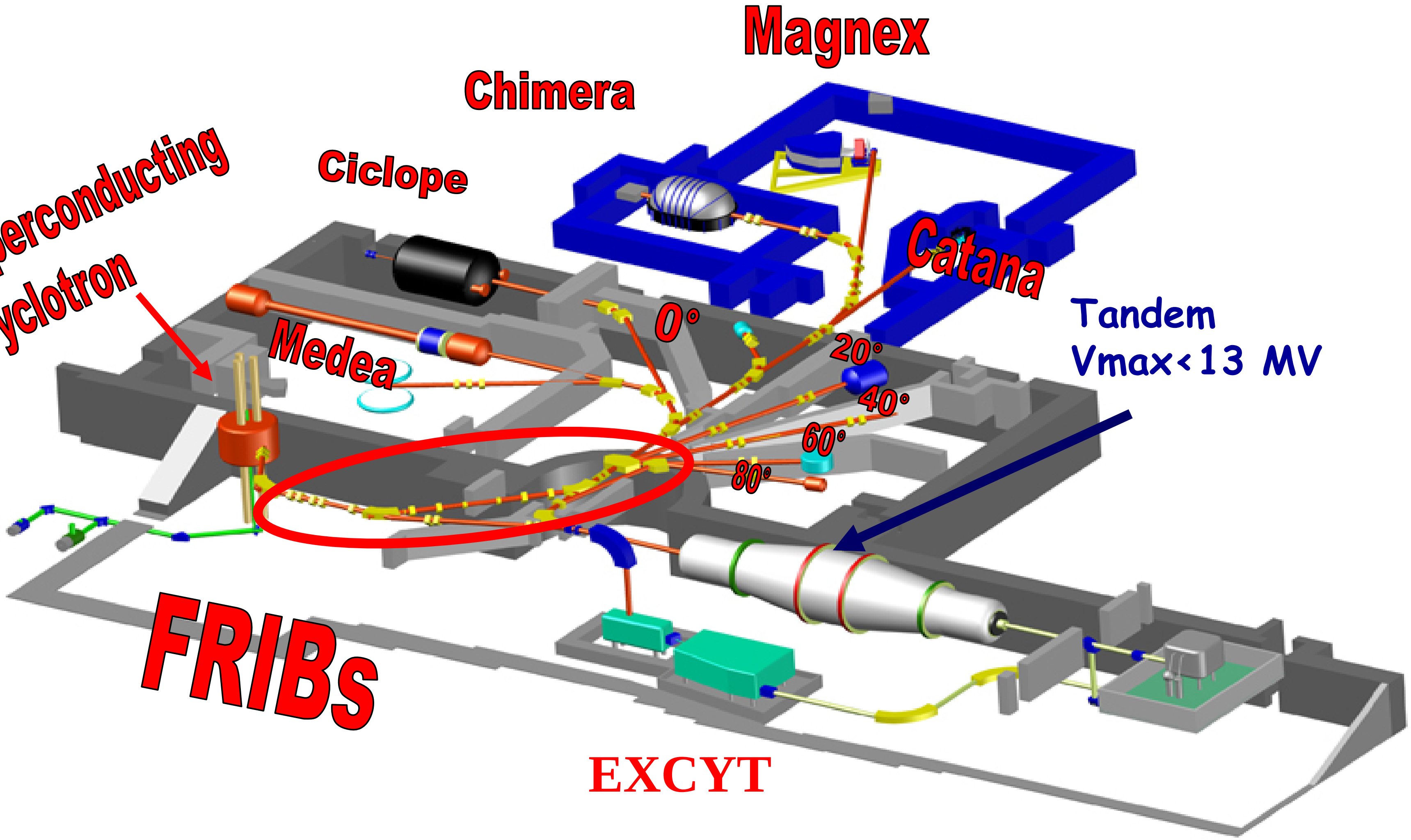
Upgrading of LNS Superconducting Cyclotron to deliver beam power higher than 2-5 kW

Luciano Calabretta on behalf of the LNS Accelerator Division

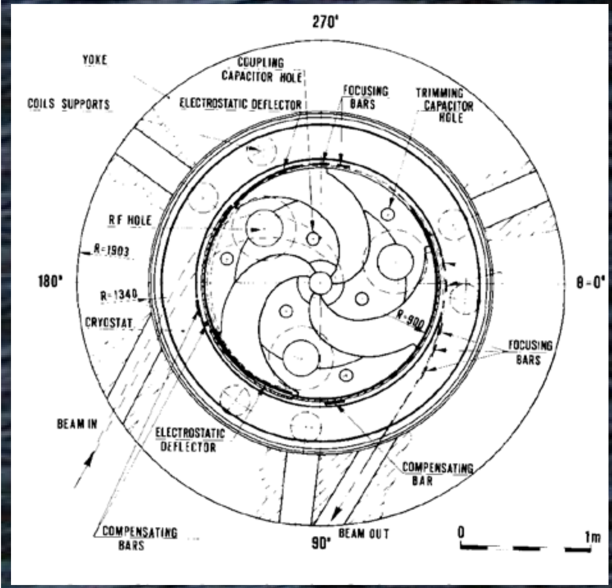
XXXX ECPM, 20-23 September, Legnaro (PD), Italy

The Cyclotron is used to deliver stable ion beams but also as driver to produce radioactive beams, separated by the in-flight method.



