Upgrading of the LNS Superconduting Cyclotron for the Production of 1 to 10 kW Light Ion Beams

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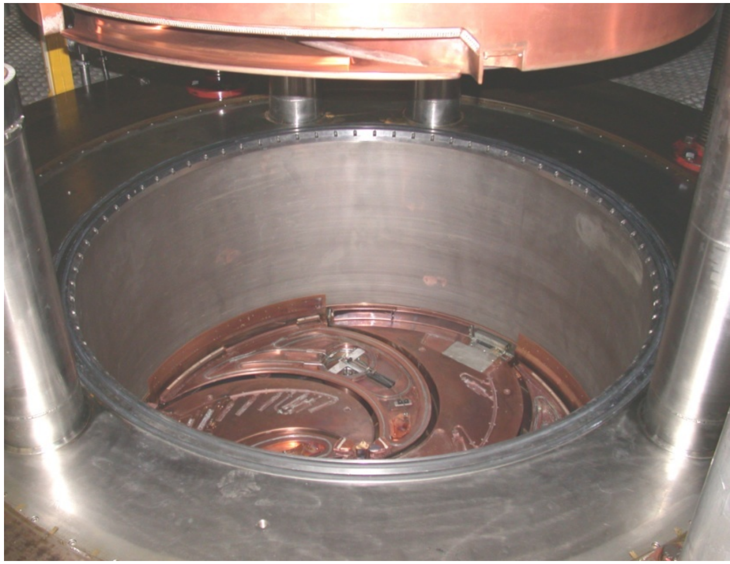
Superconducting Cyclotron Technical parameters first experiment 1995

$(T/A)_{max} = K_{bending} (Q/A)^2$

~ 25 AMeV Au36+

$(T/A)_{max} = K_{focusing} (Q/A)$

100 AMeV fully stripped



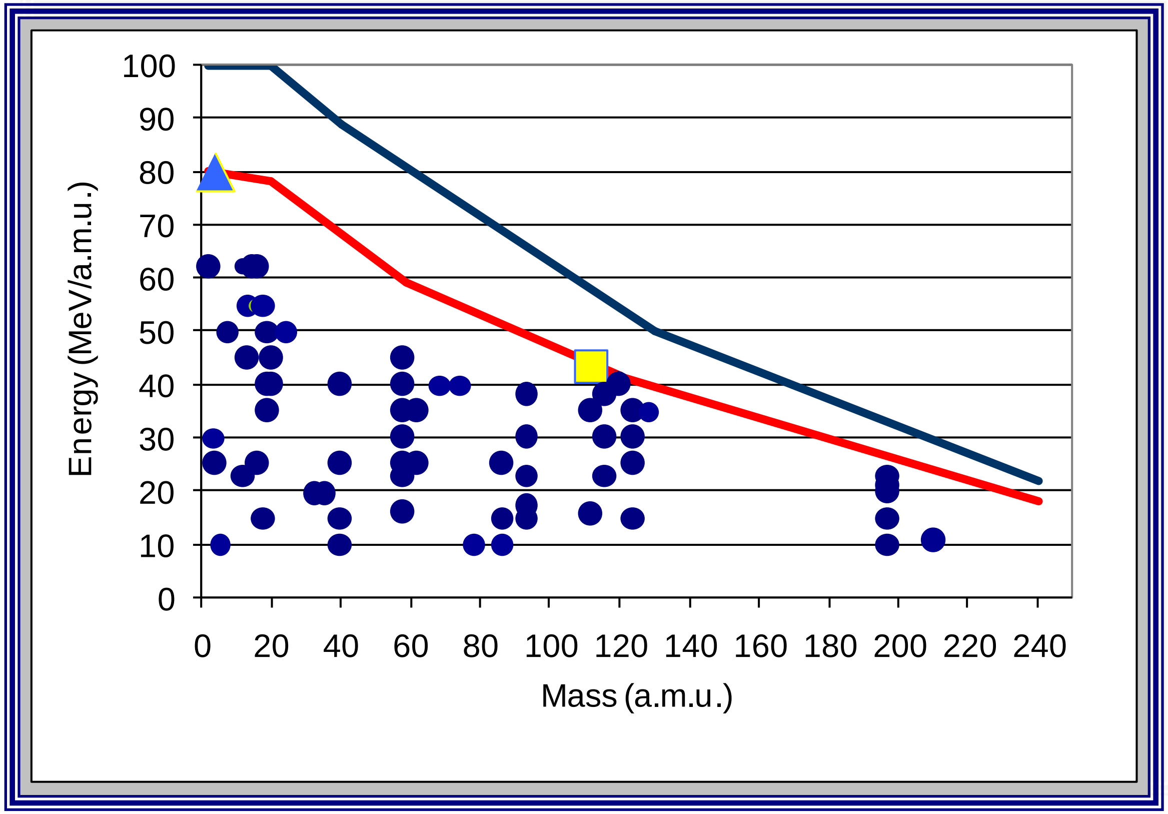
Bending limit	**K=800**
Focusing limit	**Kfoc=200**
Pole radius	**90 cm**
Yoke outer radius	**190.3 cm**
Yoke full height	**286 cm**
Min-Max field	**2.2-4.8 T**
Sectors	**3**
RF range	**15-48 MHz**

Versatility (performance)

Reliability (protontherapy)

High intensity (radioactive beams)

Superconducting Cyclotron developed beams



^{4}He 80 AMeV , 320 MeV

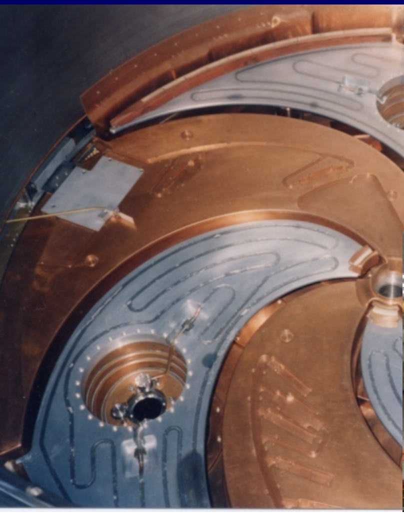
^{112}Sn 43.5 AMeV, 4.872 GeV

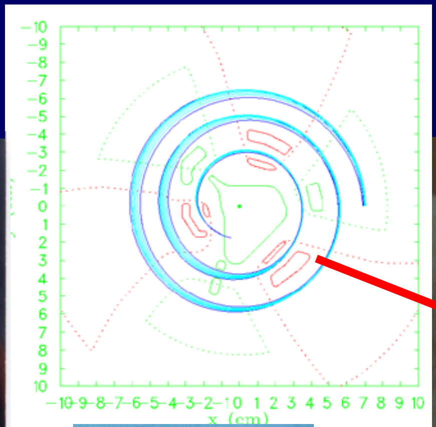
In red beams with intensity 10^{12} pps

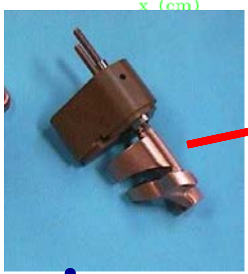
^{A}X	E (AMeV)
H_2^+	62,80
H_3^+	30,35,45
$^{2}D^{+}$	35,62,80
^{4}He	25,62,80
He-H	10, 21
^{9}Be	45
^{11}B	55
^{12}C	23,62,80
^{13}C	45,55
^{14}N	62,80
^{16}O	21,25,55,62,80
^{18}O	15,55
^{19}F	35,40,50
^{20}Ne	20,40,45,62
^{24}Mg	50
^{27}Al	40
^{36}Ar	16,38
^{40}Ar	15,20,40
^{40}Ca	10,25,40,45
$^{42,48}Ca$	10,45
^{58}Ni	16,23,25,30,35,40,45
$^{62,64}Ni$	25,35
$^{68,70}Zn$	40
^{74}Ge	40
$^{78,86}Kr$	10
^{84}Kr	10,15,20,25
^{93}Nb	15,17,23,30,38
^{107}Ag	40
^{112}Sn	15.5,35,43.5
^{116}Sn	23,30,38
^{124}Sn	15,25,30,35
^{129}Xe	20,21,23,35
^{197}Au	10,15,20,21,23
^{208}Pb	10

To increase the beam current and its versatility the Cyclotron was Upgraded in 2000: tandem injection →axial injection

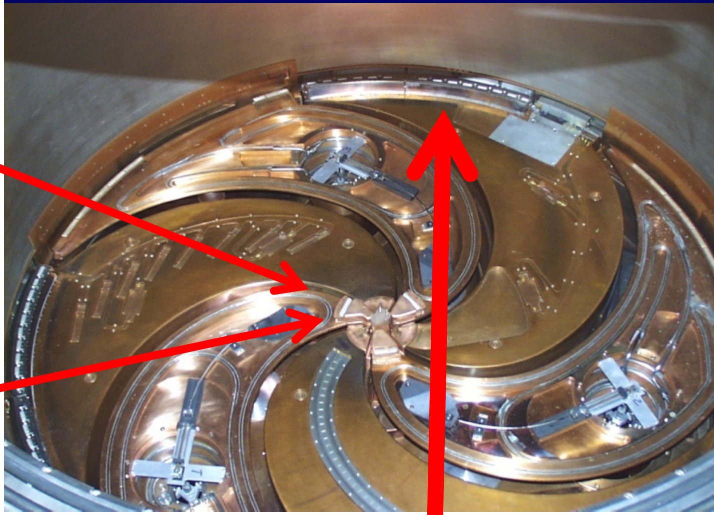
1994 – Booster of Tandem and Injection by stripper



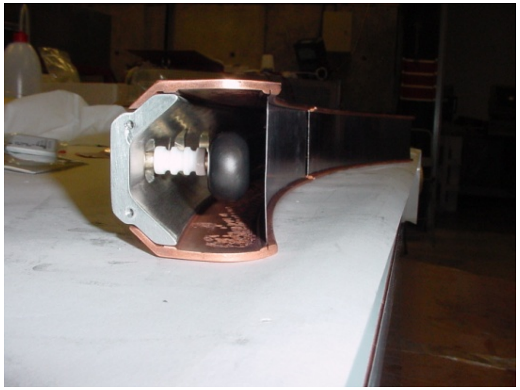




2000 – Stand alone ECR sources + axial injection

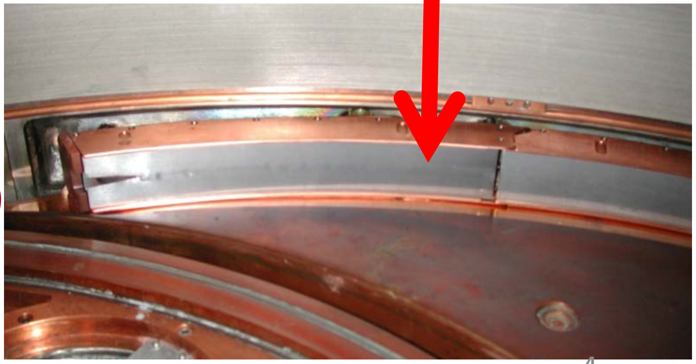


Compactness makes extraction a critical process: $\varepsilon \approx 50\%$

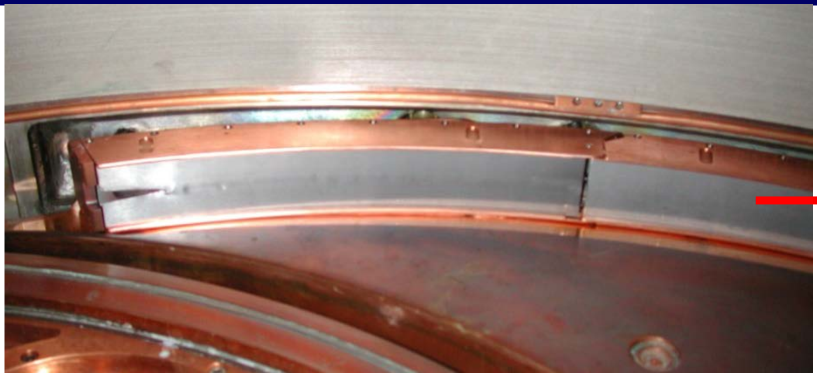


Inter-turn separation

$$\Delta R = R \cdot (\Delta E/E) \cdot (1/\nu_r^2) \cdot \gamma/(\gamma+1)$$



Cyclotron beam intensity has been increased working on E. D. and injection transport, but…



Septum: directly cooled

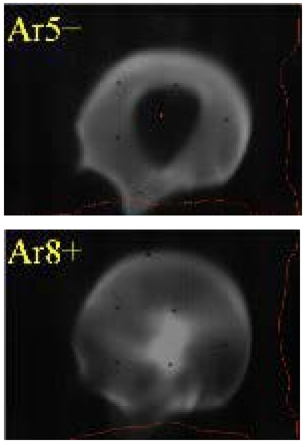
New septum material: W vs. Ta

Bigger thickness: 0.3 vs. 0.15 mm

⇨extraction efficiency 63% vs. 50%

$^{13}C^{4+}$ @ 45 AMeV (EXCYT primary beam)

