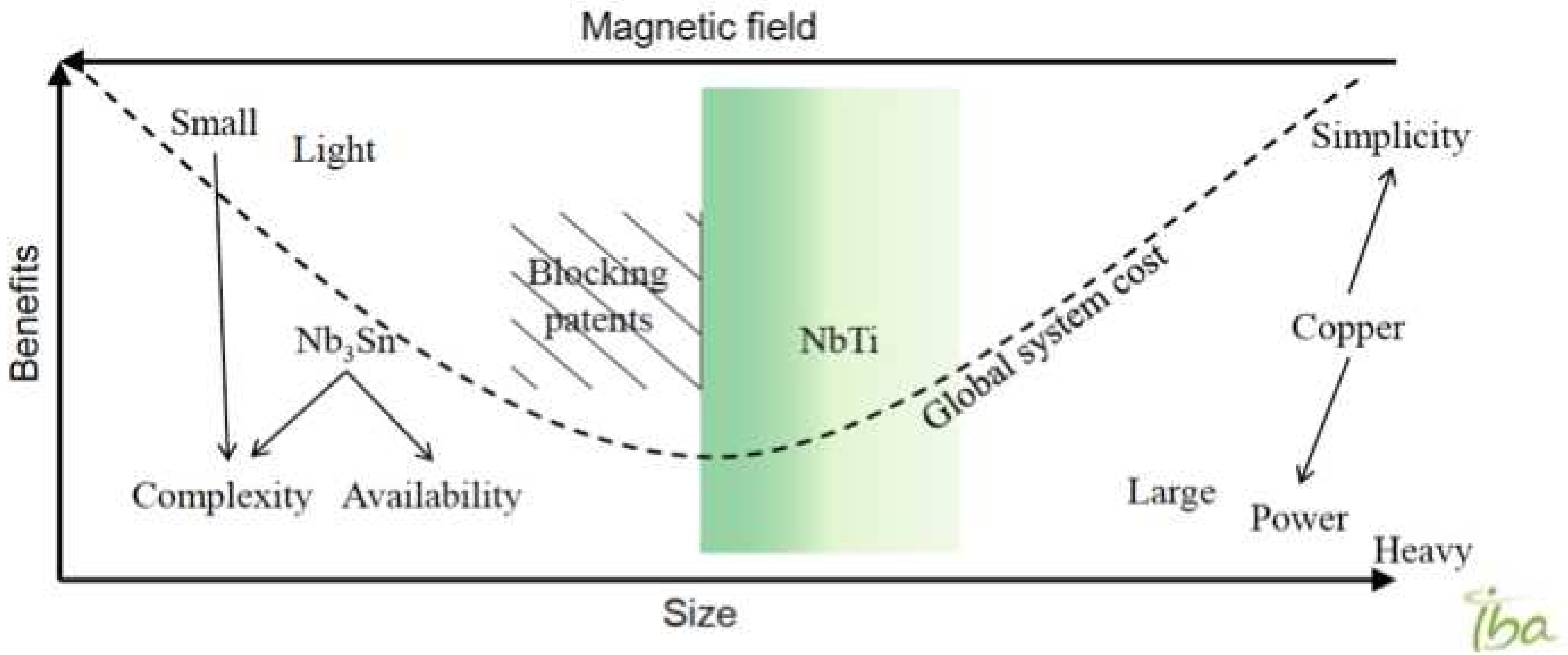
REF	X	Y
1	0	0
2	0	-82
3	50	-82
4	80.5	-99.7
5	115	-104.5
6	200	-113
7	[illegible]	-109.5
8	[illegible]	-123.8
9	375	-118
10	424	-108
11	[illegible]	-61
12	475	-44.5
13	[illegible]	-43
14	495	-43
15	497.5	-479
16	784	-479
17	784	0
18	1200	0



Diameter: 2.5m

Iron weight: 41.5tons

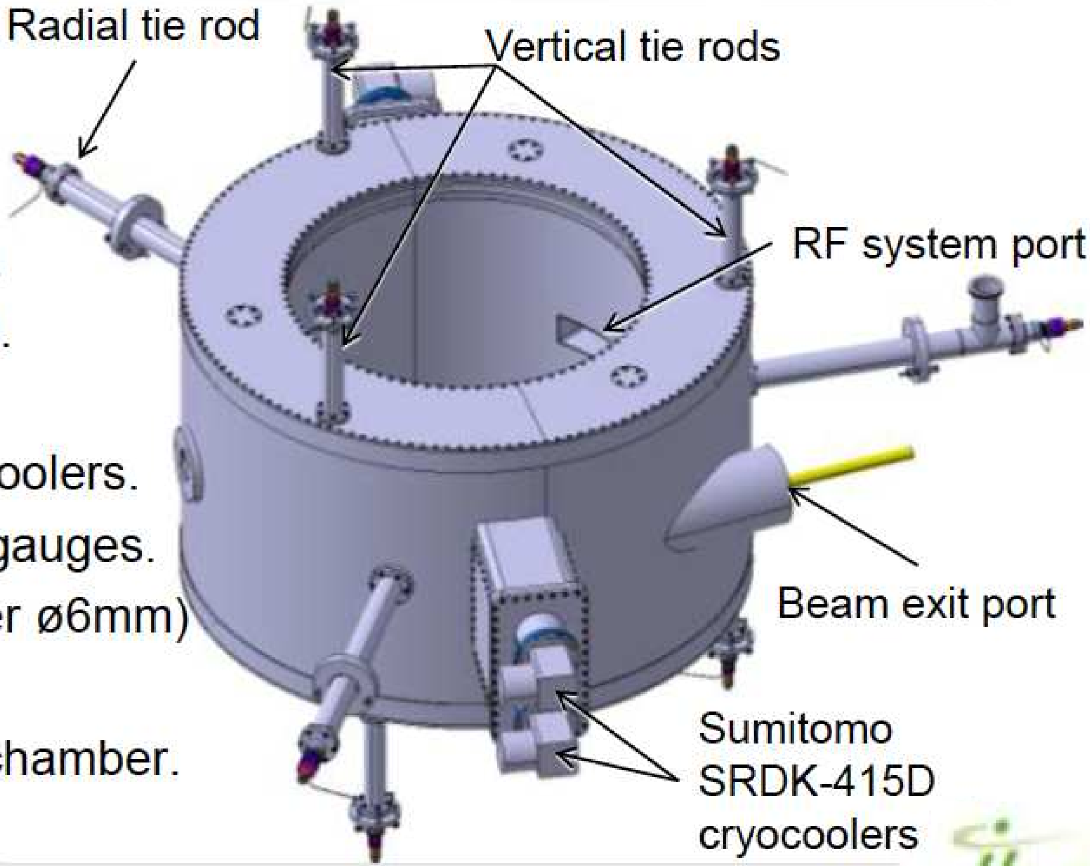
iba

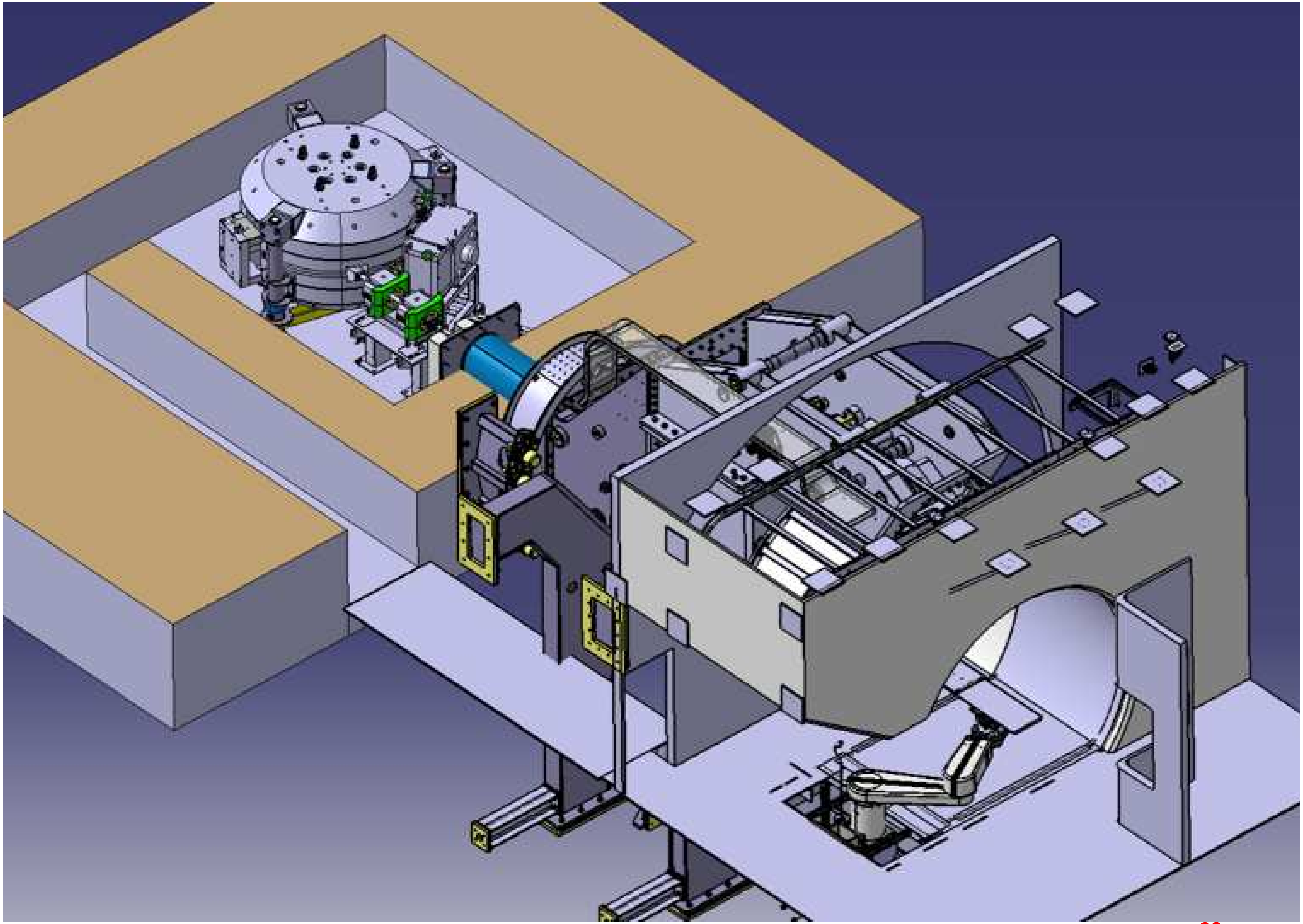


Courtesy of Y. Jongen

- NbTi wire in channel coil.
- Suspended cold mass: 3tons.
- Overall weight: 4tons.
- Nominal current: 650A (56A/mm²).
- Nominal ampere-turns: $4.3 \times 10^{+6}$At.
- Stored energy: 10MJ.
- Conduction cooled by 4 SHI cryocoolers.
- 9 Inconel tension rods with strain gauges. (radial ø14mm; upper ø8mm; lower ø6mm)

- Cryostat is the cyclotron vacuum chamber.