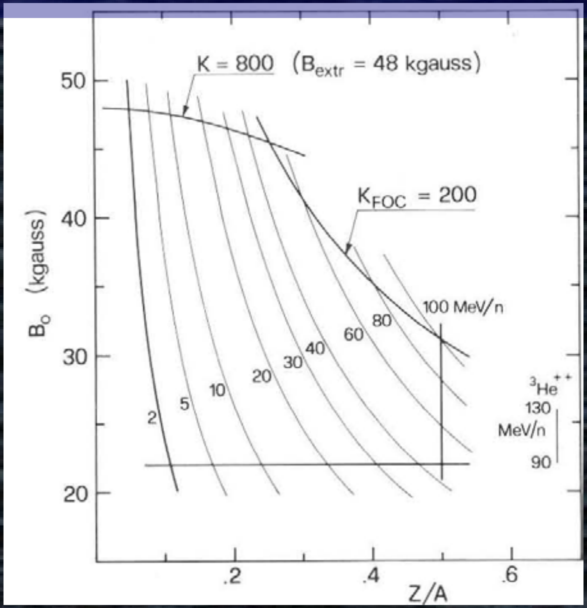
Short History of Catania Superconducting Cyclotron:

- 1980 Francesco Resmini and Milan Group study & design the K800 Superconducting Cyclotron;
- Cyclotron construction start in Milan in 1981;
- 1984 death of Resmini … and construction delays;
- 1990 the cyclotron is moved & installed in Catania with the fundamental support of Prof. C. De Martinis;
- 1994 acceleration of first beam injected by TANDEM;
- 2001 from radial injection to axial injection by ECR ion sources;



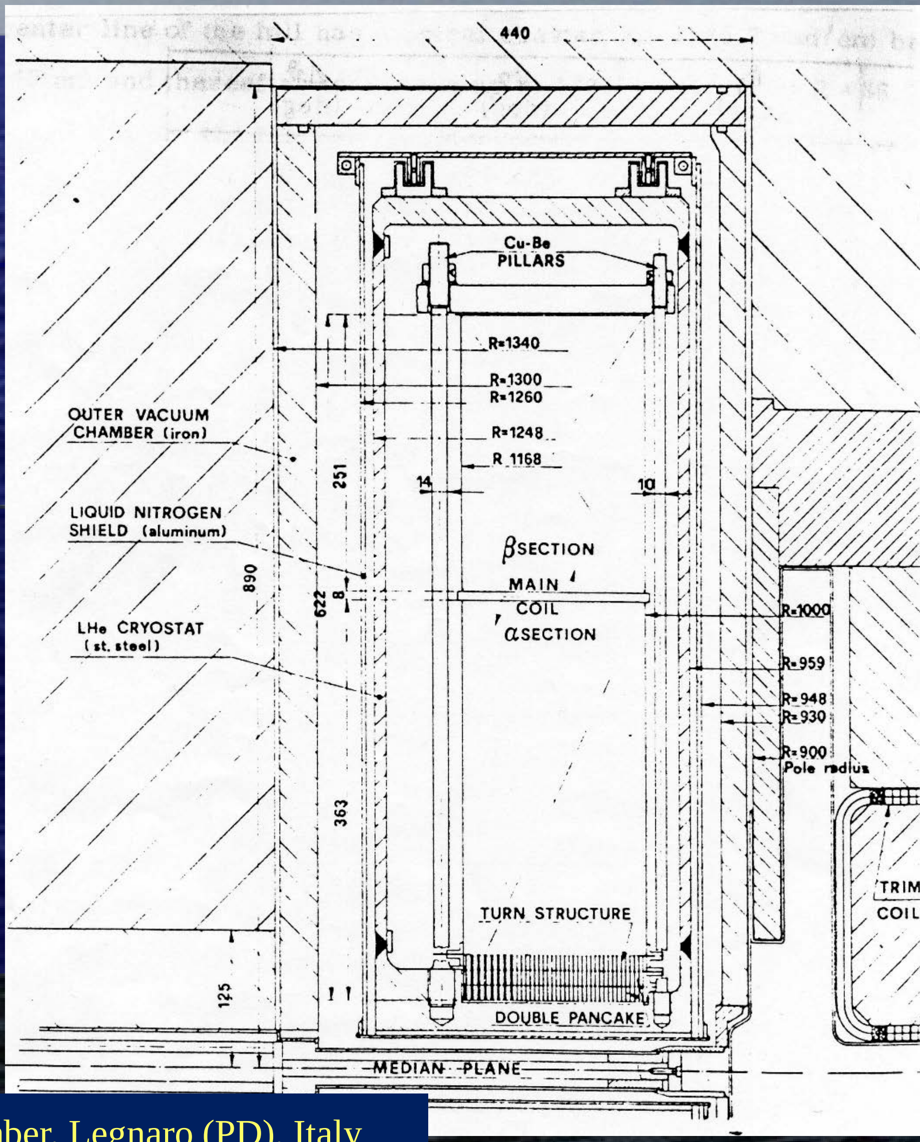
Our Cyclotron is a three sectors machine able to accelerate ions from H_2^+ up to Uranium