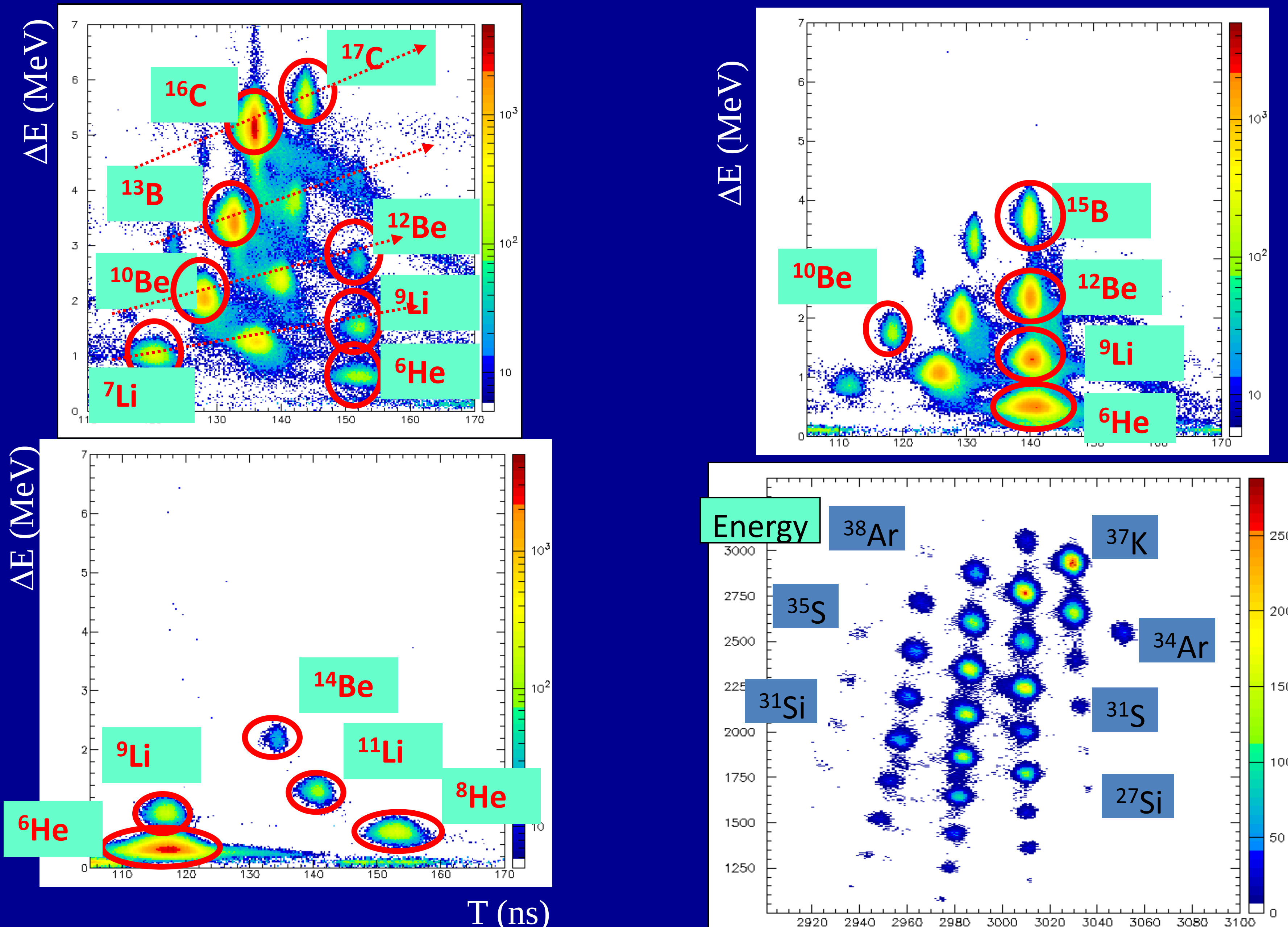
Pextr = 150 watt I=1020 enA= 1.5×10^{12} pps



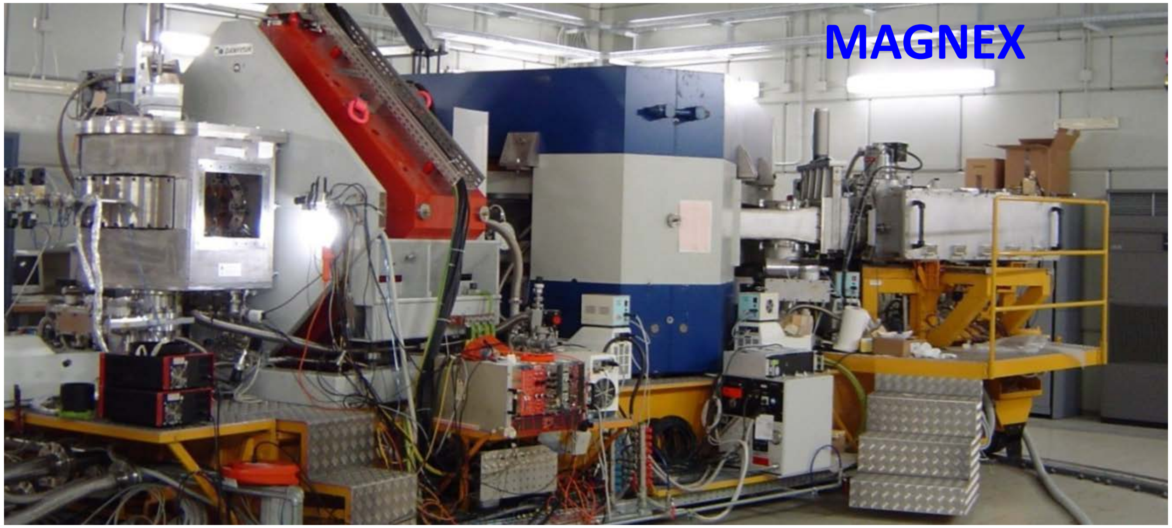
The source-cyclotron matching needs to be improved

Beam transport along the injection line is now being considered, following the MSU, JYFL, KVI methods

La Produzione di fasci di frammentazione in volo (FRIBs) richiedono fasci primari con potenza maggiore (Esperimenti con il rivelatore CHIMERA)



Ma il Physics case che richiede potenza di fascio di 1-10 kW
È il double β decay 0 ν

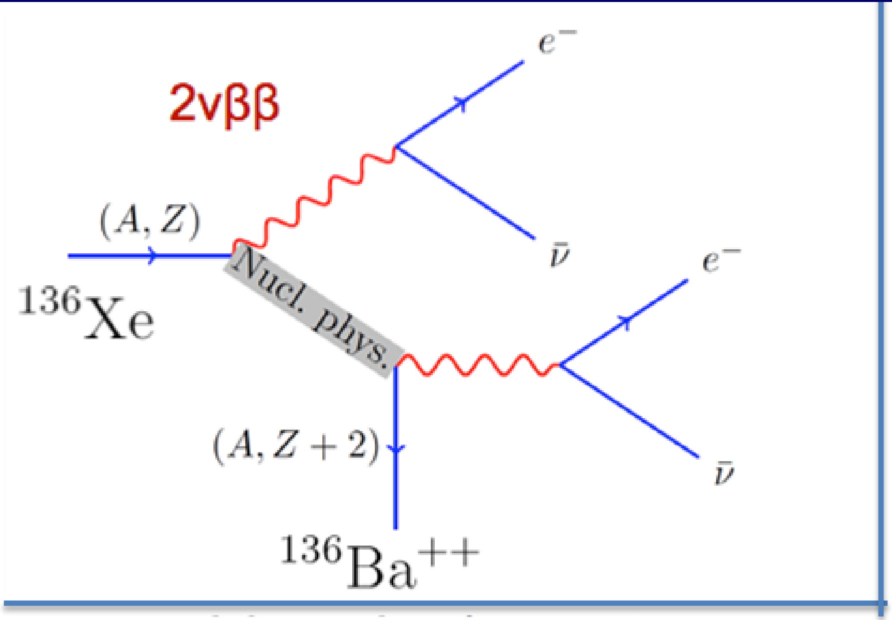


- Large angular acceptance
- Possibility of measuring at 0°
- Possibility of detection of ^{16}O, ^{18}F, ^{18}Ne, ^{20}Ne
- High resolution spectra
- Angular distributions up to10 nb/sr

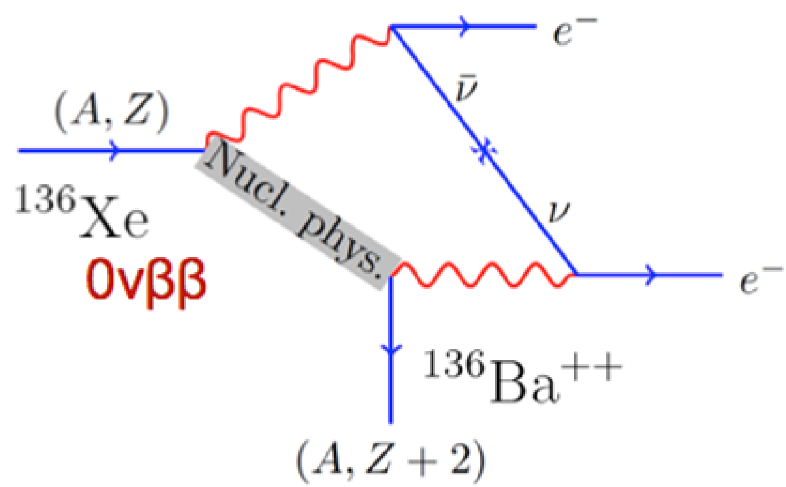
Double charge exchange reactions (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) towards the determination of the nuclear matrix element of the double β decay

^{40}Ca(^{18}O,^{18}Ne)^{40}Ar – exp. DOCET nov.2012

L'esperimento NUMEN può misurare l'elemento di matrice nucleare rilevante per capire il doppio β decay 0 neutrini



(simple 0νββ mechanism)



A lot of new physics inside

$$1/T^{0\nu}_{1/2}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

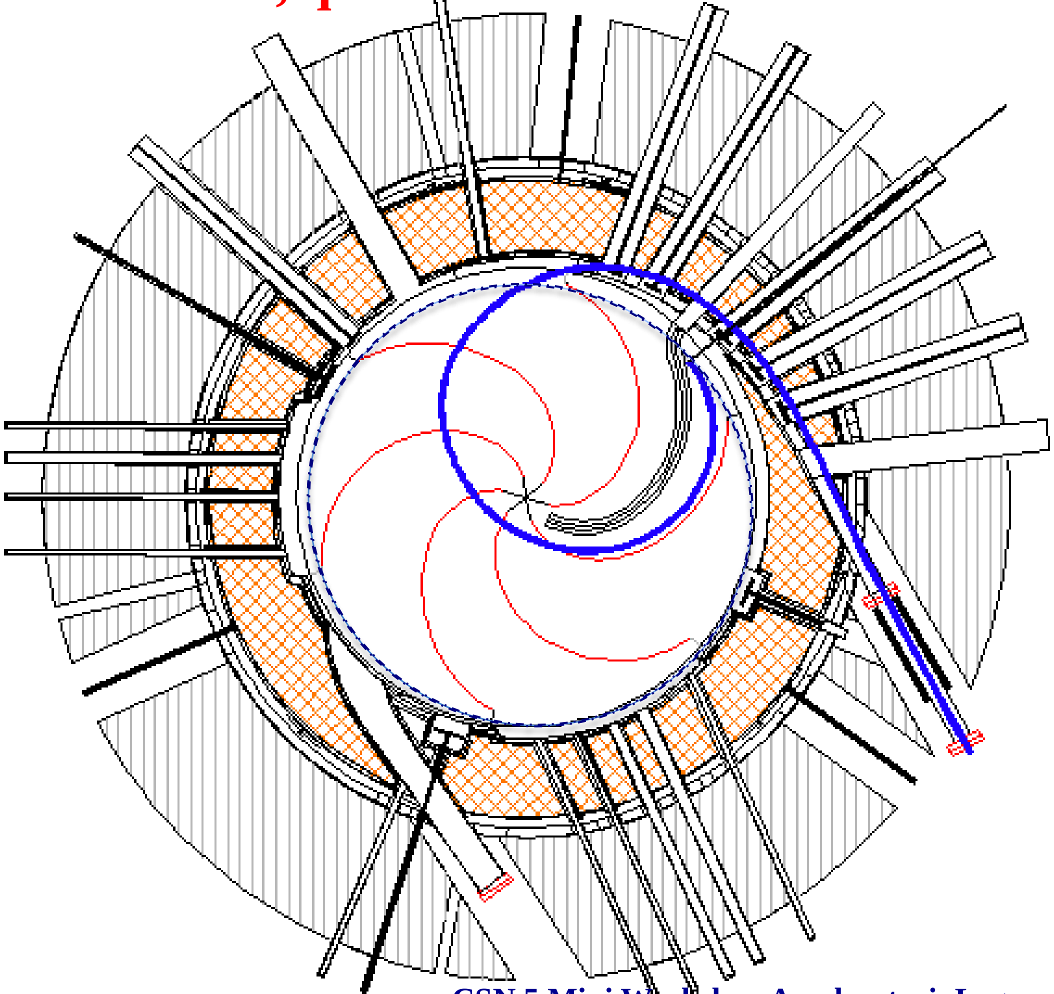
$$\langle m_\nu \rangle = \sum_i \left|U_{ei}\right|^2 m_i e^{i\alpha_i}$$

but one should know **Nuclear Matrix Element** (NME)

$$\left|M_\varepsilon^{\beta\beta 0\nu}\right|^2 = \left|\left\langle 0_f \left\| \hat{O}_\varepsilon^{\beta\beta 0\nu} \right\| 0_i \right\rangle\right|^2$$

Per aumentare l'intensità dei fasci forniti abbiamo proposto l'estrazione per stripper: efficienzadi **estrazione ≥*99%!*** ***senza Deflettori!***

Extraction trajectory
^{20}Ne, q=6+ → 10+ E=29 MeV/amu



Extraction by stripping is based on the reduction of magnetic rigidity of the accelerated ion, caused by an increase of charge state, after crossing a thin carbon foil (stripper).