Courtesy of Y. Jongen

S2C2P SYNCHROCYCLOTRON - IBA

Assembly of the magnet inside the yoke at the Customer's site

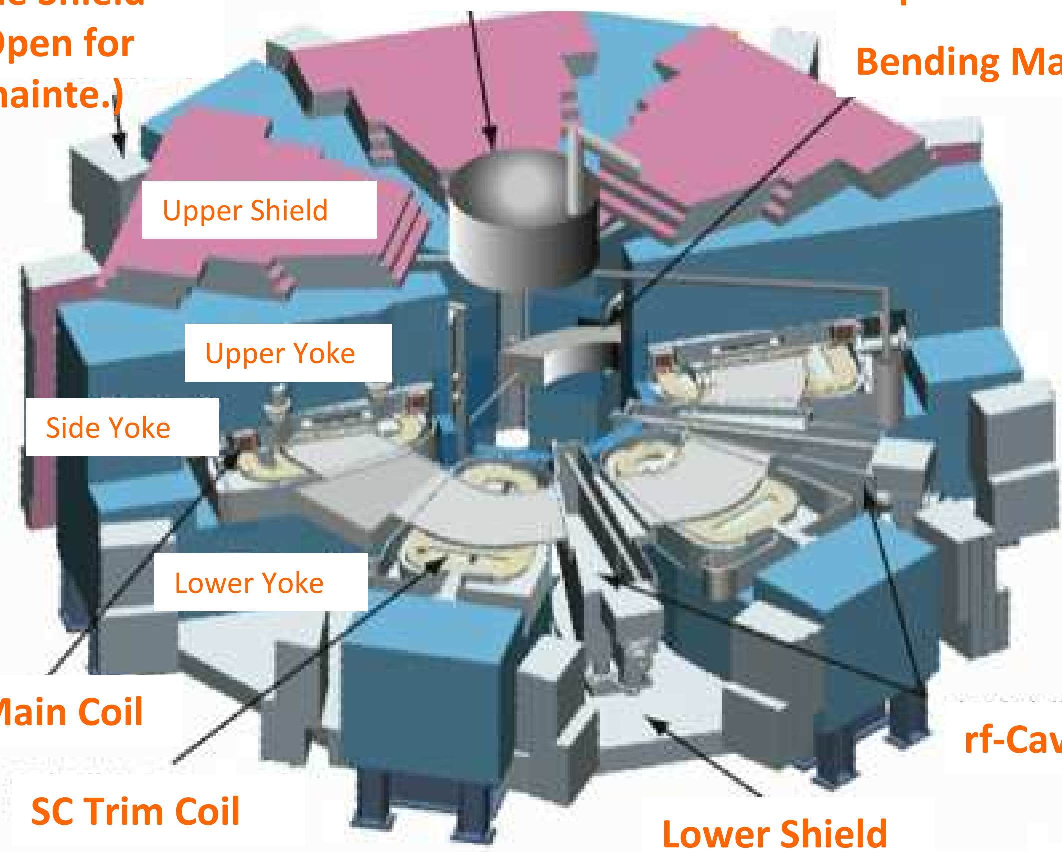
3D simulation IBA ProteusONE™ is a single-room compact proton therapy solution

SRC: the World's First Superconducting Ring Cyclotron 2001-2006

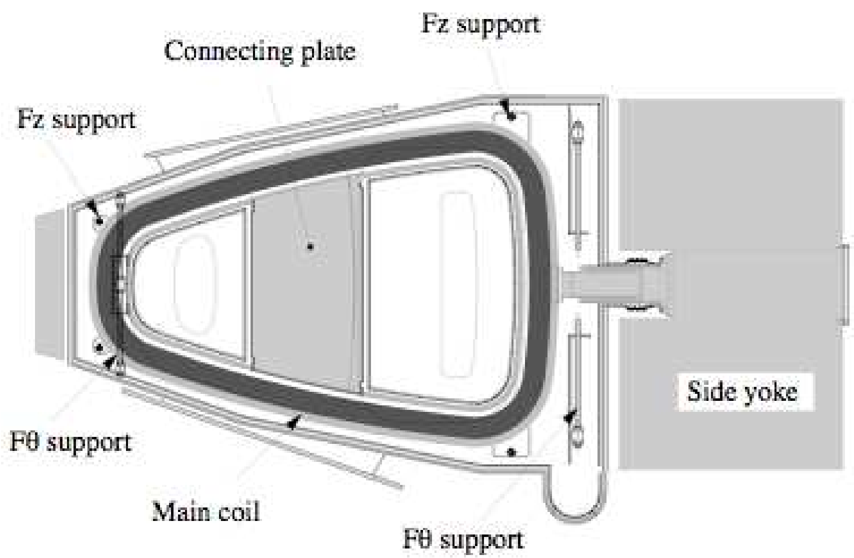
K = 2,500 MeV
Self Magnetic Shield
Self Radiation Shield
Max. Field: 3.8T (240 MJ)
Rf frequency: 18-38 MHz
Weight: 8,300 tons
Diameter: 19m Height: 8m

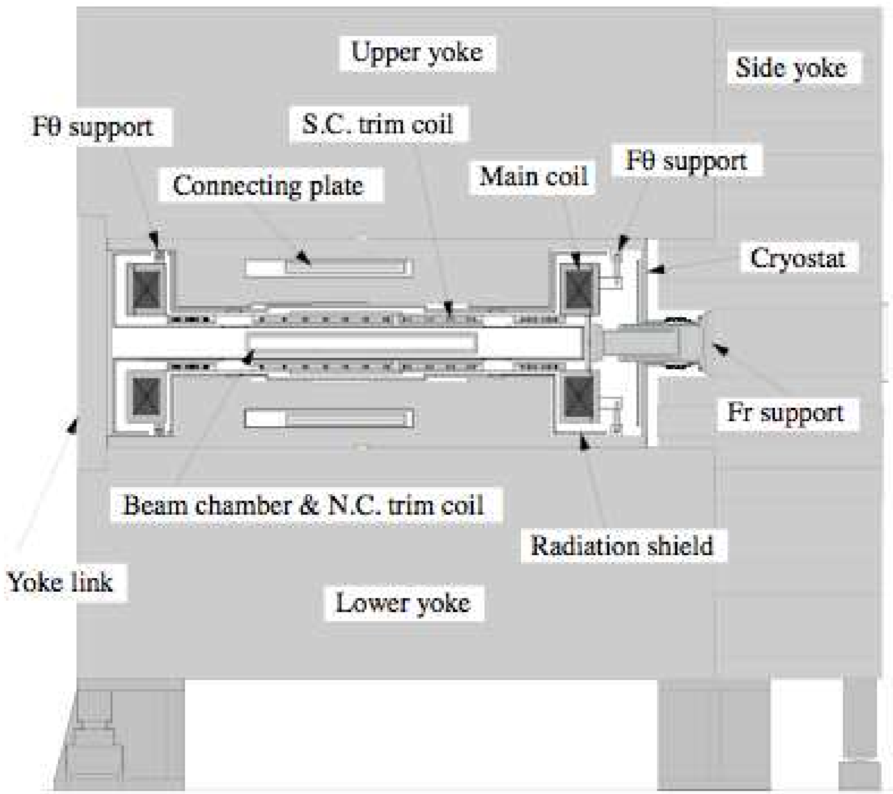
Superconducting Magnets in SRC

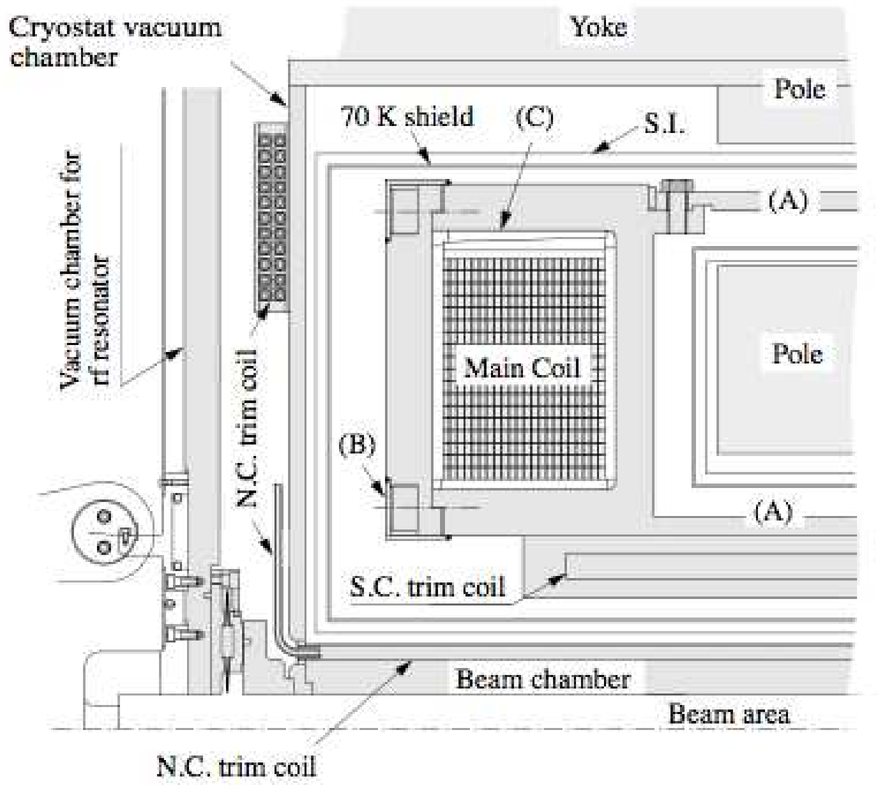
1) Sector Magnet
2) SBM for beam injection + Power Supplies + Cryogenic Cooling system