- Maximum energy for fully stripped ions about 80 AMeV;
- Heavy ions up to 30-20 AMeV;
- Maximum power of extracted beam 140 W



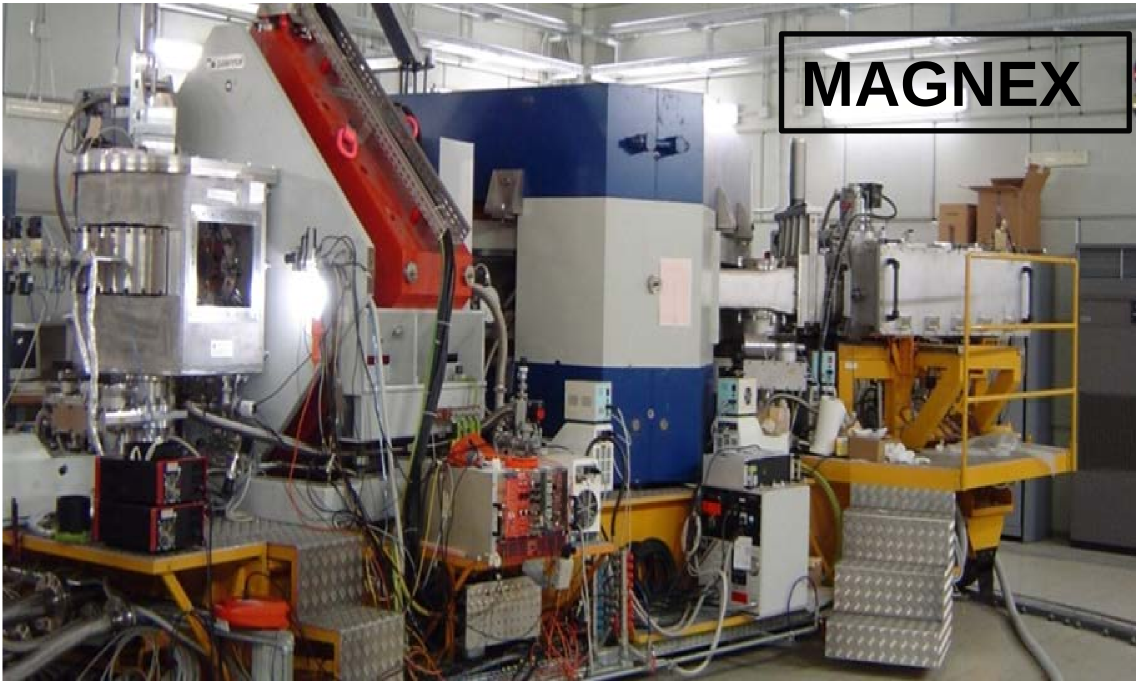
Present critical issues of our Cyclotron!

- We have 3 independent LN shields, but one is already closed due to a leak and the 2nd shields has also a small leak;
- Recently we found a leak between the main cryostat and the acceleration chamber of the cyclotron;
- There are small leaks from bad vacuum to the vacuum chamber through the LINER cover and this become a problem for the higher beam power and because the bad vacuum with time became worst, because the sealing of Trim Coils is not very good!



The NUMEN experiment at LNS

is measuring the Nuclear Matrix Element through reaction of Double Charge Exchange using as projectile ^{12}C, ^{18}O ^{20}Ne with energies in the range15-70 AMeV. The NME is also a relevant parameter to evaluate the expected rate of the neutrino less double beta decay.