For light ions at high energies the charge state fraction for q=Z after a stripper with thickness bigger than the equilibrium thickness is >99%

Extraction by stripping: high efficiency >99%

Atomic Data and Nuclear Data Tables, Vol. 51, No. 2, July 1992, Table 2 pag.187

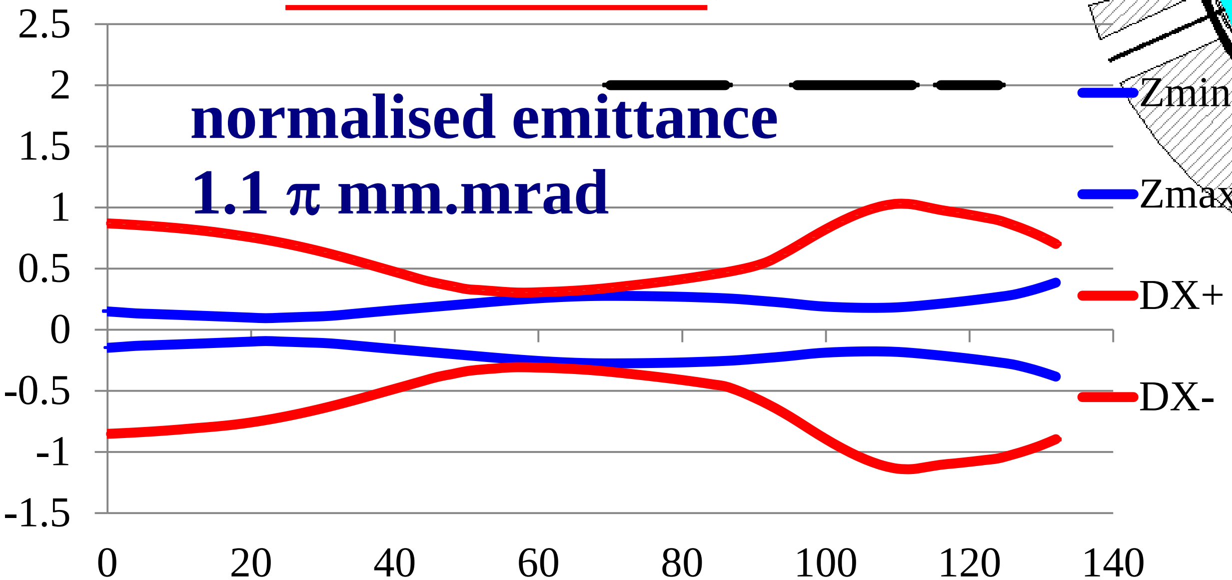
Carbon:	E=15 MeV/u	F(4)=1.74e-7	F(5)=8.35e-4	F(6)=0.99917
	E=20 MeV/u	F(4)=2.56e-8	F(5)=3.20e-4	F(6)=0.99968
Oxygen:	E=15 MeV/u	F(6)=2.48e-6	F(7)=3.14e-3	F(8)=0.9969
	E=20 MeV/u	F(6)=4.18e-7	F(7)=1.29e-3	F(8)=0.9987
	E=30 MeV/u	F(6)=3.50e-8	F(7)=3.74e-4	F(8)=0.99963
Neon:	E=15 MeV/u	F(8)=2.00e-5	F(9)=8.90e-3	F(10)=0.9911
	E=20 MeV/u	F(8)=2.66e-6	F(9)=3.26e-3	F(10)=0.9967
	E=30 MeV/u	F(8)=2.26e-7	F(9)=9.51e-4	F(10)=0.9991

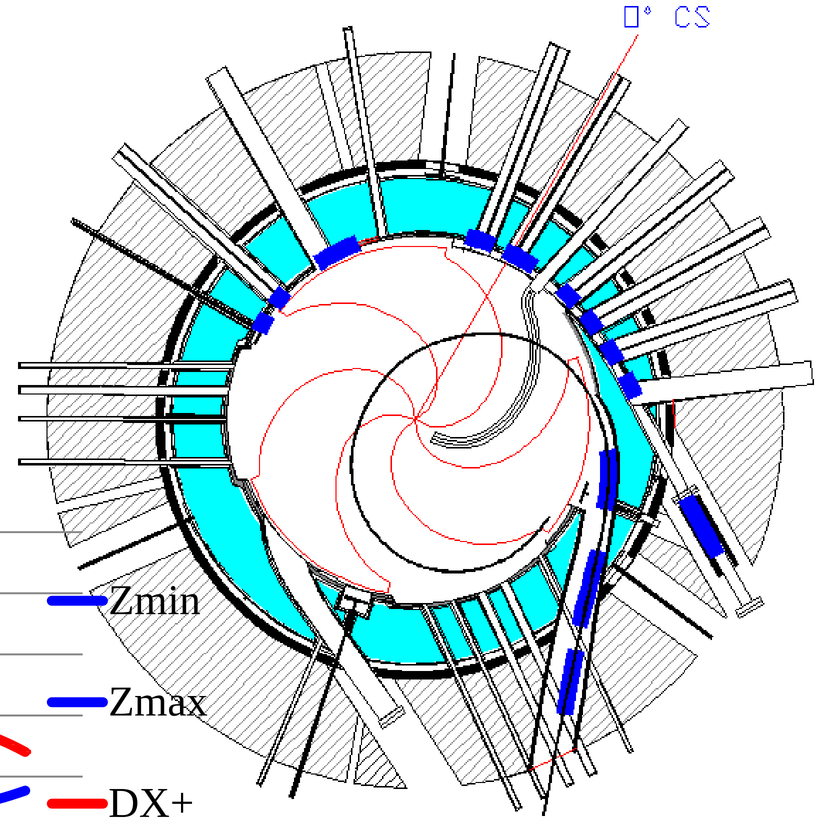
Ion	Energy	Isource	Iacc	Iextr	Iextr	Pextr
	MeV/u	eμA	eμA	eμA	pps	Watt
^{12}C q=4+	30	300	45(4+)	66.8(6+)	$6.9 \bullet 10^{13}$	4009
^{18}O q=6+	60	150	22.5 (6+)	30 (8+)	$2.3 \bullet 10^{13}$	4050
^{20}Ne q=4+	20	500	75(4+)	185.6(10+)	$1.1 \bullet 10^{14}$	5569

Major problems: - direction of the extraction trajectories - beam envelope along the trajectories

Beam dynamics calculations are mandatory to ascertain the feasibility of extraction by stripping. Beam envelopes have to be carefully evaluated, emittance values used 2.5 larger than previous simulation.

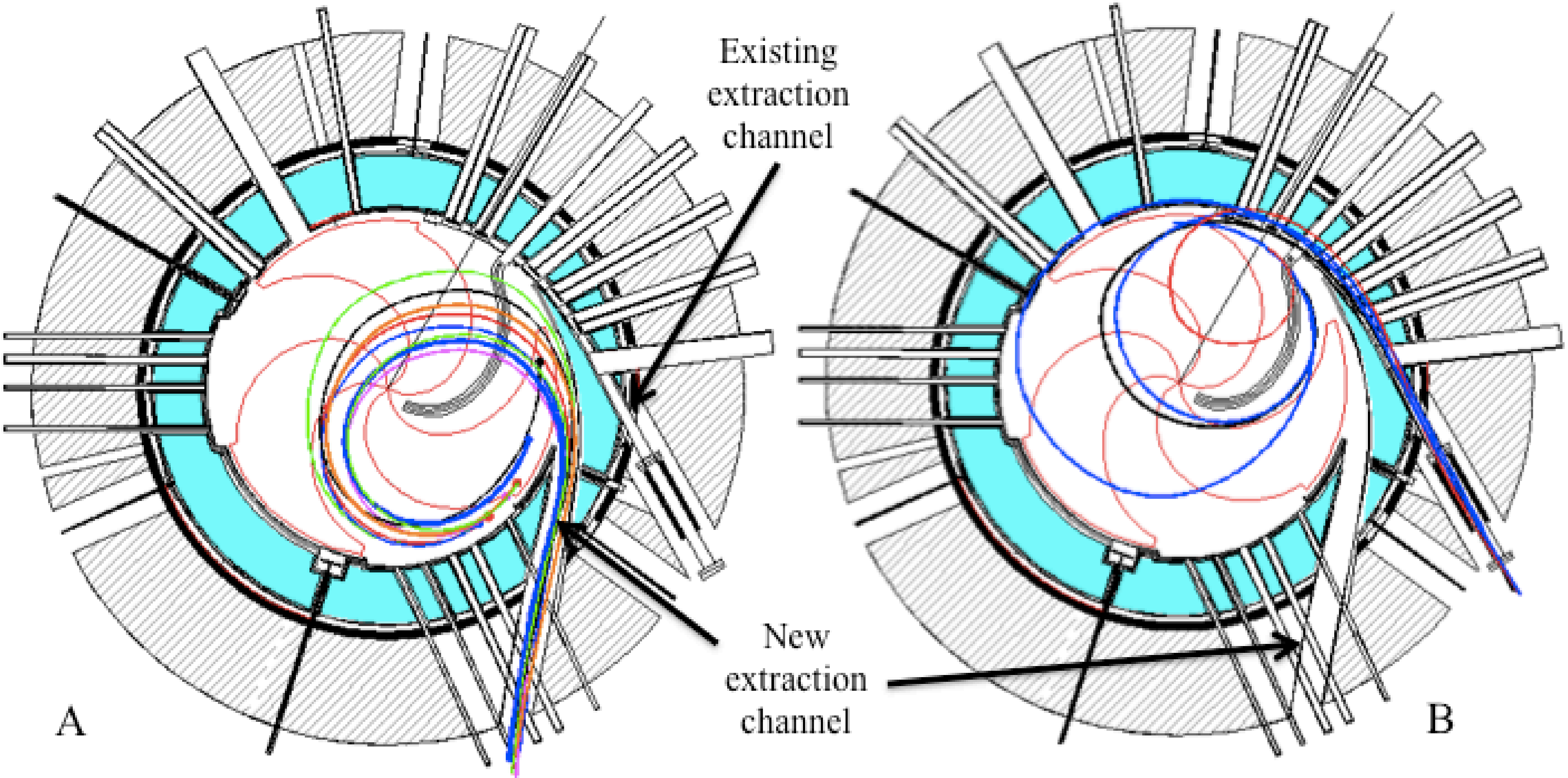
Unfortunately for many ions the extraction trajectory does not match the existing extraction channel!