Courtesy of H. Okuno, Riken

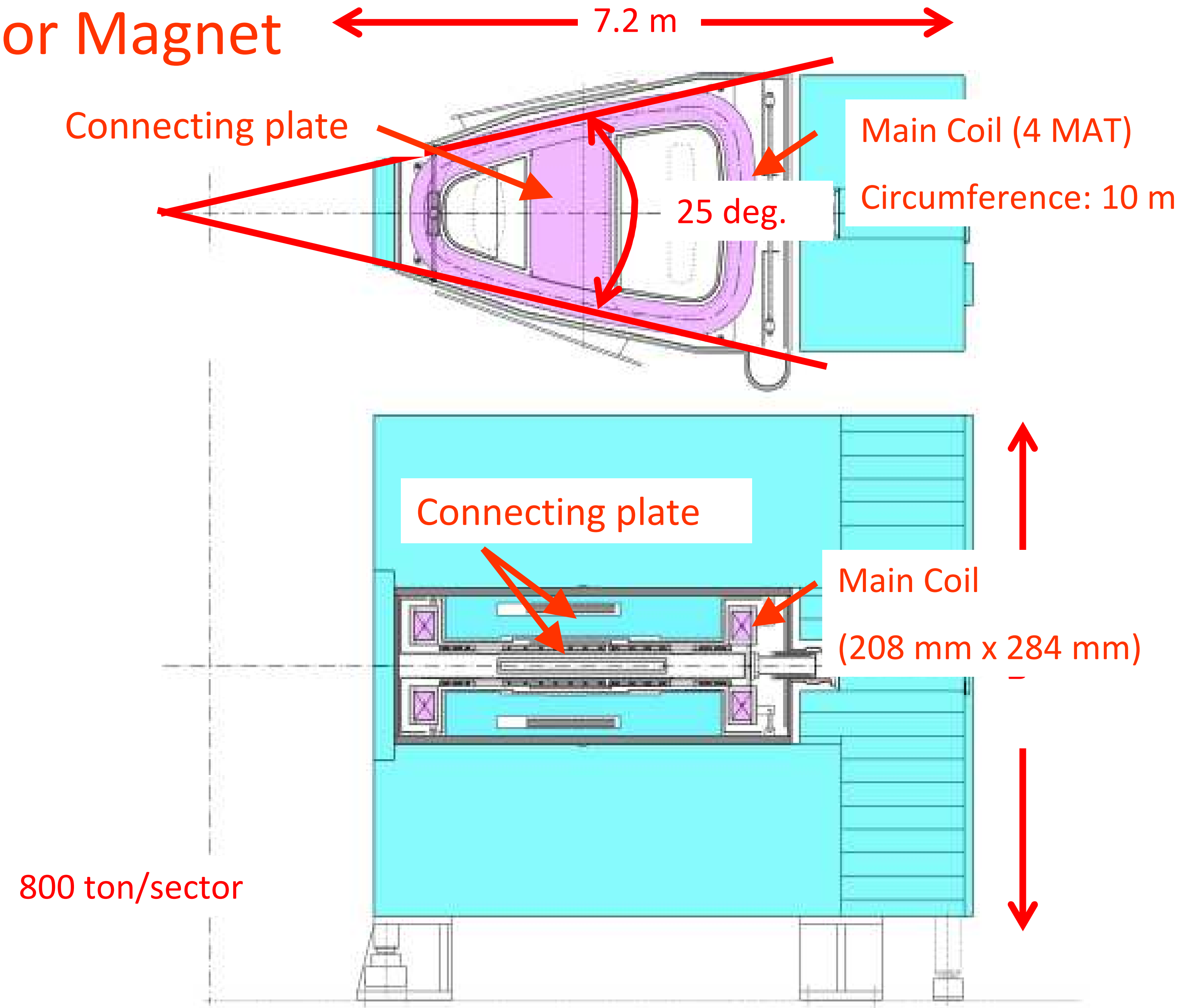






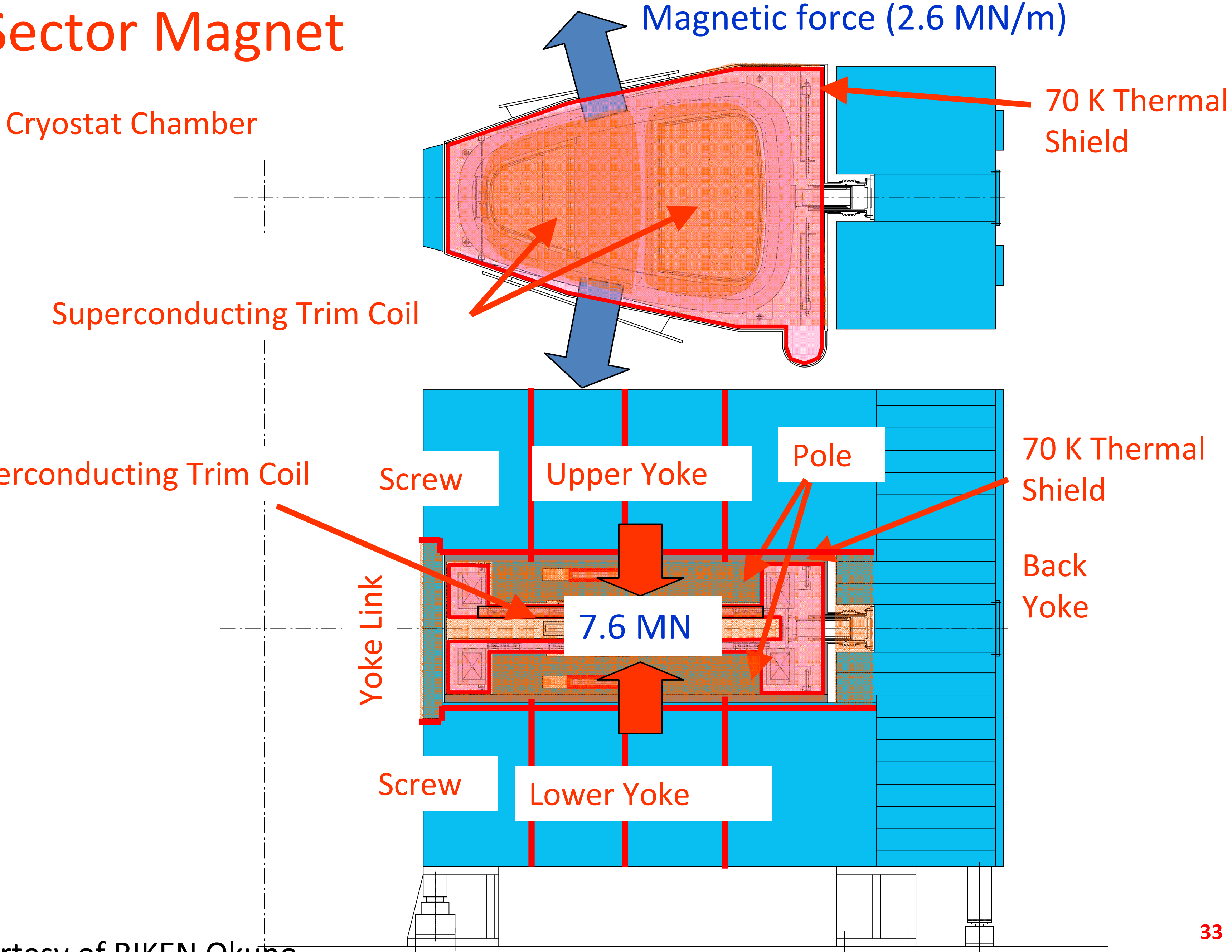
(A) : Connecting plate (B) : Seal cover (C) : Cotta