- Experiments are performed by the magnetic spectrometer MAGNEX
- Wide angular acceptance
- Possibility to measure at 0°
- High resolution spectrum
- Angular distribution up to 10 nb/sr

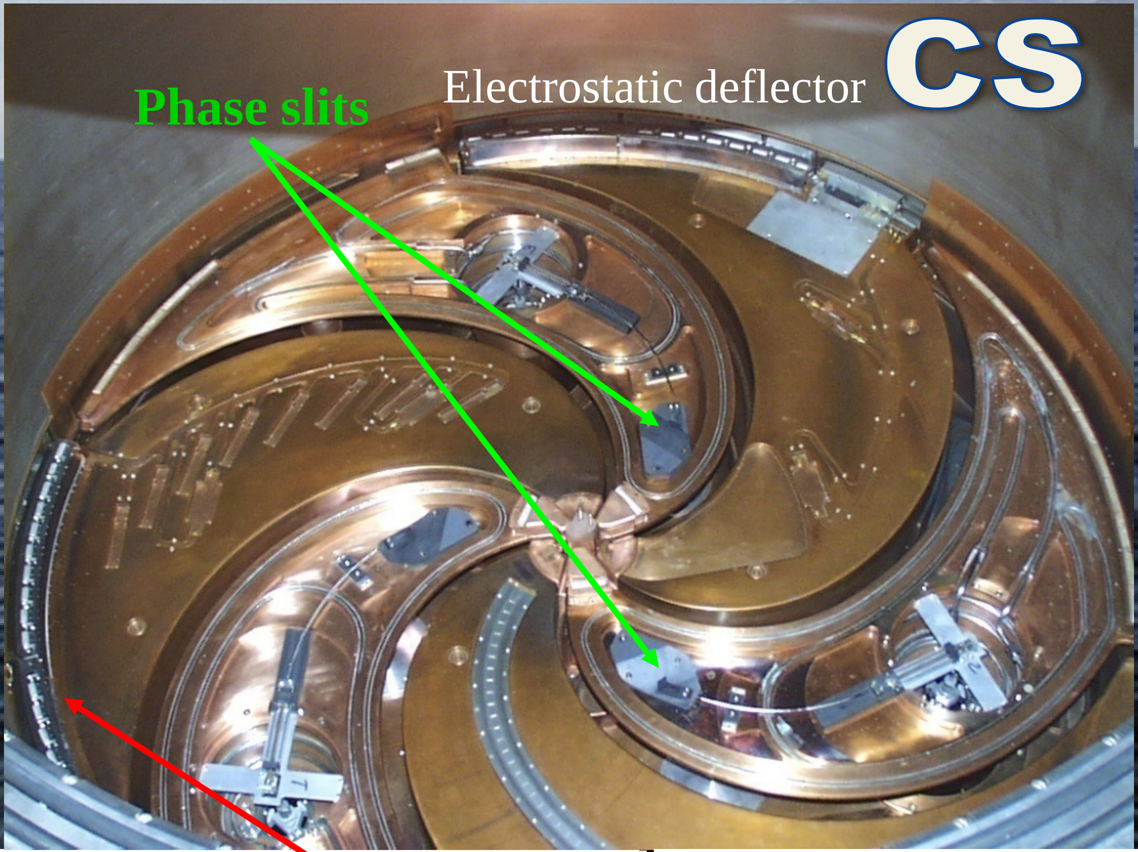
Preliminary experiments performed from 2014, using beam intensity of about 10 pnA, demonstrated the **need to increase the beam intensity of a factor 100 → 2-10 kW!**

Radioactive Beams developed at LNS

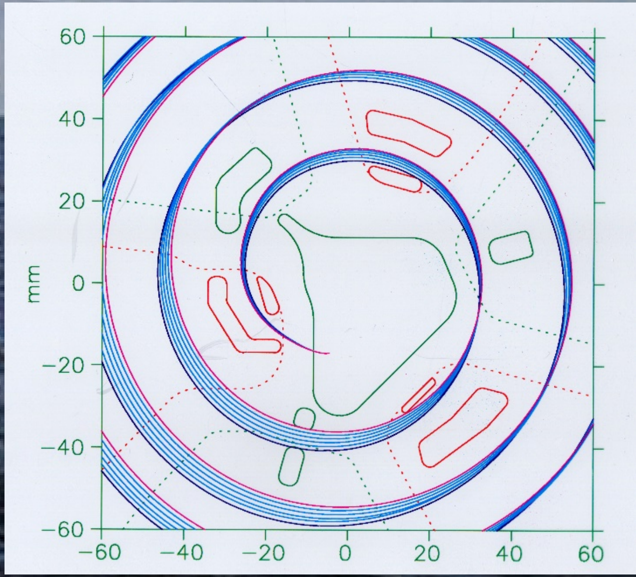
primary beam	beam	intensity (kHz/100W)
18O 55 AMeV	16C	120
setting 11Be	17C	12
	13B	80
	11Be	20
	10Be	60
	8Li	20
18O 55 AMeV	14B	3
setting 12Be	12Be	5
	9Li	6
	6He	12
13C 55 AMeV	11Be	50
setting 11Be	12B	100
36Ar 42 AMeV	37K	100
setting 34Ar	35Ar	70
	36Ar	100
	37Ar	25
	33Cl	10
	34Cl	50
	35Cl	50
20Ne 35 AMeV	18Ne	50
setting ne18	17F	20
	21Na	100
70Zn 40 AMeV		
setting 68Ni	68Ni	20

To increase the delivered power beam up to 10 kW could be very interesting also for experiment using radioactive ion beams.