Extraction

$^{18}O^{6+} \rightarrow {}^{18}O^{8+}$

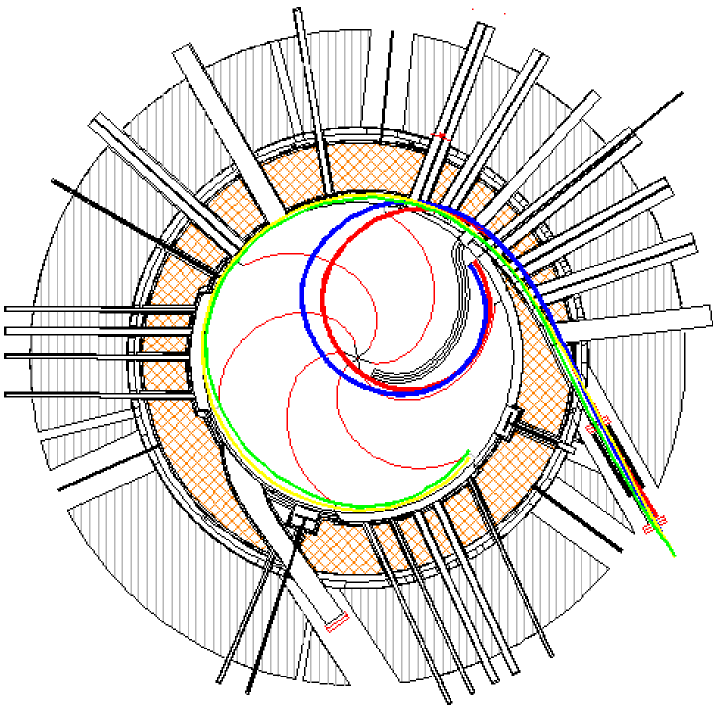


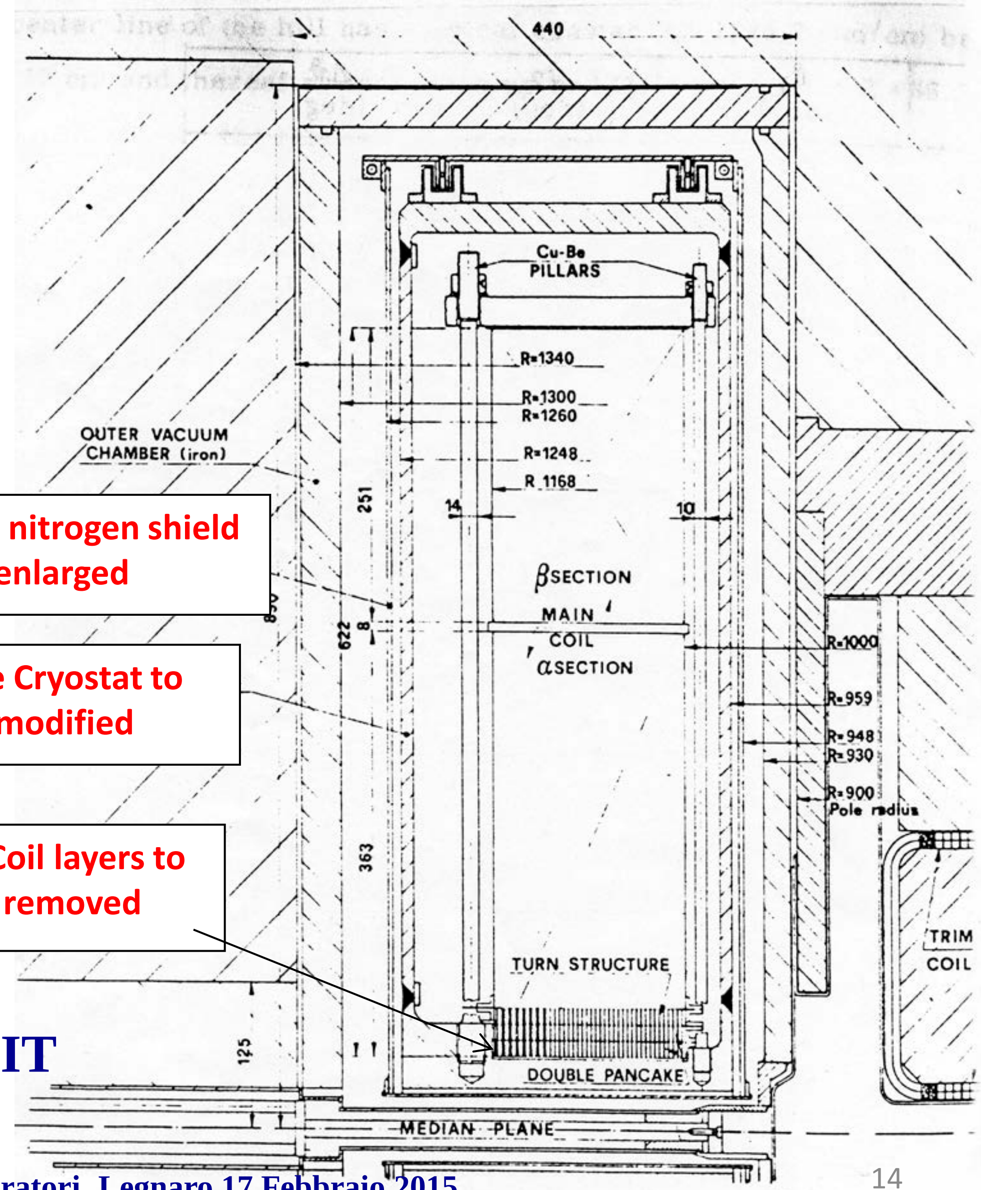
Neon 20, 28 AMeV, 8+→10+, θs=50°, R=86.5 cm
Neon 20, 27.8 AMeV, 7+→10+, θs=80°, R=80.2 cm
Oxygen 18, 60 AMeV, 6+→8+, θs=96°, R=85.4 cm
Carbon 12, 60.5 AMeV,, 4+→6+, θs=96°, R=86,2 cm
Carbon 12, 45 A MeV, 4+→6+, θs=102°, R=85.4 cm
Carbon 12, 30.5 AMeV, 5+→6+, θs=112°, R=86,5 cm
Oxygen 18, 45.5 AMeV, 6+ →8+, θs=112°, R=87.3 cm
Oxygen 18, 29 A MeV, 6+ →8+, θs=116°, R=86.9 cm

Oxygen 18, 70.4 A MeV, 6+→8+, θs=-32°, R=85.4 cm
Neon 20, 15 A MeV, 4+→10+, θs= 4°, R=86.3 cm
Carbon 12, 26.2 A MeV, 4+→ 6+, θs=20° R=83.3 cm
Carbon 12, 18 A MeV, 4+→6+, θs=24° R=83.8 cm

Helium 4, 15 AMeV, 1+ →2+

From electrostatic extraction to extraction by stripping: Main change a New Cryostat and Magnet!





Liquid nitrogen shield to be enlarged

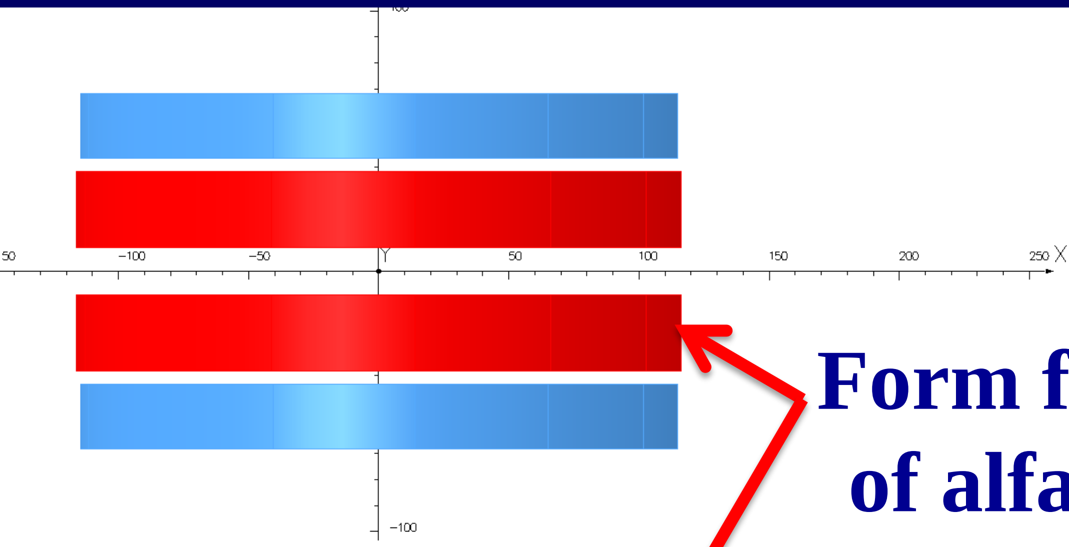
LHe Cryostat to be modified

α-Coil layers to be removed

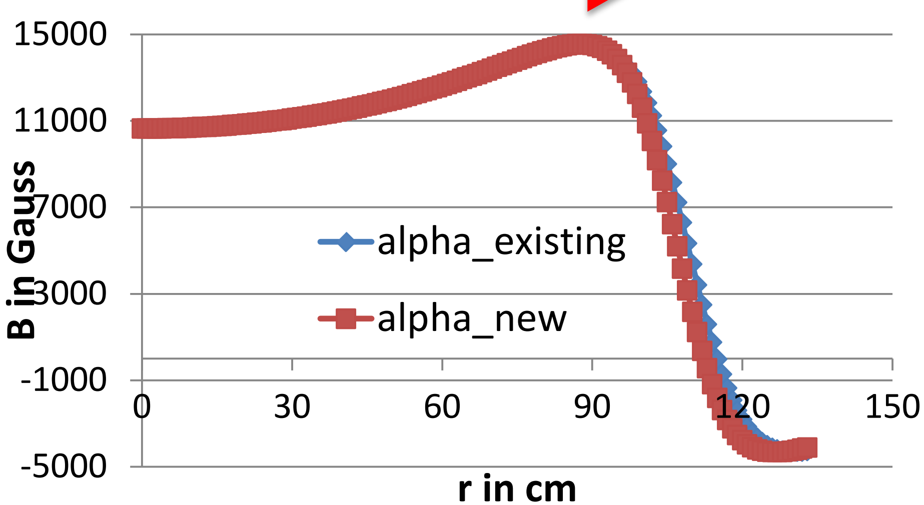
A new cryostat

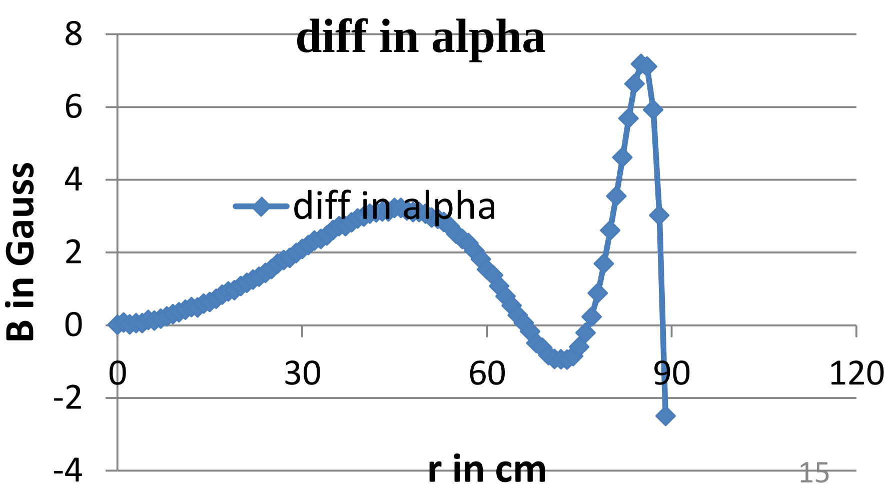
A conceptual design study is being accomplished in collaboration with MIT

A new superconducting magnet and cryostat, but form factor of main coils unchanged