Sector Magnet



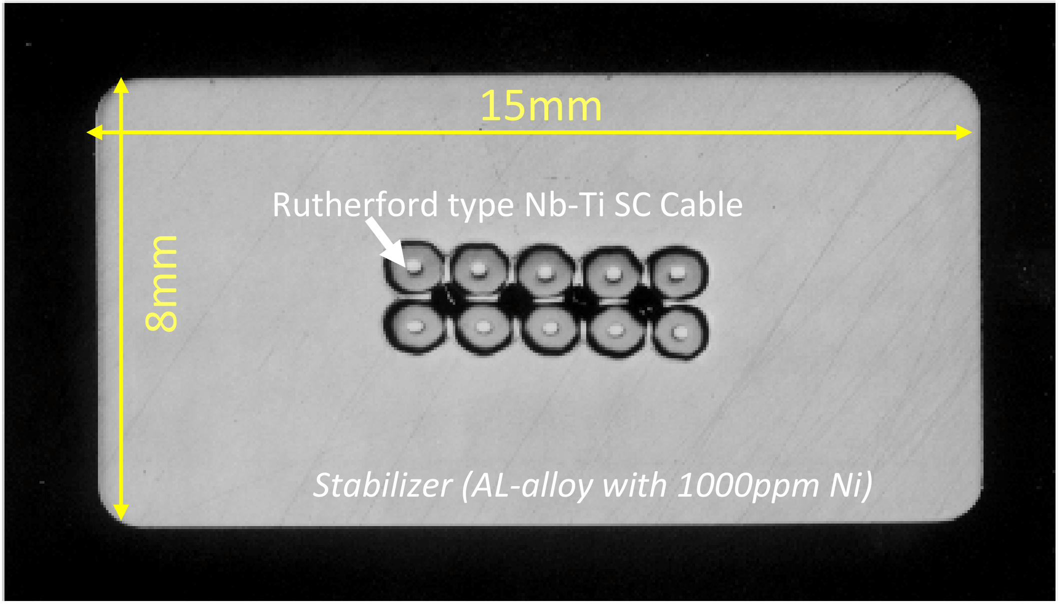
Courtesy of RIKEN Okuno

Sector Magnet



Courtesy of RIKEN Okuno

Superconductor



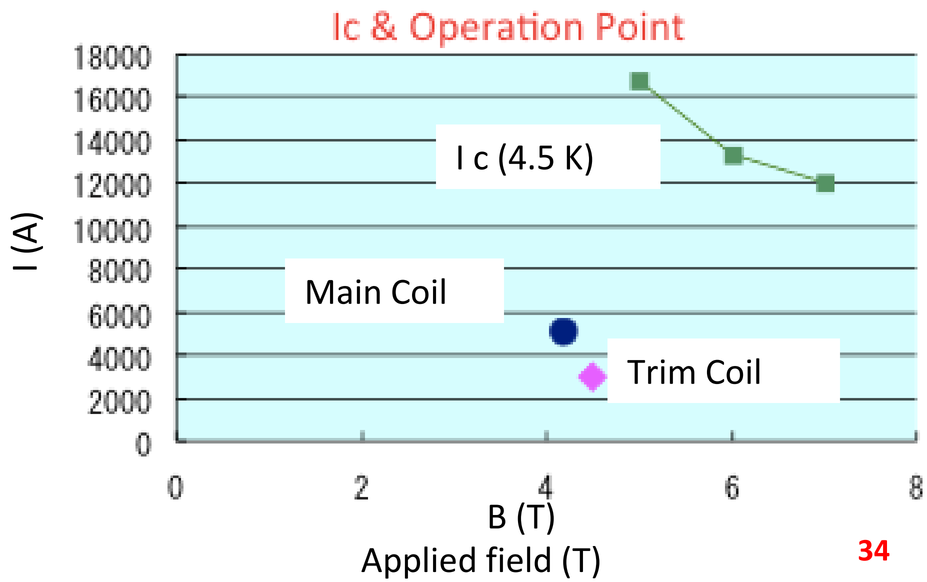
R (NbTi [SC]) = 0

R (NbTi [NC]) > 1000 R (Al)

→ Suppression of heat generation

Yield Strength = 55 MPa

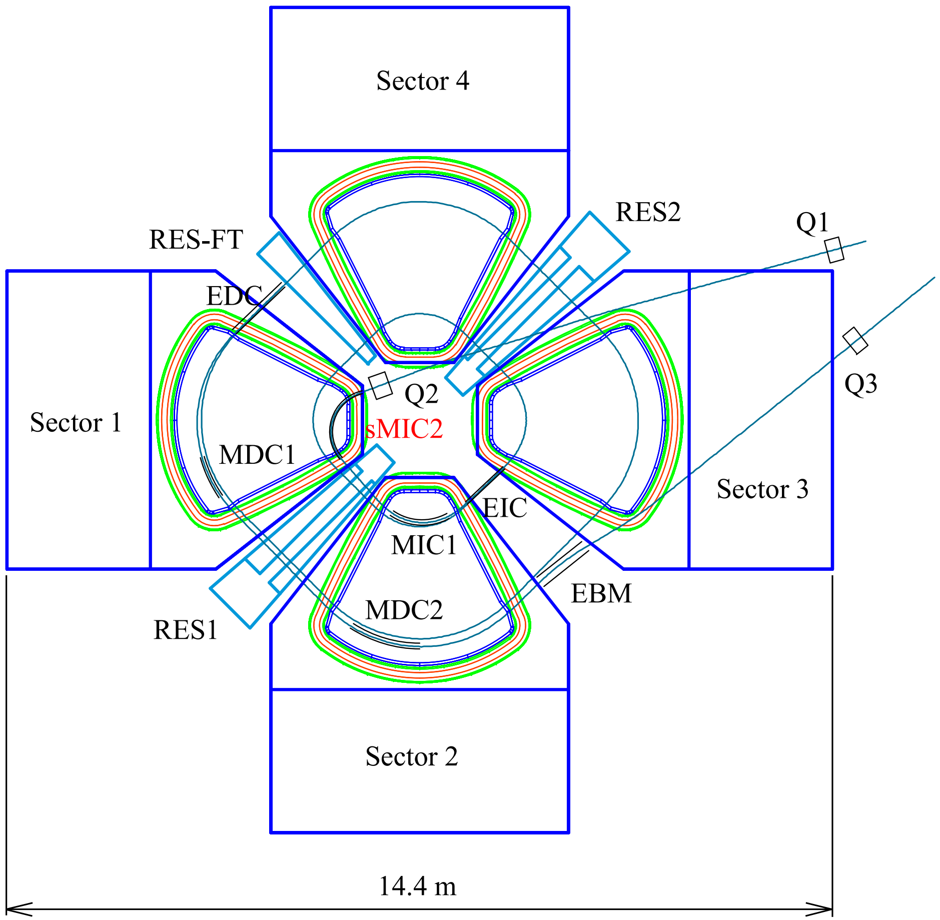
(cf. 40 MPa for pure Al)



Courtesy of H. Okuno, RIKEN

S.C. fRC for RIBF upgrade

Ohnishi, Okuno 9th PASJ (2012)



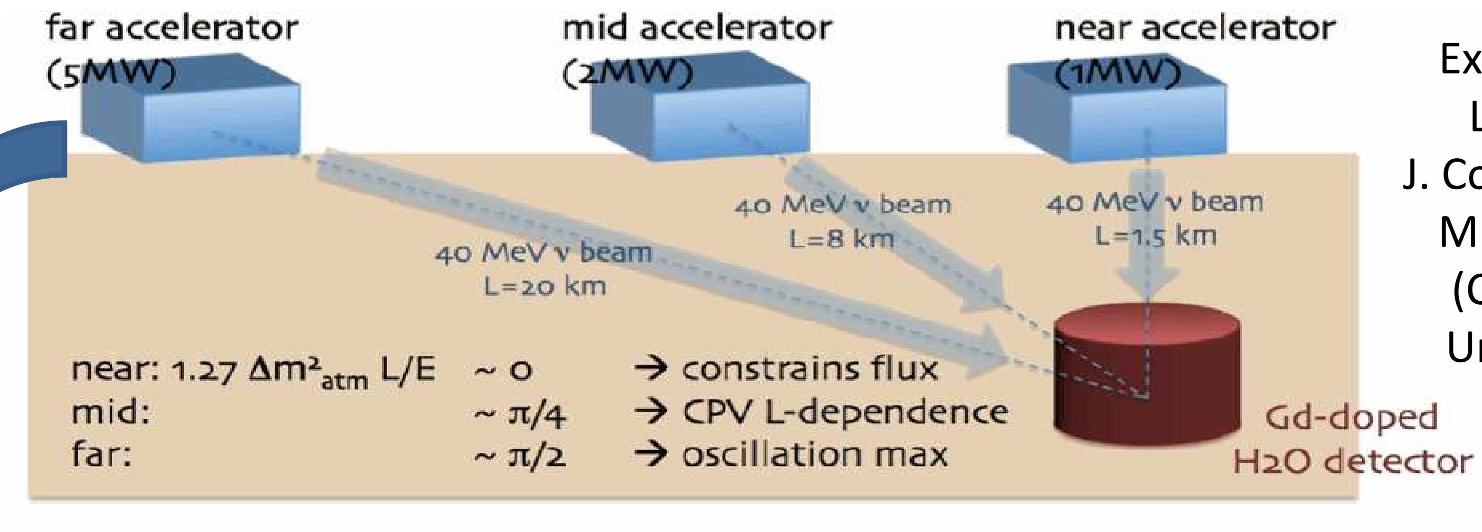
Parameter of s-FRC	
K-value	2220 MeV
Velocity Gain	2.06
Injection Energy	10.8 MeV/u
Extraction Energy	48.0 MeV/u
RF frequency	36.5 MHz
Harmonics	9
Injection Radius	1.775 m
Extraction Radius	3.65 m

Parameters of Sector magnets	
Sector number	4
Weight/sector	1200 t
Pole gap	180 mm
Magnet motive force	1.62 MA
Bmax in the orbit	3.2 T
N.C. trim coils	20 pairs

Details are in discussion.

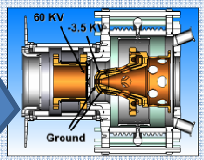
Courtesy of H. Okuno, Riken

DAE δ ALUS: experiment overview

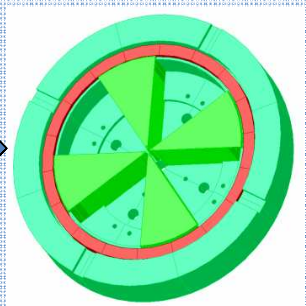


Experiment Leaders:
J. Conrad (MIT)
M. Shaevitz (Columbia University)

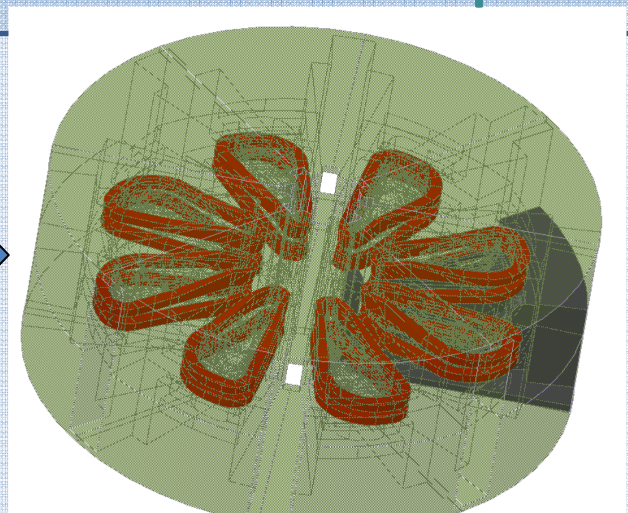
Accelerator Complex (INFN-LNS Catania expertise)