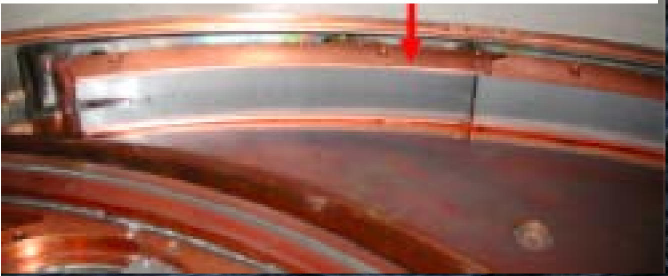
Unfortunately, due to radioprotection constraints the maximum beam power to produce radioactive beam will be limited to 2-3 kW



Central Region

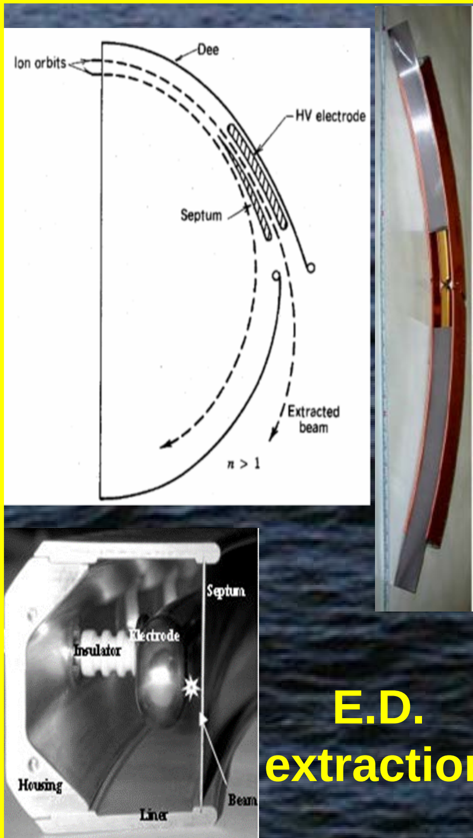


Electrostatic deflector

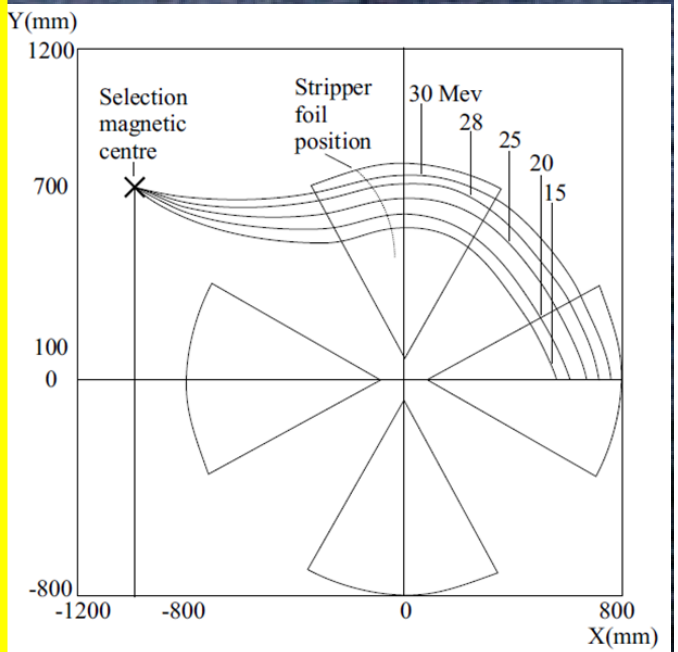


Unfortunately the extraction efficiency is only 50%!
Despite the deflector is water cooled the maximum beam extracted stay around 100 W!