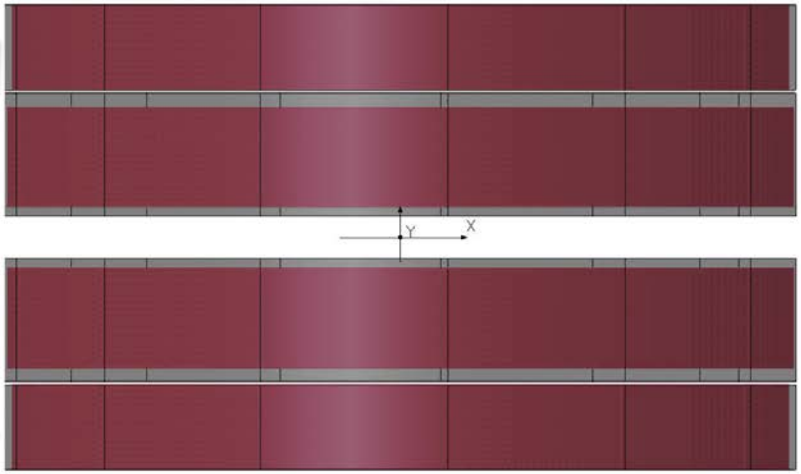


Form factor of alfa coil

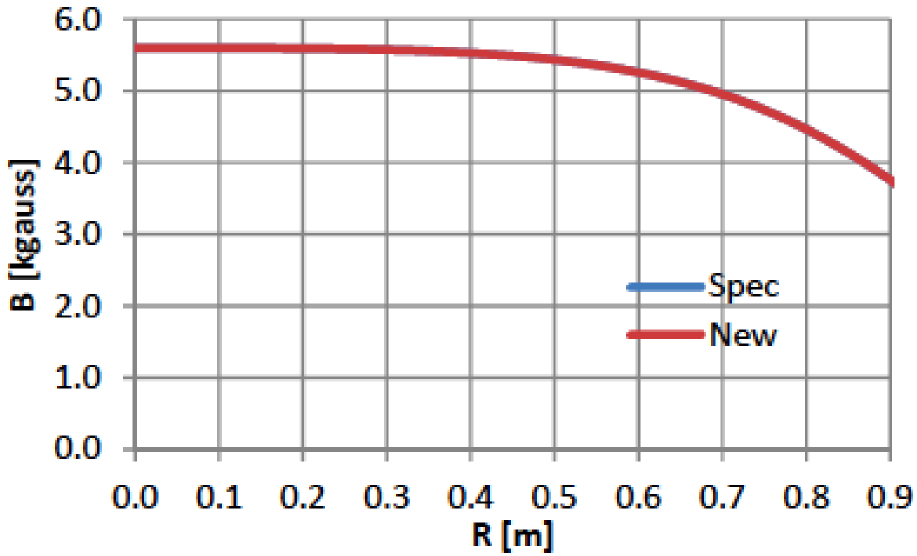




Form factor of main coils unchanged



Form factor of beta coil



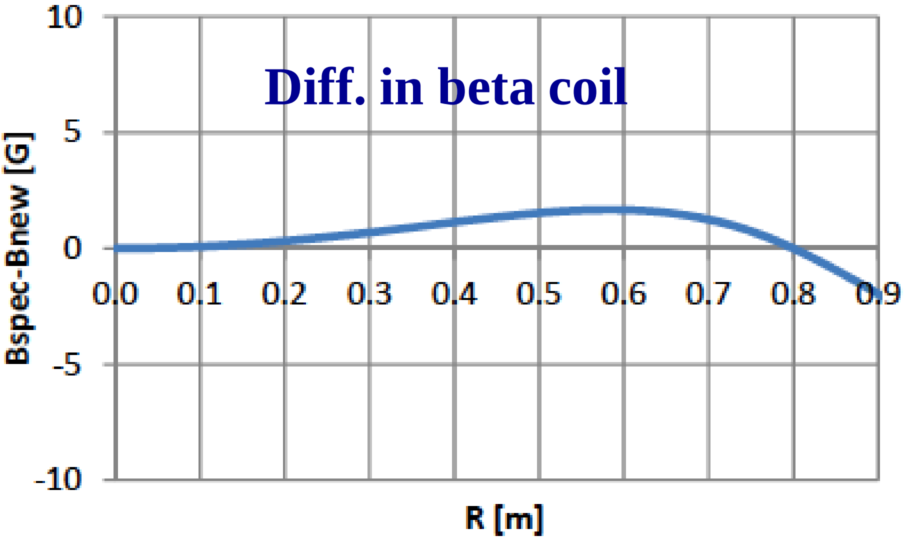


Table 1. Summary of Coil Characteristic Parameters

Parameter	Units	alpha-old	beta-old	alpha-new	beta-new
Rmin	m	1.000	1.000	1.027	1.000
Rmax	m	1.168	1.168	1.162	1.147
Zmin	m	0.062	0.434	0.090	0.433
Zmax	m	0.426	0.686	0.385	0.684
Mode A					
j	A/m2	3.5000E+07	3.5000E+07	5.3826E+07	3.9943E+07
NI	MA-t	2.14	1.48	2.14	1.47
Bmax	T	5.59	5.34	6.11	5.20
(RBJ)max	MPa			337.8	207.7
Sh (smeared)	MPa			131.5	87.3
Fz	MN	-17.47		-15.8	
E	MJ	53.95		55.37	
Mode B with Iron					
j	A/m2	3.5000E+07	-1.5000E+07	5.3826E+07	-1.7118E+07
Fz	MN		6.0*		6.4

Magnetic field distribution in the new set of coils for Modes A and B

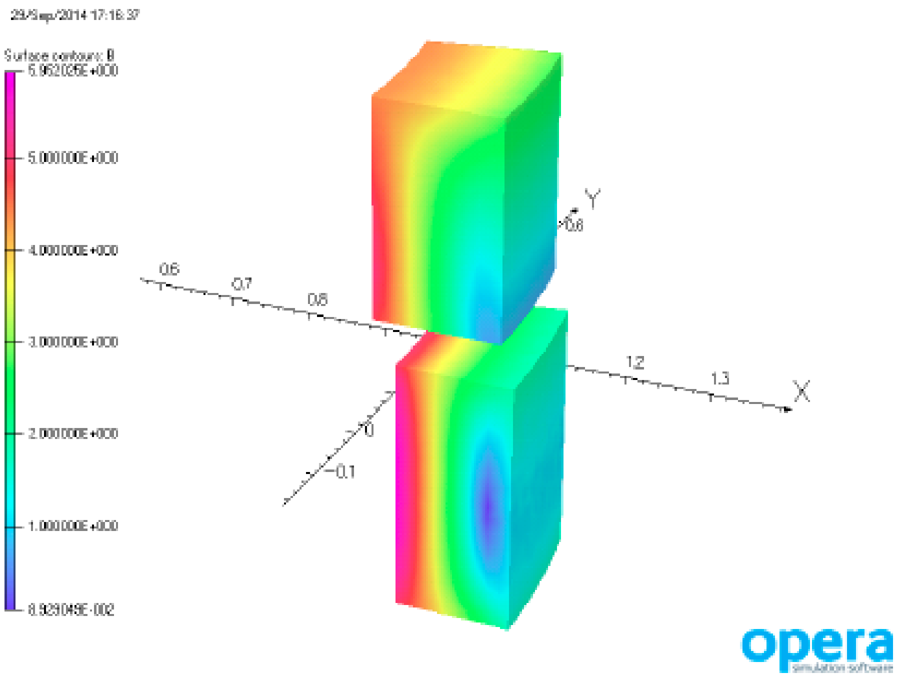


Fig. 1.2.a. B-field. Mode A.

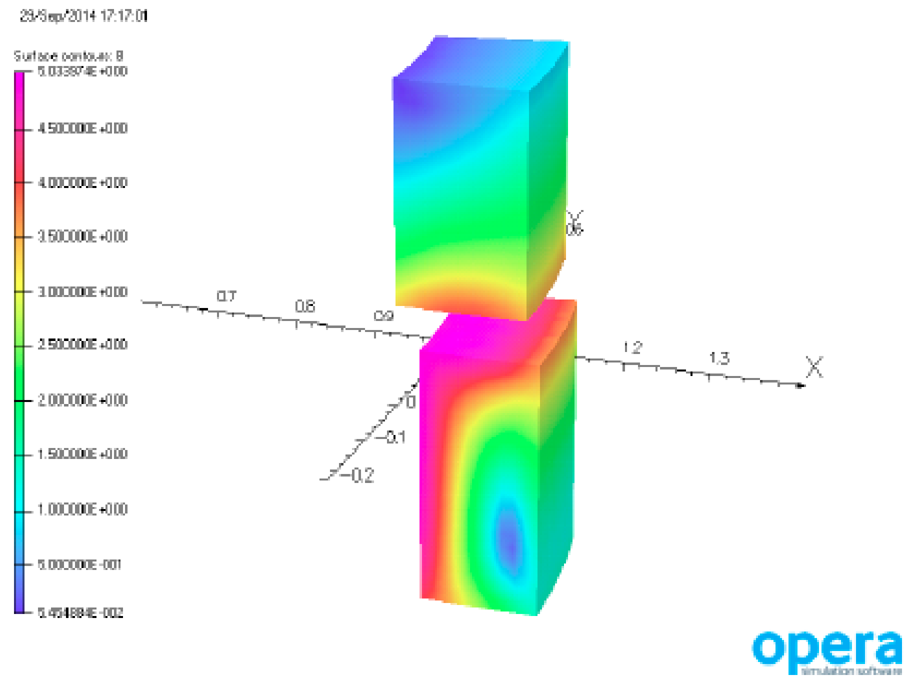


Fig. 1.2.b. B-field. Mode B.

EM Energy

Parameter	Units	W/o iron		With Iron (scaled)
E_{tot}	MJ	48.27	100.00%	55.37
E_{beta}	MJ	8.65	17.92%	9.92
E_{alpha}	MJ	22.47	46.54%	25.77
E_{couple}	MJ	17.15	35.54%	19.68

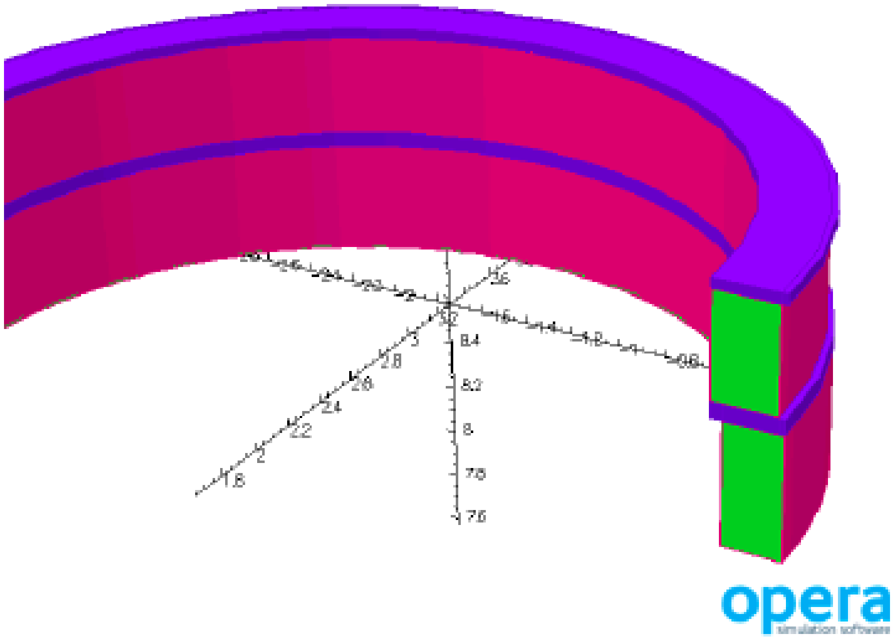


Fig. 2.5 Coil Assembly

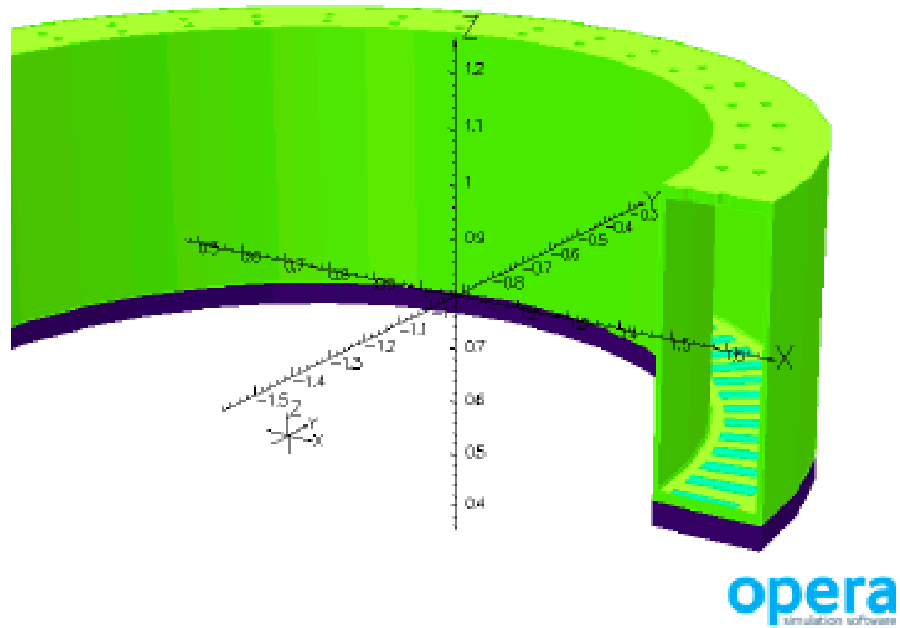


Fig. 2.6 He Can with G10 Spacers

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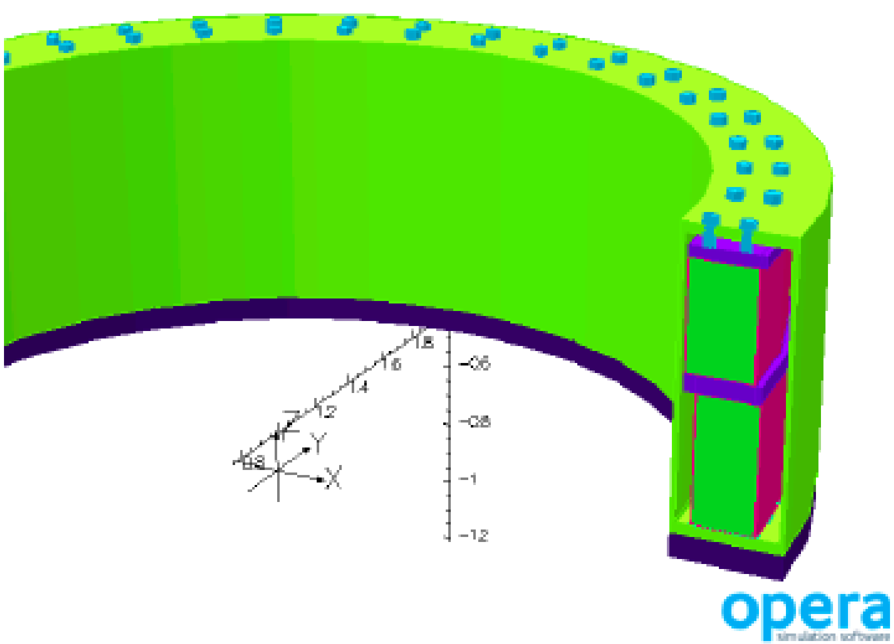