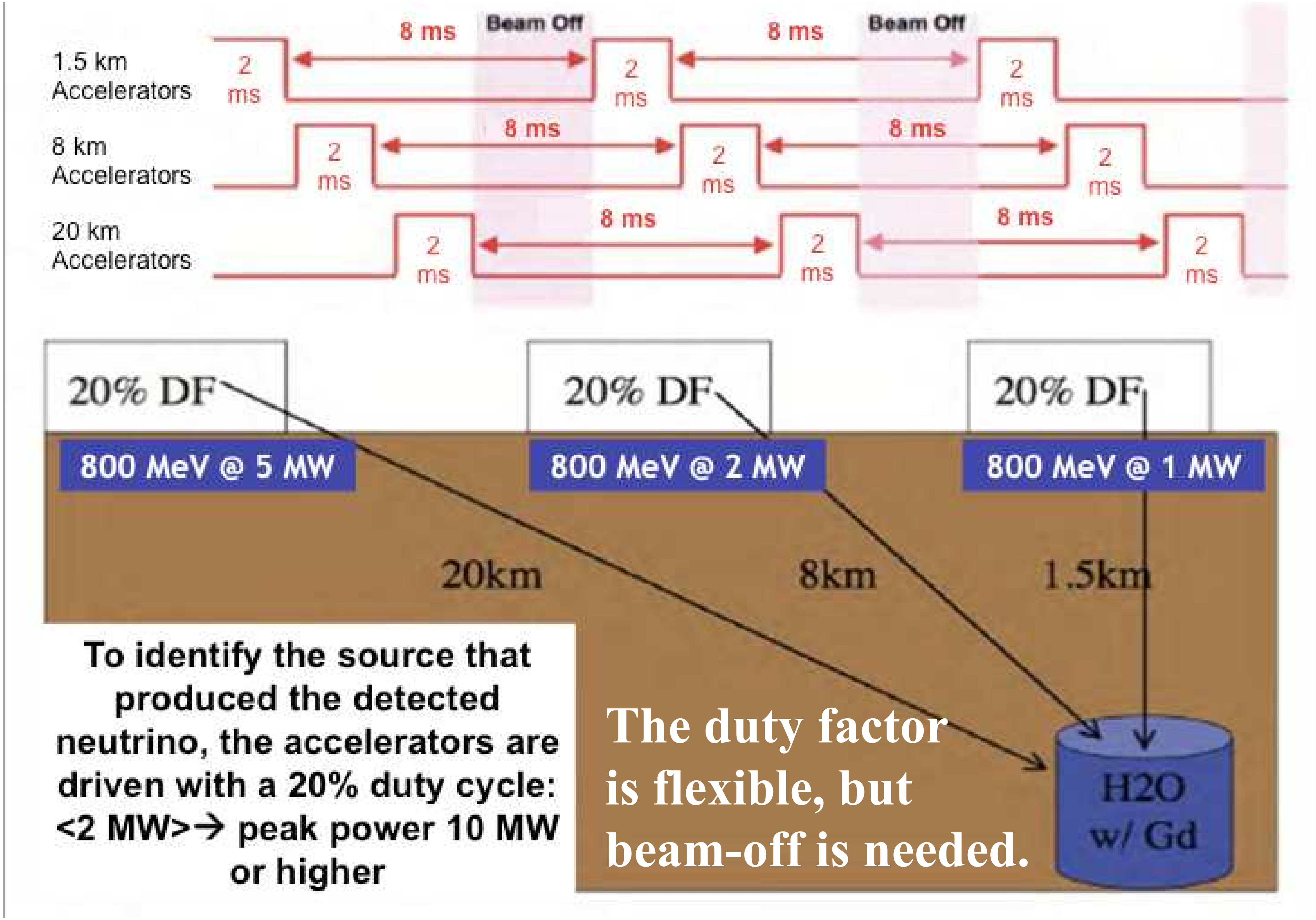
VIS source



Normal conducting Cyclotron



Superconducting Ring Cyclotron


1.5 km Accelerators
8 km Accelerators
20 km Accelerators
8 ms
Beam Off
2 ms
20% DF
800 MeV @ 5 MW
800 MeV @ 2 MW
800 MeV @ 1 MW
20km
8km
1.5km
H2O w/ Gd
To identify the source that produced the detected neutrino, the accelerators are driven with a 20% duty cycle: <2 MW>→ peak power 10 MW or higher
The duty factor is flexible, but beam-off is needed.

Cyclotrons: Viable technology?

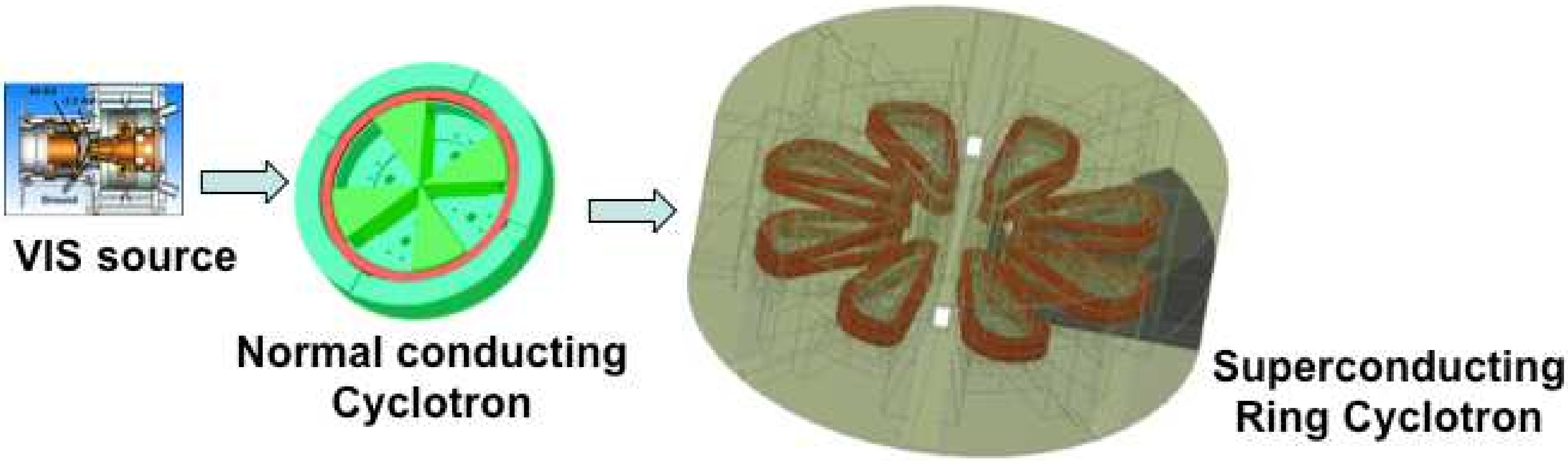
PSI is current world power leader in this energy range

~ 1.4 MW average, 590 MeV protons

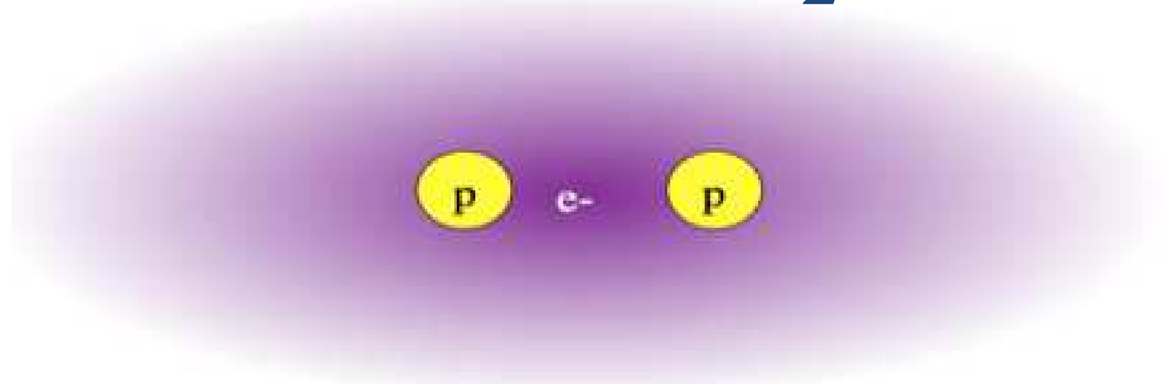
Extrapolation to higher power?

Problems:

1. Capture of more ions… space-charge at injection
2. Clean extraction… max loss 200 W (~10^{-4})



Proposed Solution: H_2^+ ions

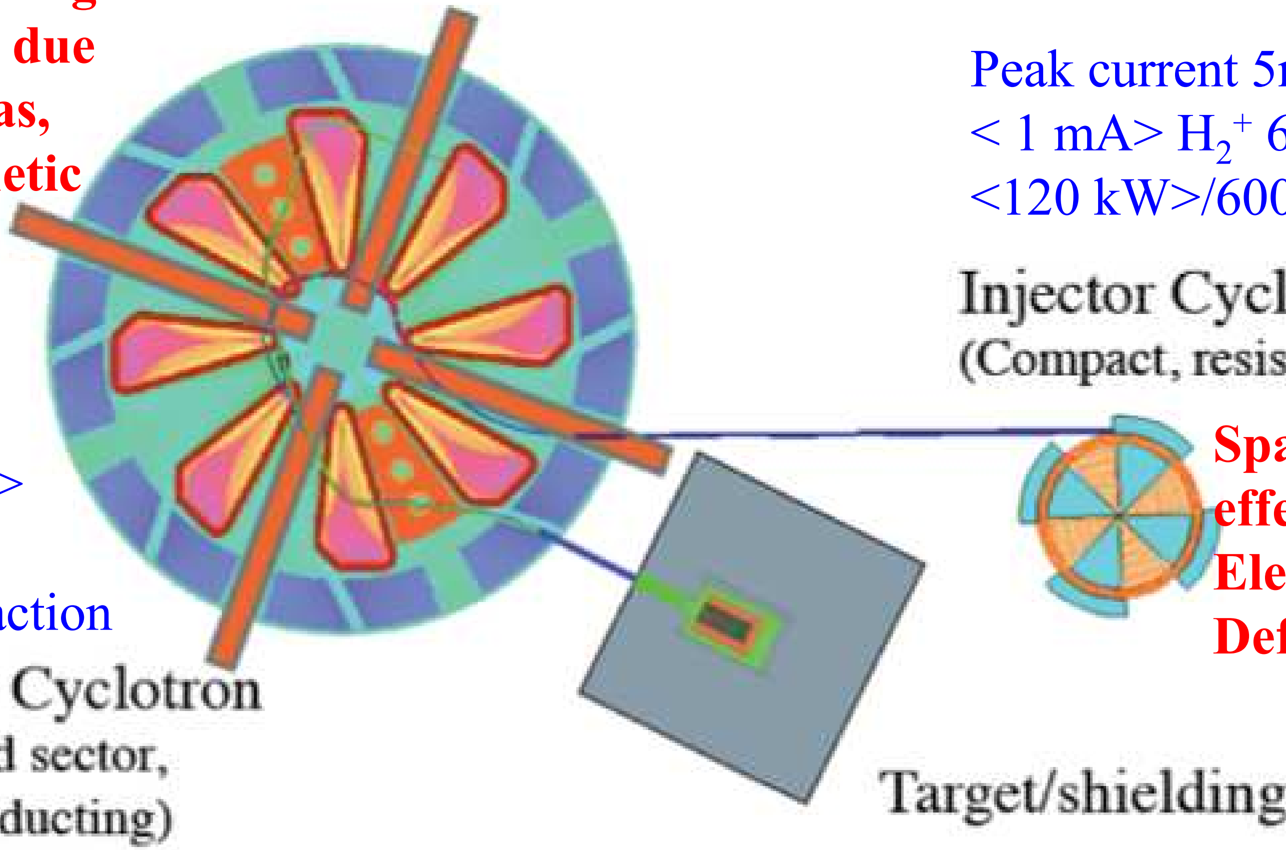


- Two protons for every ion (1 emA = 2 pmA)
- Perveance of 5 emA H_2^+ at 35 keV/amu same as 2 emA of 30 keV protons
  - Axial injection of 2 emA protons at 30 keV is well within state of the art
- Extraction with stripping foil
  - Clean turn separation is not needed, only high-acceptance extraction channel

The base cyclotron module for DAEDALUS is designed to deliver proton beam 10 mA @ 800 MeV duty cycle 20%, average power <1.6 MW>

Superconducting Coils, Losses due to residual gas, Electromagnetic stripping

< 1 mA> H_2^+
800 MeV/n
20%<1.6 MW>
8 MW peak
Stripping extraction

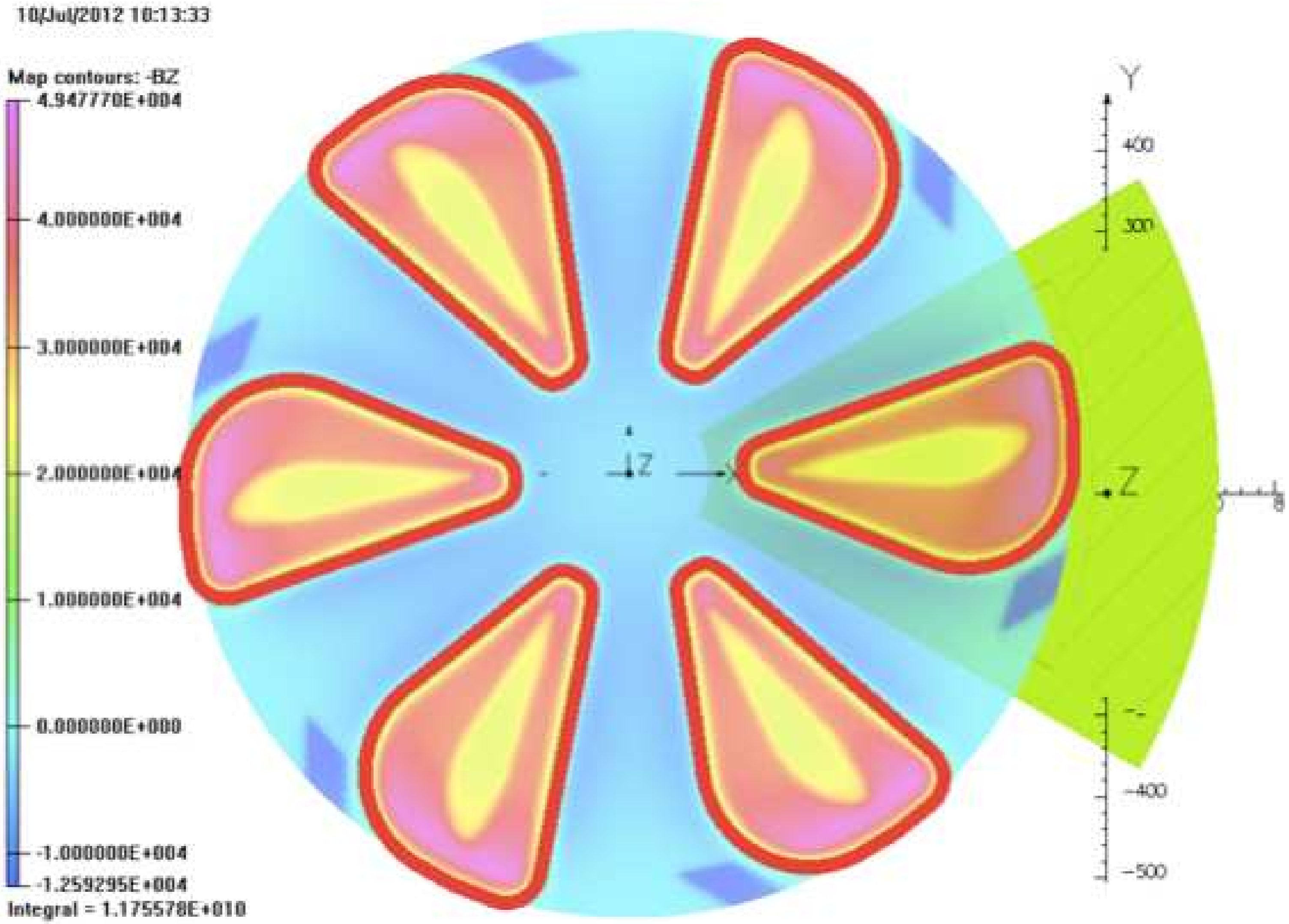


Peak current 5mA of H_2^+
< 1 mA> H_2^+ 60 MeV/n
<120 kW>/600 kW peak

Space Charge effects, Electrostatic Deflectors

arXiv.org > physics > arXiv:1207.4895

The proposed SRC for DAEdALUS

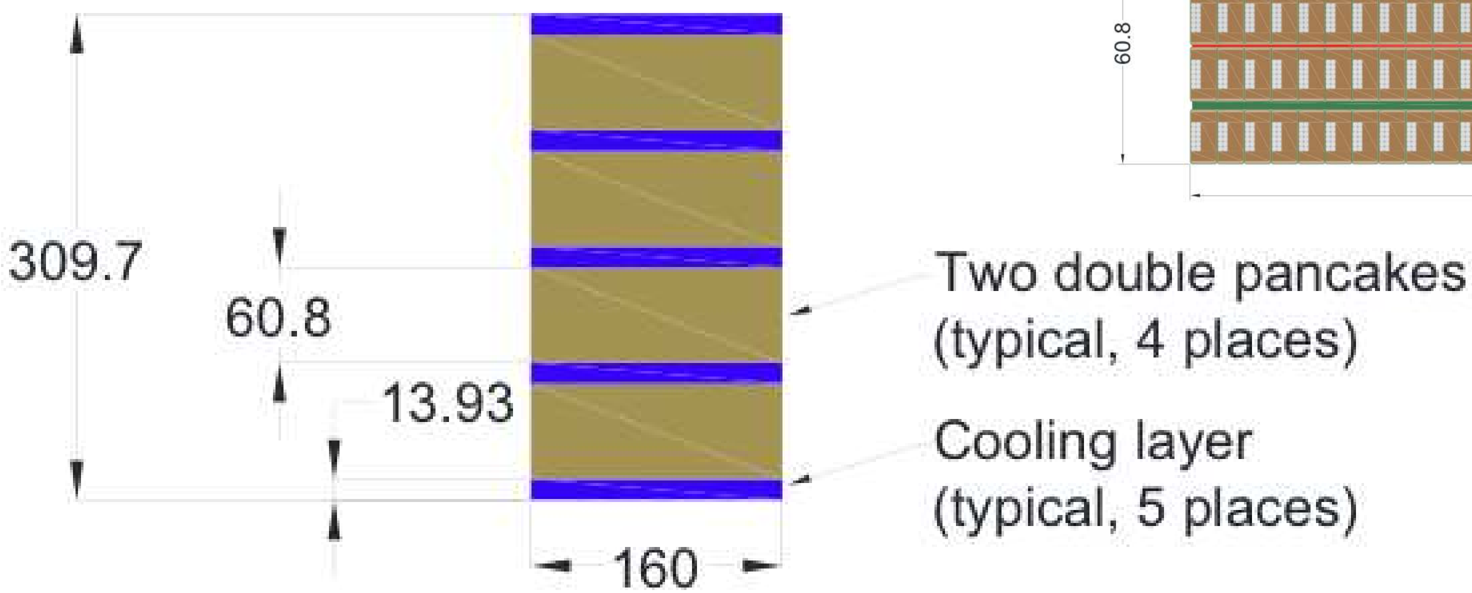


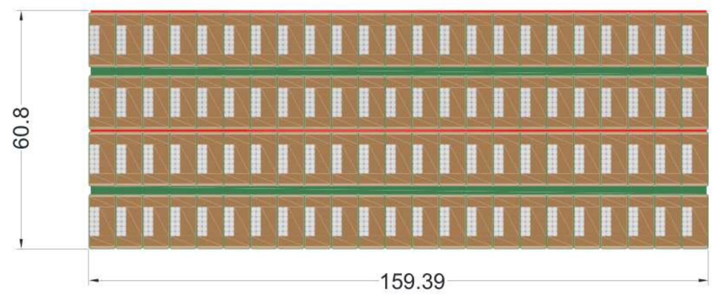
Preliminary parameters of the superconducting coils