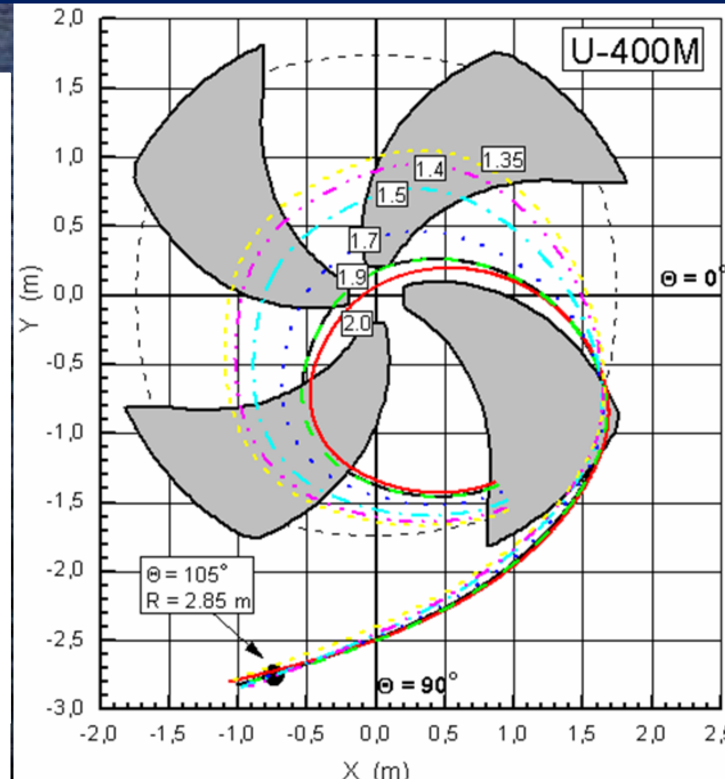
Stripping extraction to deliver higher power : Pros & Cons



E.D. extraction



Extraction by stripping of H- used in commercial cyclotron



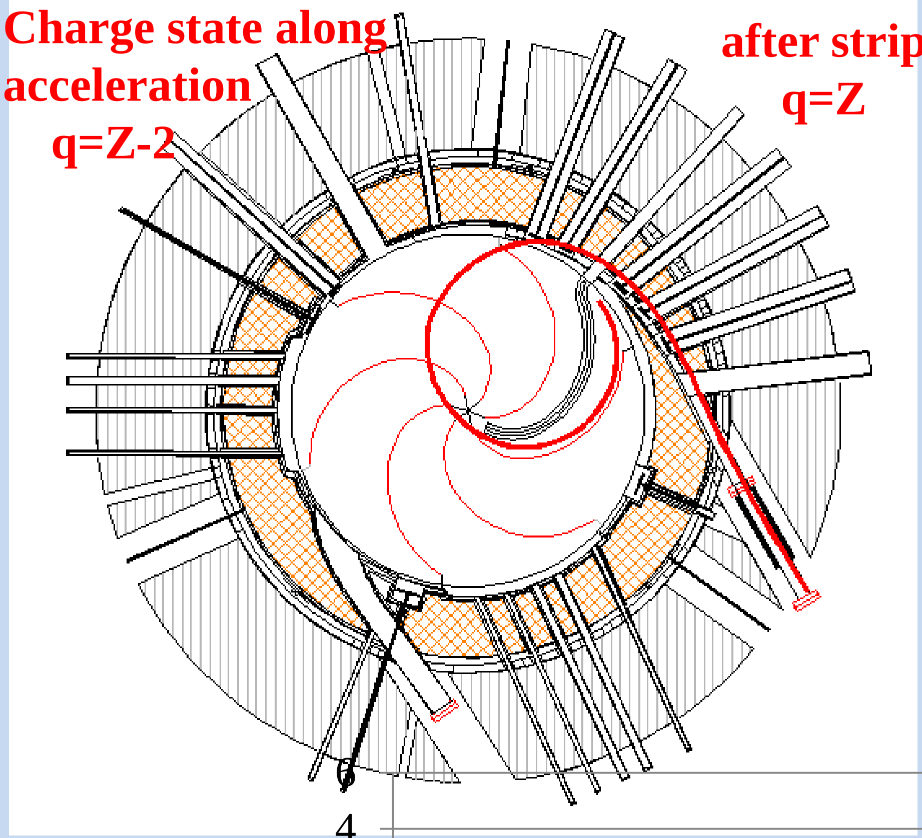
Dubna U-400M, positive ions before and after the stripper. Stripper increases the charge state!

For light ions, with enough energy and stripper thickness longer than the equilibrium thickness, the amount of ions stripped at charge state q=Z is ≥ 99%