Fig. 2.7 Coil Assembly Preloaded by Tension Bolts

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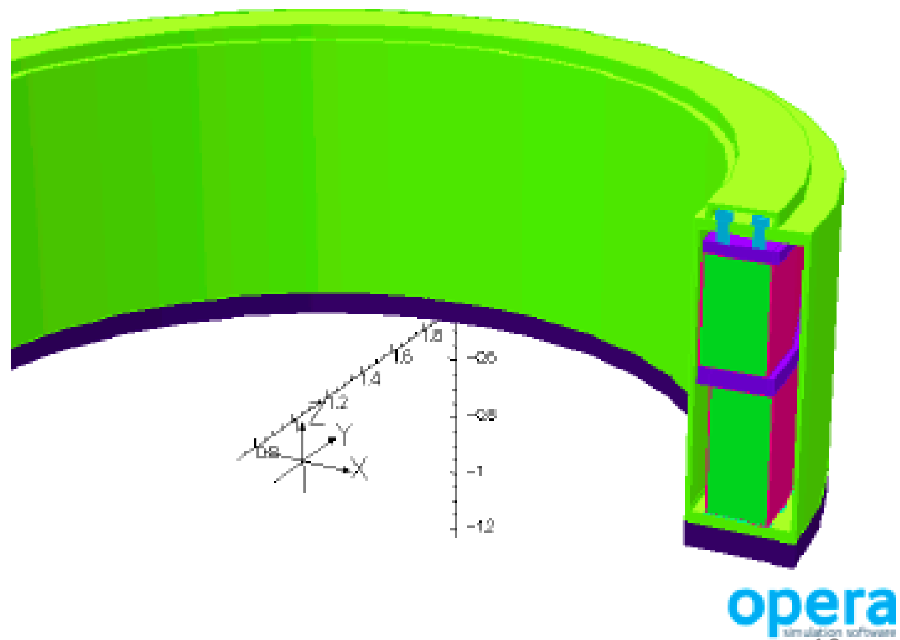
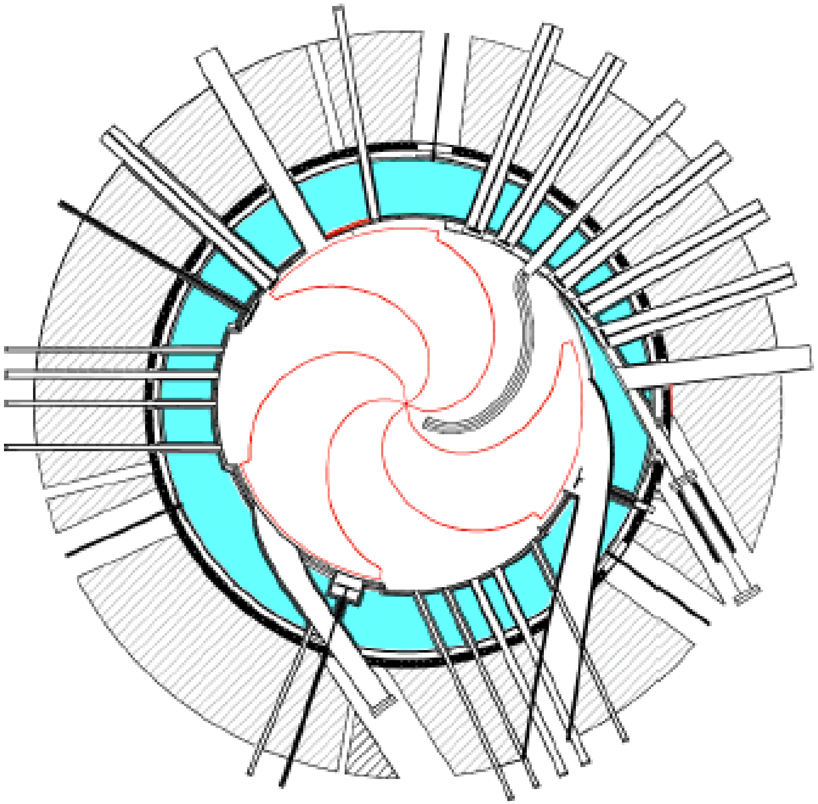
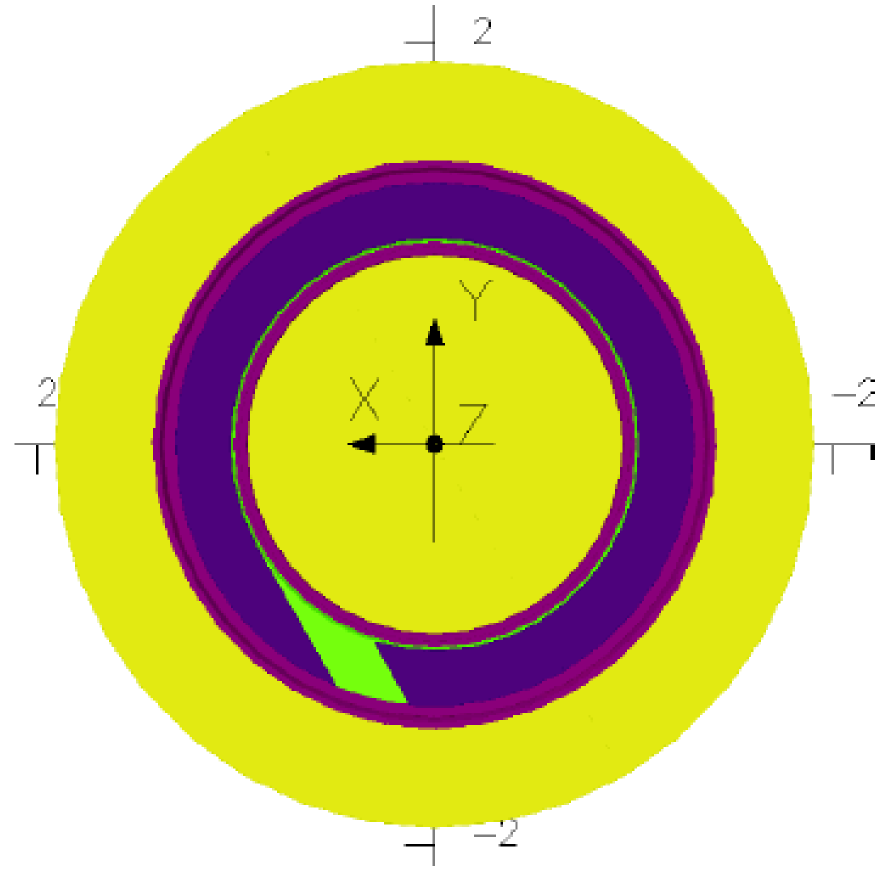


Fig. 2.8 Tension Bolts Sealed by Welded Lid





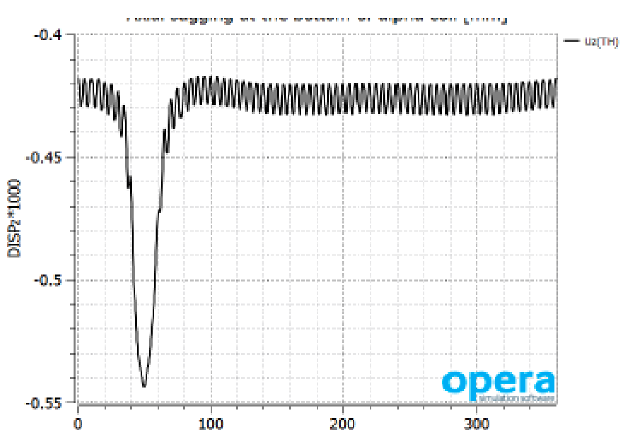


Fig. 2.31. Axial Displacements at the bottom of alpha coil

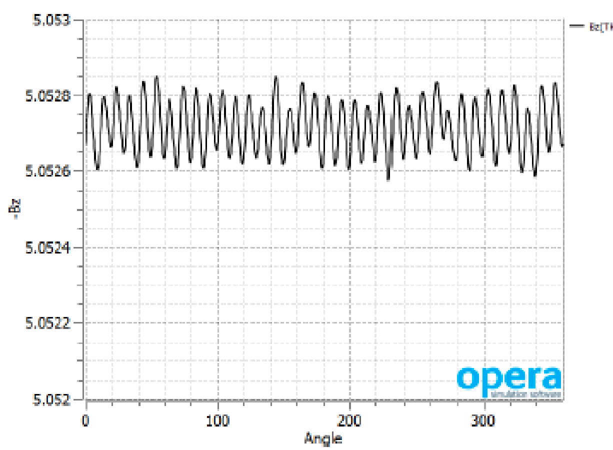
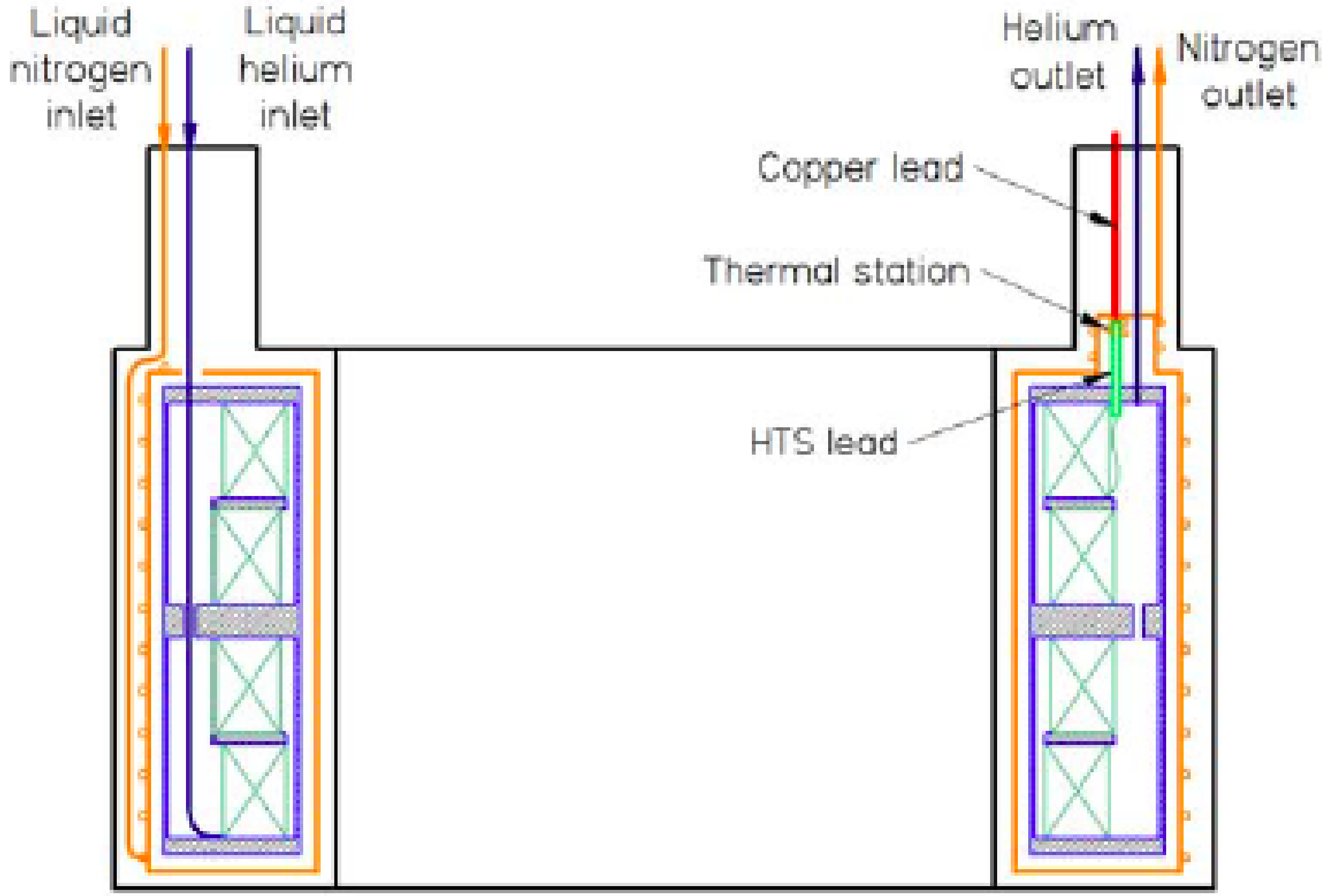