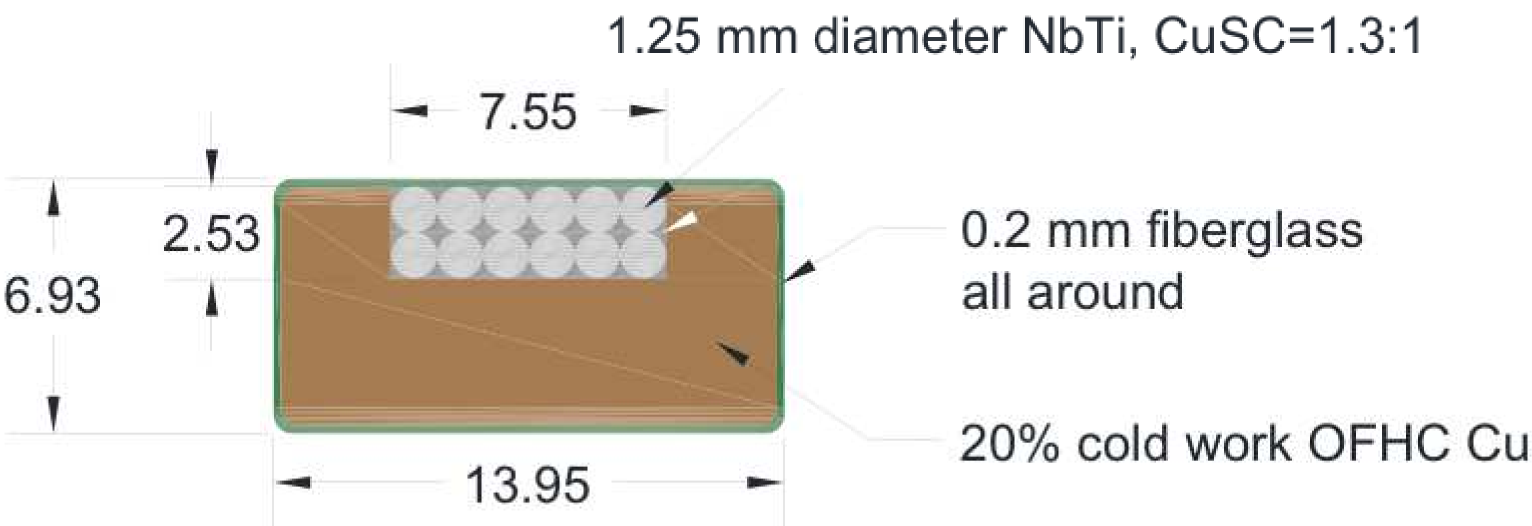
Number of Sectors		6	
Coils per Sector		2	
Coil Current Density	A/mm^2	34.68	
Coil X-section	cm x cm	16 x 31	
Coil X-section Area	m^2	0.0496	
Coil Average Length	m	10.85	
Coil Volume	m^3	0.5383	
Data Source		Opera	ANSYS
Coil Peak Field	T	4.37	4.45
Total Energy	MJ	319.72	381.12
Energy/Sector	MJ	53.29	63.52

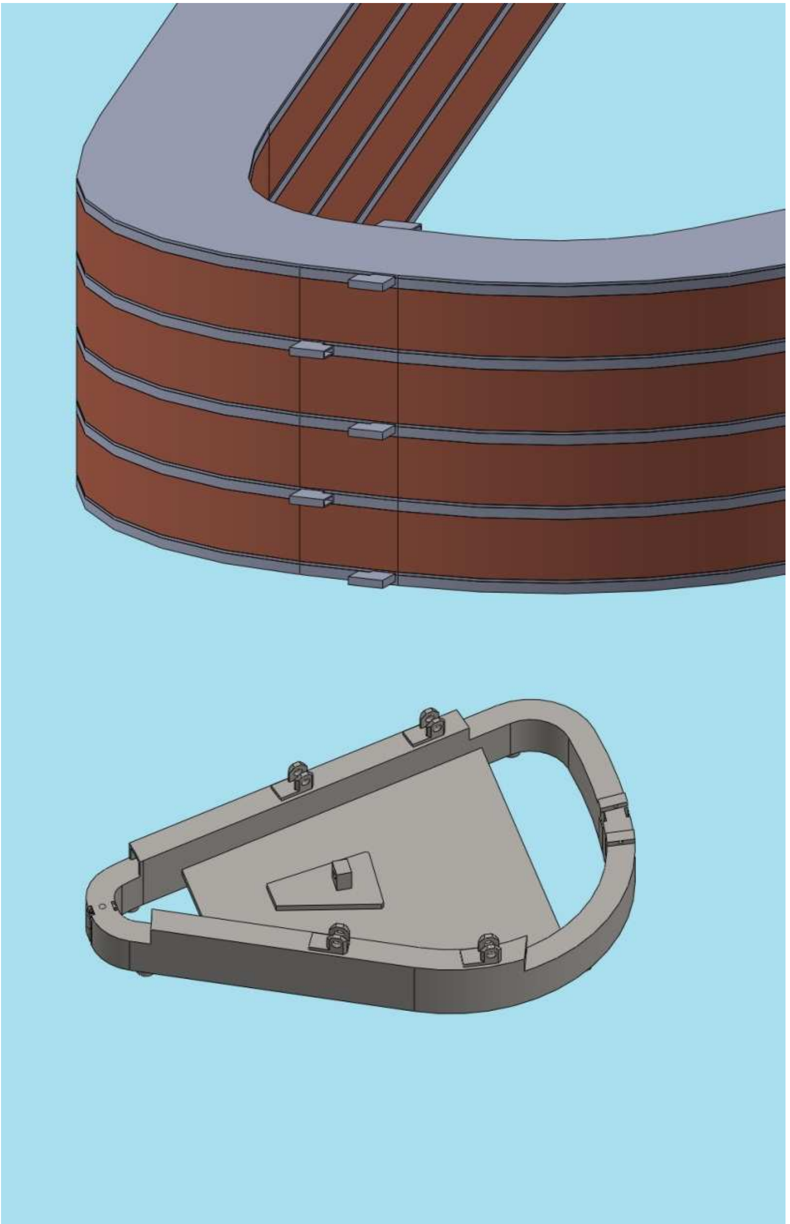
- NbTi Sc cable in Cu channel;
- Double-pancake winding;
- Conduction cooled sandwich coil scheme with pairs of double pancakes (quadro pancakes) interlaced by Stainless Steel (SS)
- cooling plates cooled by LHe flow in parallel channels;
- Structural SS Coil Case reinforced by stiffening boxes to reduce sagging over long unsupported coil spans bridging over the beam chamber space;
- Cold mass support using only SS support struts.

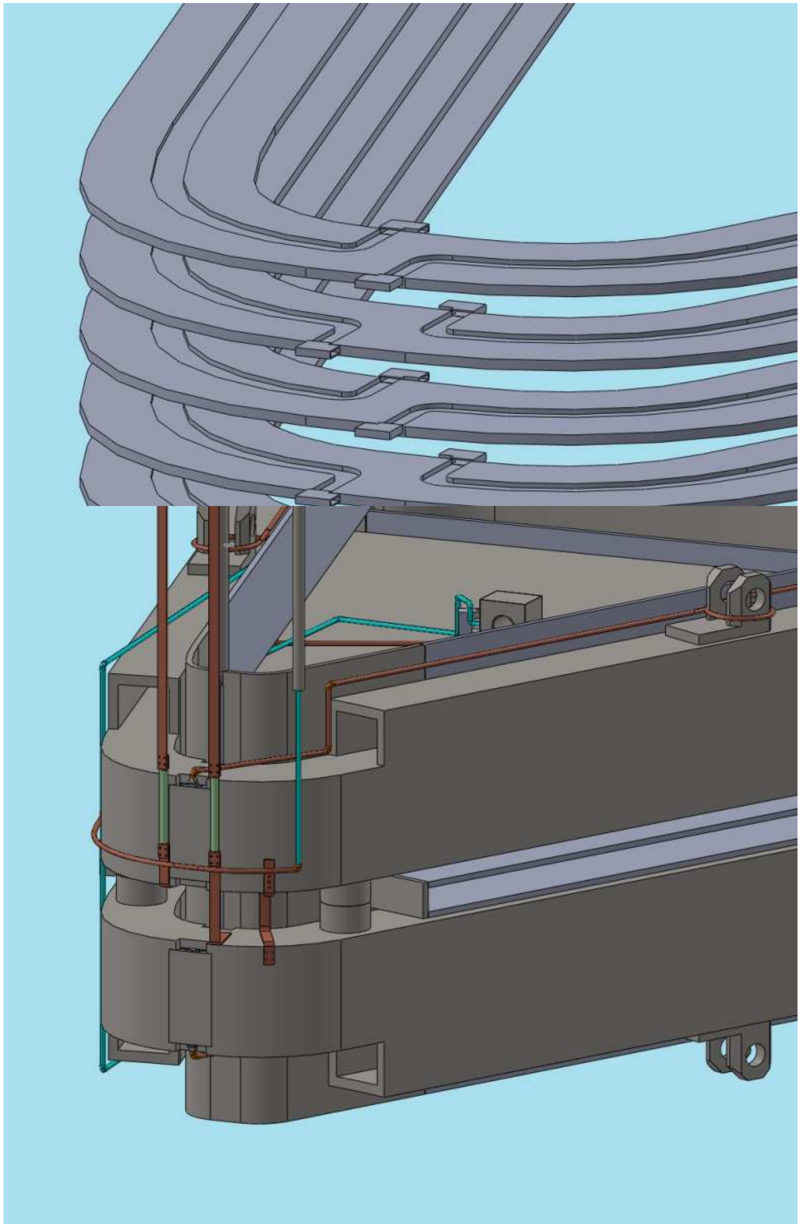
Study by PSFC (MIT)