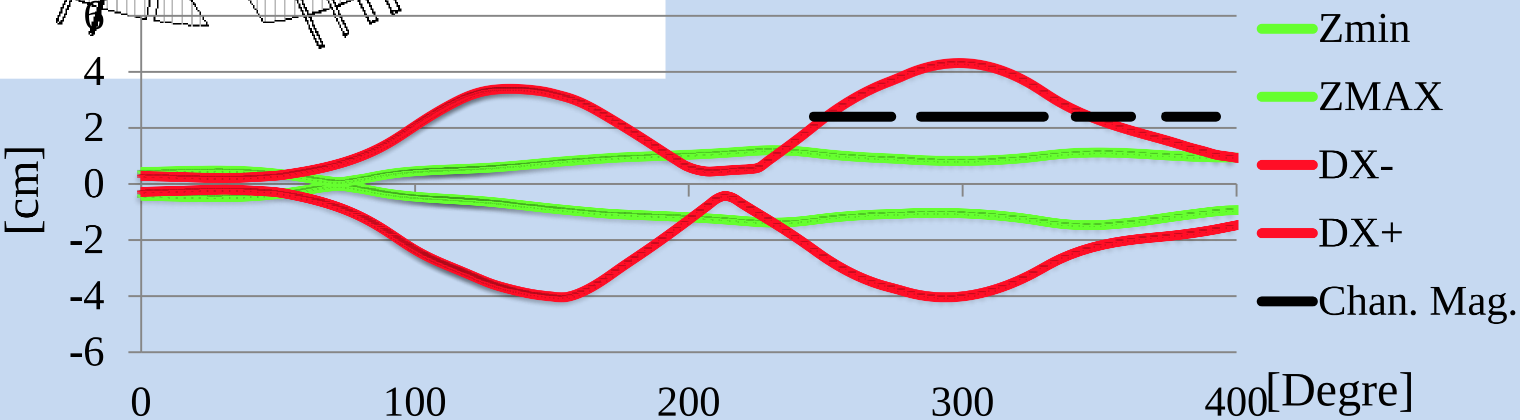
Ion	Energy	Isource	**Iacc.	*Stripping	Iextracted	Pextracted
	AMeV	eμA	eμA	efficiency	pps	Watt
$^{12}C^{4+}$	45	400	60(4+)	4+ → 6+, 100%	9.4*10^13	8100
$^{12}C^{4+}$	60	400	60(4+)	4+ → 6+, 100%	9.4*10^13	10800
$^{18}O^{6+}$	29	400	60(6+)	6+ → 8+, 99.96%	6.2*10^13	5220
$^{18}O^{6+}$	45	400	60(6+)	6+ → 8+, 100%	6.2*10^13	8100
$^{18}O^{6+}$	60	400	60(6+)	6+ → 8+, 100%	6.2*10^13	10800
$^{18}O^{7+}$	70	200	30(7+)	6+ → 8+, 100%	2.7*10^13	5400
$^{20}Ne^{7+}$	28	400	60(7+)	7+ → 10+, 99.91%	5.3*10^13	4800
$^{20}Ne^{7+}$	60	400	60(7+)	7+ → 10+, 99.95%	5.3*10^13	10280
$^{40}Ar^{14+}$	60	400	60(14+)	14+ → 38+, 99.8%	2.7*10^13	10280

*Atomic Data and Nuclear Data tables, Vol. 51, N° 2, July 1992, table 2 pag. 187
**injection efficiency 15%, using existing buncher

Trajectories extracted by stripping don't fit the existing extraction channel and their sizes are too large.

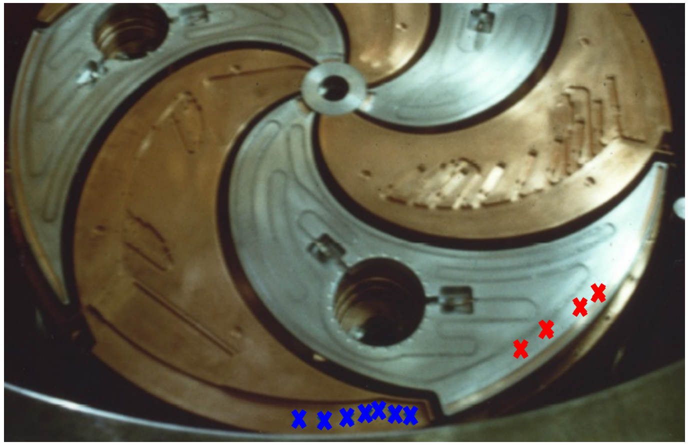


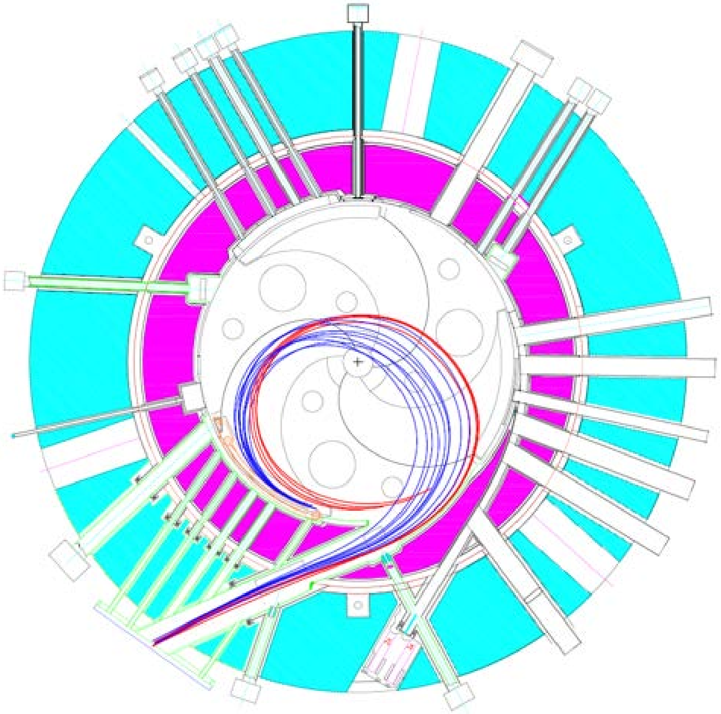
Extraction trajectory
Ne20, q=6+ → 10+
E=29 MeV/amu
Normalised emittance
1.13 πmm-mrd
about 2.5 larger than emittance of beams delivered by Catania ion sources



According to Mario Maggiore suggestion, we decided to perform the extraction through a new extraction channel, with larger radial and vertical size!