Fig. 2.32. B-field at Extraction Radius (Z=0, R=0.9 m)



Coolant	H	Gspec	P
	J/lt	lt/hr	W
He (4K)	2600	20	14.4
N2 (77K)	161000	18	805

The whole upgrade

Looking for intensity

- New s.c. magnet: cryostat with coils
- Stripper systems
- Magnetic channels
- New liner
- Source-Cyclotron matching
- Cyclotron-Magnex beam line

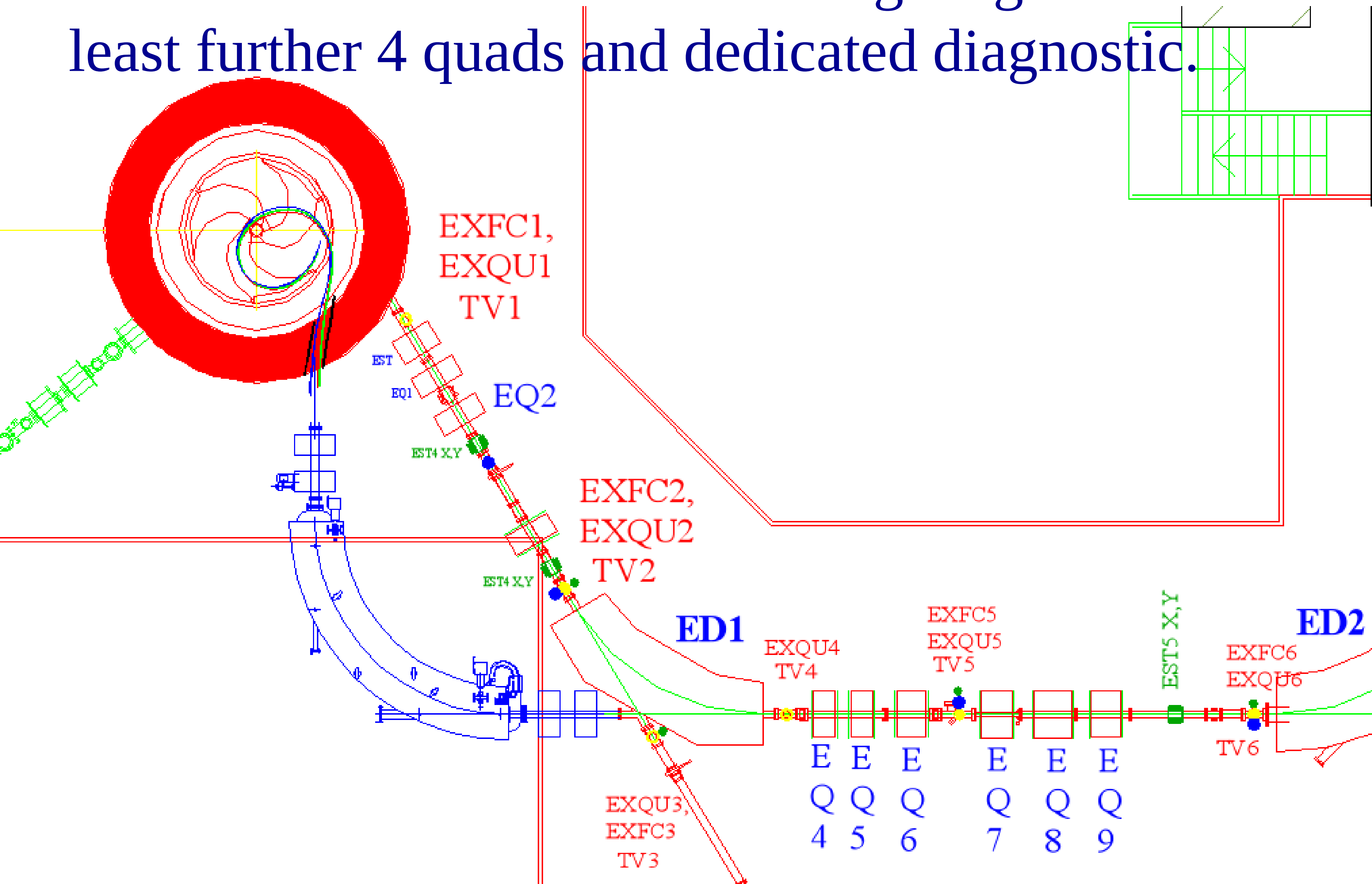
Looking for reliability

- New trim coils
- RF cavities insulators
- New power supplies
- New Helium liquefier

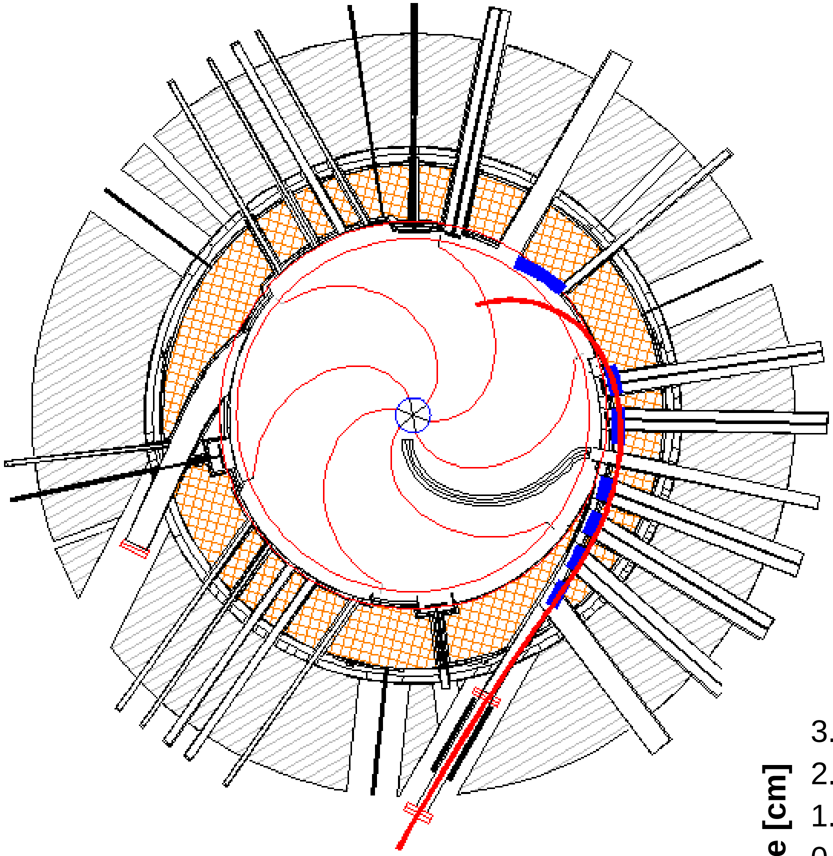
Roughly estimated cost

Superconducting magnet	5.4 M€
“Intensity” equipment	2.2 M€
“Reliability” equipment	4.5 M€
Total	12.1 M€

To deliver the new high power beam to the existing beam lines we need a 90° bending magnet and at least further 4 quads and dedicated diagnostic.

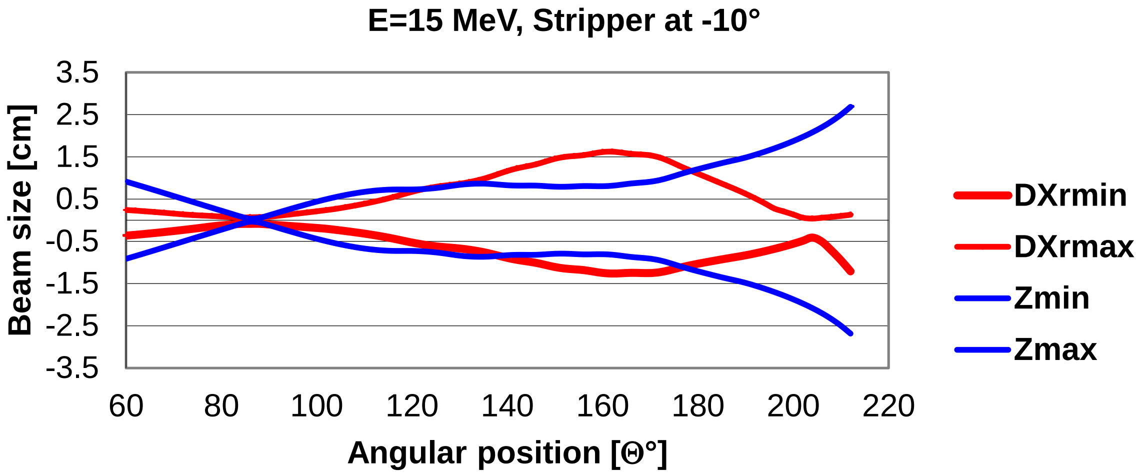


Application of low energy/high intensity Helium beam



Production of At 211
Bi 209 (alpha, 2n) At 211

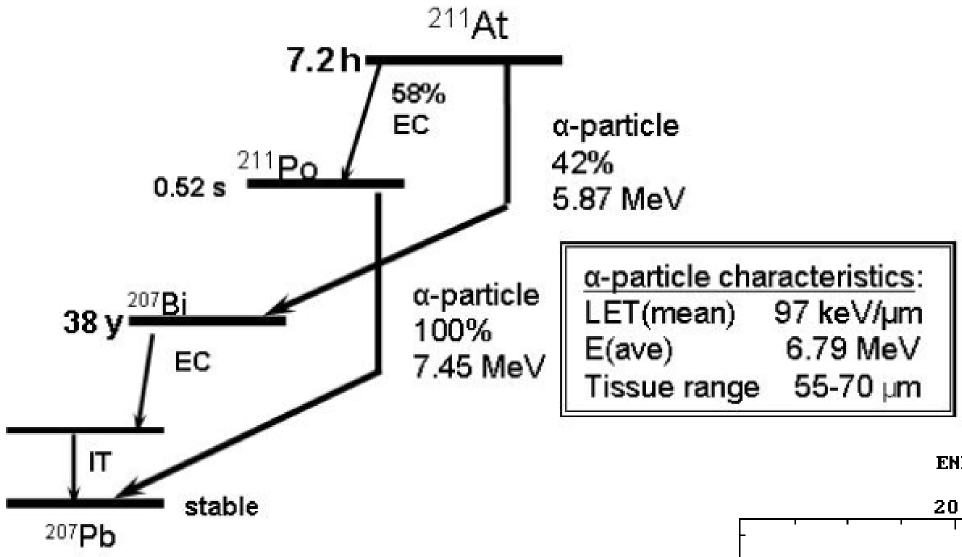
Beam current requested 50-60 μA
Beam extracted at 15 AMeV
→ 1.5-1.8 kW!