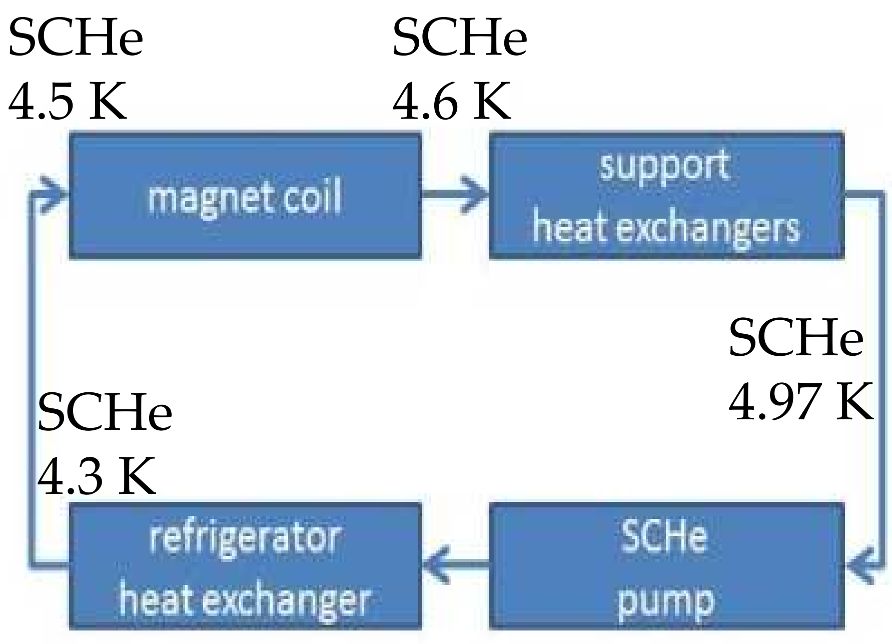










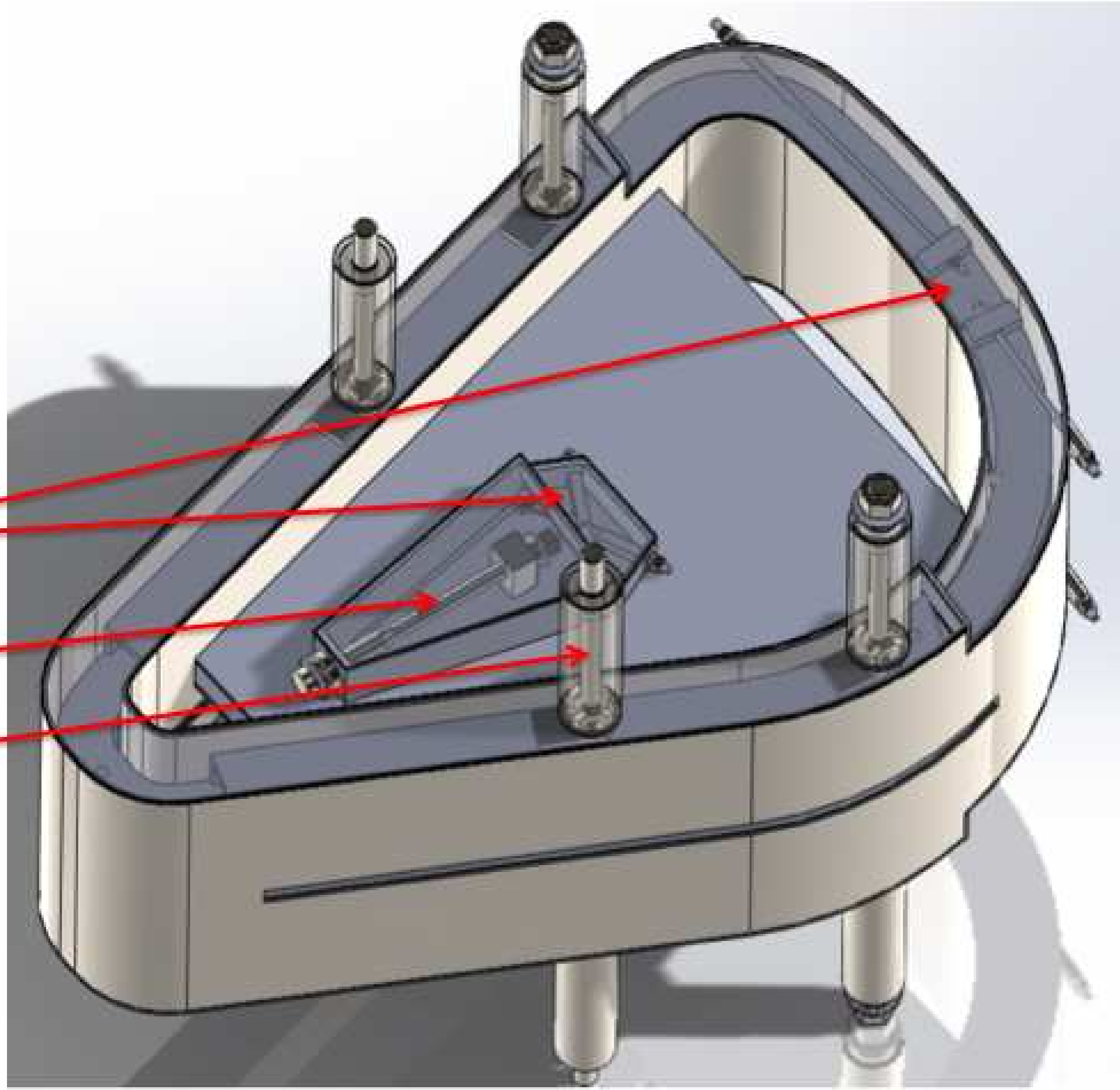


Channel height	H_{ch}	5.0	mm
Channel width	W_{ch}	30.0	mm
Channel length	L_{ch}	11.0	m
Hydraulic diameter	D_h	8.57	mm
Density	ρ	152	kg/m^3
Viscosity	μ	4.92E-6	kg/m-s
Mass flow rate	$\dot{m}$	3.0	g/s
Velocity	v	0.132	m/s
Reynolds number	Re	34900	-
Pressure drop	ΔP	40.0	Pa
Heat transfer coefficient	h	221	W/m^2-K

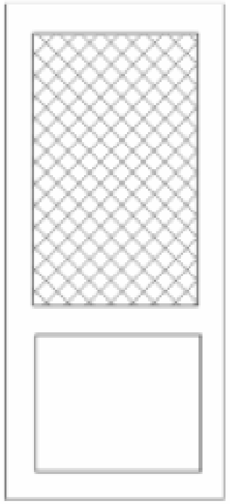
The superconducting coil and associated cold mass are cooled to 4.5K via forced flow of supercritical helium (SCHe) within a closed loop at 3.0atm. SCHe enters each of 12 magnet coils at 4.5K, 3.0atm, and a flow rate of 15g/s, and accepts a thermal load of approximately 16 W, and exits at 4.6K without any ionizing heat load into the coil. The SCHe passes through heat exchangers at the base of 7 structural supports where it accepts a load of 16.2W, exiting above 4.97K. The SCHe enters the refrigerator heat exchanger where it exchanges heat with a 4.2K liquid Helium bath. The SCHe enters slightly below 5.0K and exits at 4.3K. The heat exchanger is a simple coiled 12.7mm inner diameter tube 1.4m in length.

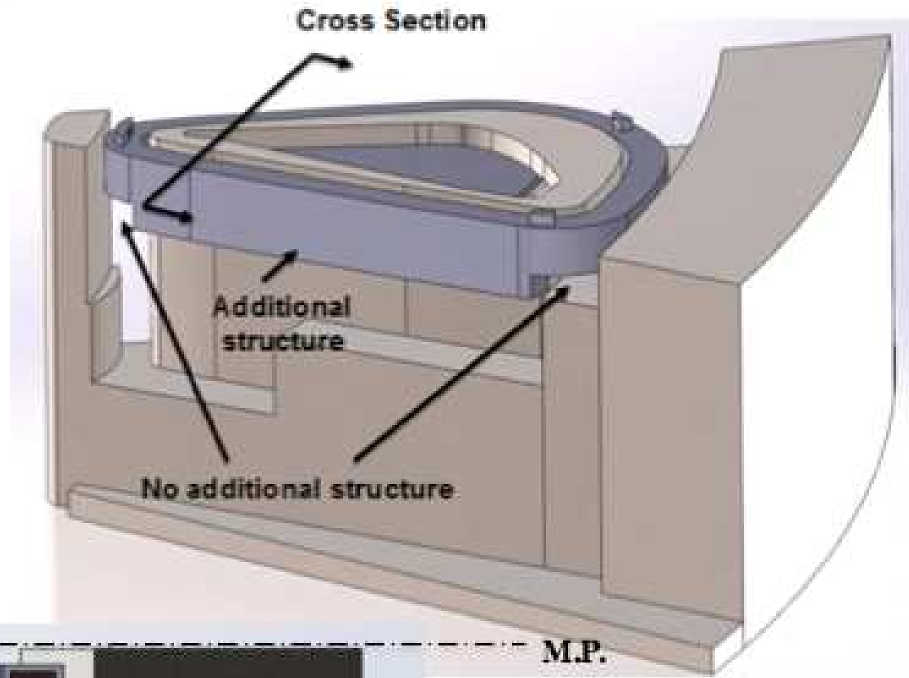
Solid Model of Magnet Support Concept

- Single cryostat enclosing both coils with top layers transparent showing warm-to-cold supports and portions of coil case
- Two pairs of azimuthal supports
- Radial support
- Axial supports (4 on each side)



First evaluations on how the cryostat could be constructed:
35 mm thick Coil Case with a Stiffening Box along





With the courtesy of PSFC MIT Engineering Group