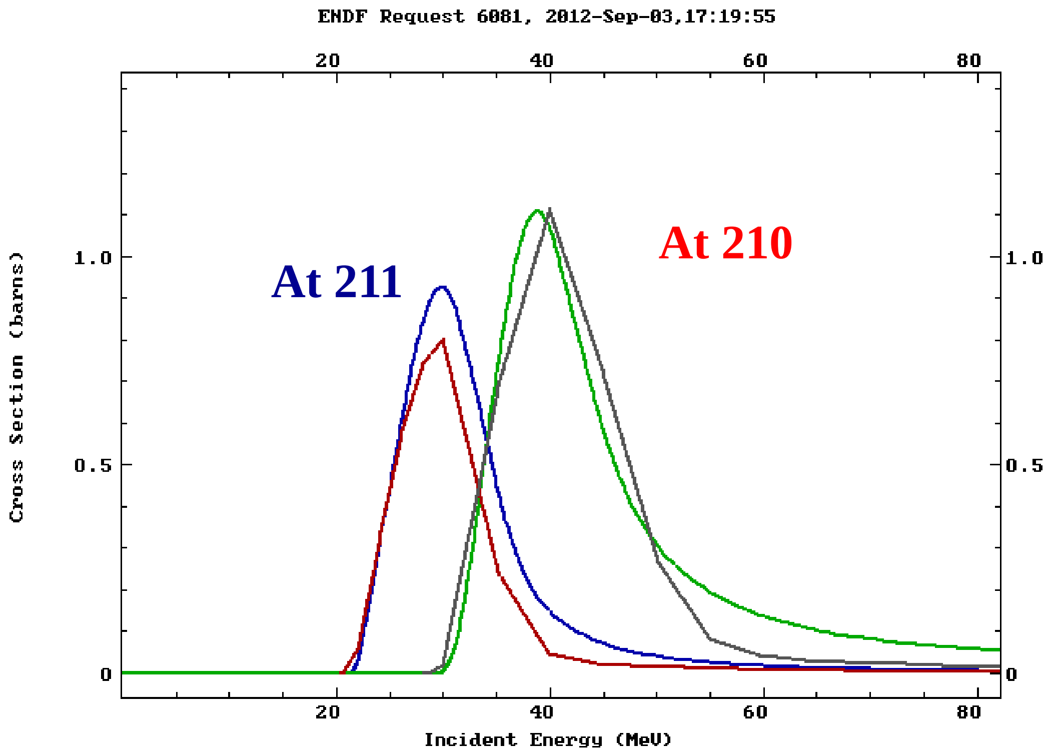
At 211 decay scheme

At 210 contaminant beta decay to Po 210. T1/2 138 days

Energy range limited from about 30 MeV to 20 MeV



Zalutsky et al 2007



Nb: I131 LET~0.3 keV/um

^{211}At Internal Target

$^{209}Bi(\alpha,2n)^{211}At$

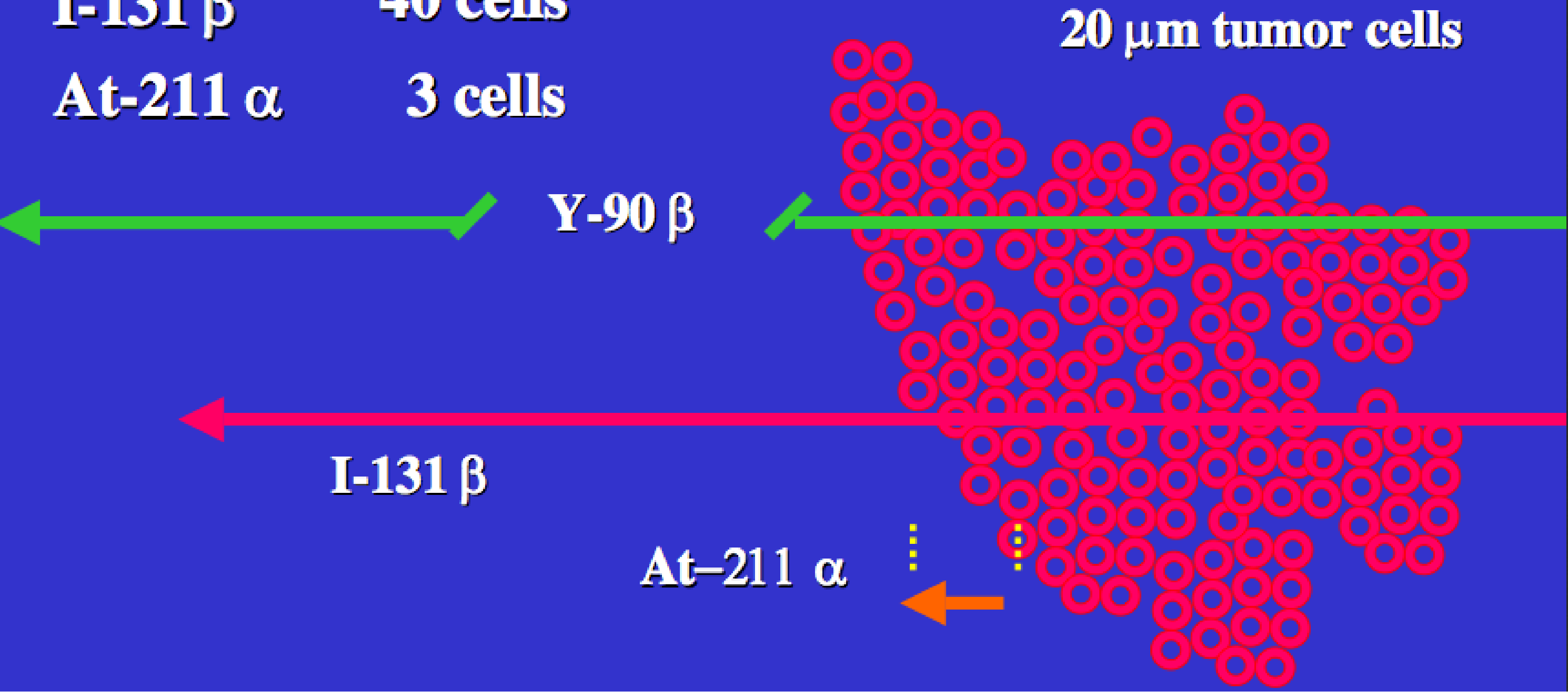
- Beam currents of 50-60 μA, 28 MeV α-particles, and 1.5-4.5 hr runs
- 0.8 ± 0.1 mCi/μA·h
- Maximum to date:

  55 μA × 4.0 h = 178 mCi
- 67 ± 16% distillation yield

50 μA @ 28MeV
750 Watts!

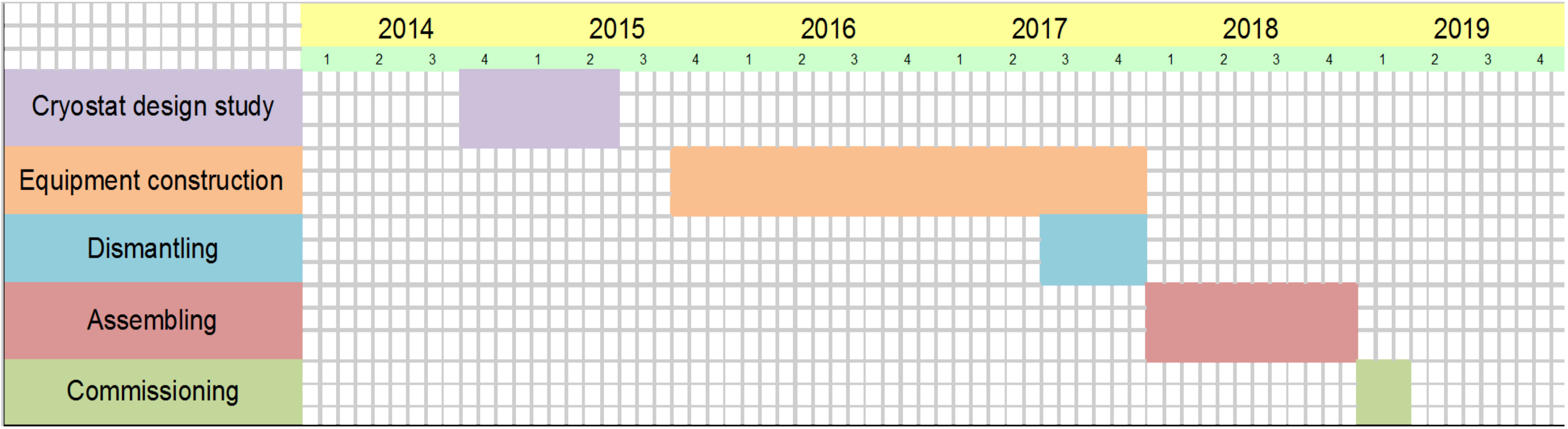
Range of α- and β-Particles

	Mean range
Y-90 β	215 cells
I-131 β	40 cells
At-211 α	3 cells




…And thats all folks!
Thanks for your attention!

Estimated time



Start End

Cryostat design study 09/2014 06/2015 Equipment construction 10/2015 12/2017
Dismantling 07/2017 12/2017
Assembling 01/2018 12/2018
Commissioning 01/2019 04/2019

ECR Ion Source Supernanogan: queste figure mostrano come aumenta la corrente quando si accelerano stati di carica più bassi

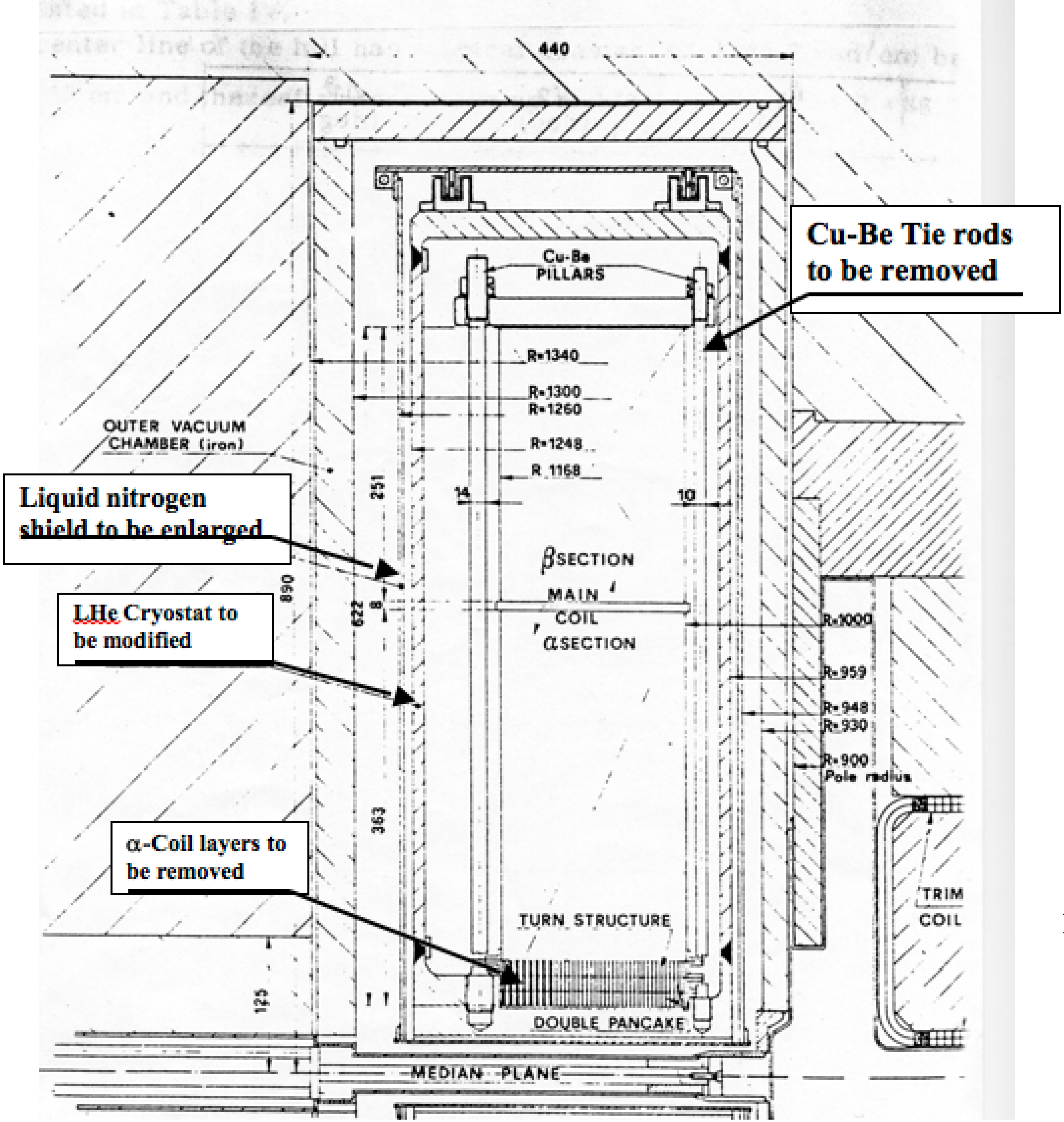
ion / Q	1	2	4	6	8	9	20	27
H	2000							
He	2000	1000						
C			200	2.5				
Ar	1000		250	200	200	90		
Xe	500				220		15	1
Au							20	6
Pb							10	1

Beam intensity for various charge states given in electric μA. This table indicates typical intensities for selected charge states.

SERSE

A/q	2+	4+	6+	7+	8+	12+	14+	16+	27+	30+	33+
12C		**300**	**50**								
16O			**800**	**240**	**55**						
20Ne*				**230***	**170***	**14***					
40Ar						200	84	21			
129Xe									78	38	9
181Ta									35	10	3
197Au									55	30	12

***Caesar**



Le bobine potranno essere costruite differentemente per avere maggior spazio per il criostato.
In particolare l'eliminazione dei Tie rods permetterebbe di avere un maggior spazio per il criostato ed anche attorno al piano mediano per un canale di estrazione più alto.

La riduzione del diagramma operativo delle correnti della macchina permetteranno di rilassare i parametri dei coils

Design of magnetic channels for beam focusing