All the ions of interest can be extracted using stripper placed in two regions:
- One region is on the hill where the 1st deflector is placed;
- Another region is in the Dee before deflector 1.





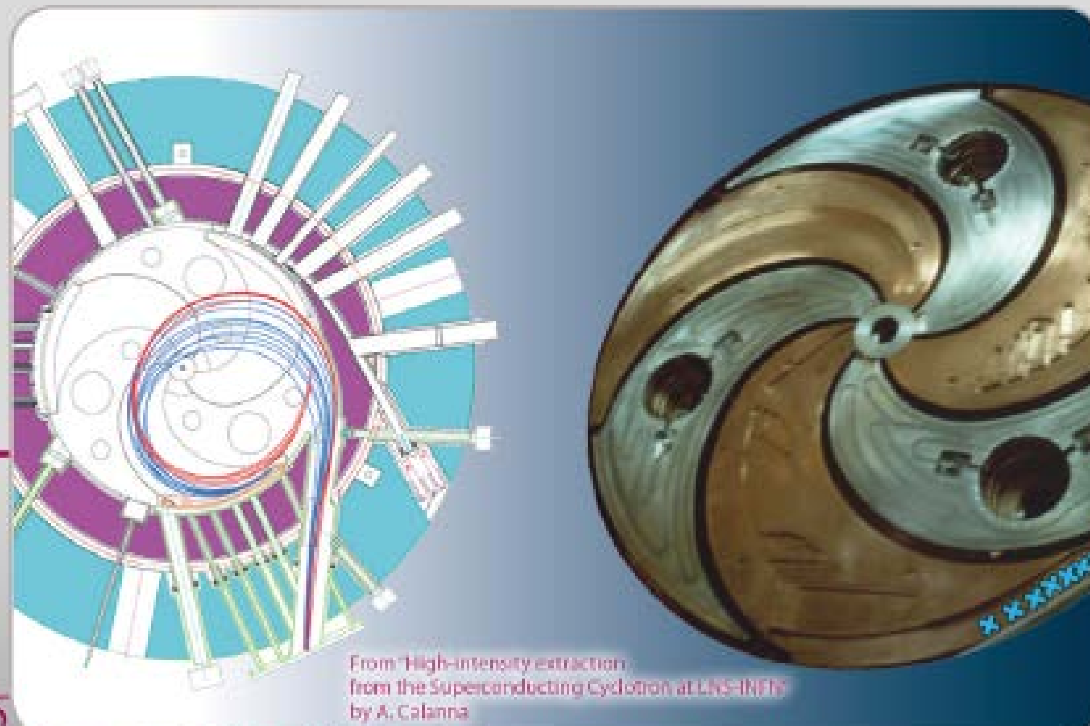
The biggest drawbacks are:
- Construction of a set of new coils ;
- Construction of a new cryostat;
- Stop of laboratory activity for about 18 months.

The advantages are:
- A new cryostat with better LN cooling, lower cryogenic liquid consumption, a longer life;
- More room for extracted beams;
- New perspectives for our laboratory.

IL NUOVO CIMENTO
della Società Italiana di Fisica

Selection of the best communications
presented at the
102nd National Congress of the Italian Physical Society
Padova, 26-30 September 2016

Sped. in A.P. – D.L. 353/2003 (conv. in L. 27/02/2004 n. 46) art. 1 comma 1



From "High-intensity extraction from the Superconducting Cyclotron at LNS-INFN" by A. Calanna

Mean life of the stripper foils

Eric Baron (Ganil) suggest this formula to evaluate the mean life of carbon stripper foil

$$T(\text{hours}) = 3.6 \cdot 10^{4} \, \frac{W(\text{MeV/A})}{Z^{2} \cdot \overline{\nu} \cdot \dot{j}(\text{p}\mu\text{A/cm}^{2})}$$

$$\overline{\nu} \sim 5 \text{ to } 8$$

For a Oxigen-18 beam of 60 μA, and at 60 MeV/n (10 kW), the expected mean life according to the previous formula is 126-202 hours (beam spot 3x10 mm^2), equivalent to 5-8 days!

We must achieve update experimental data of mean life!

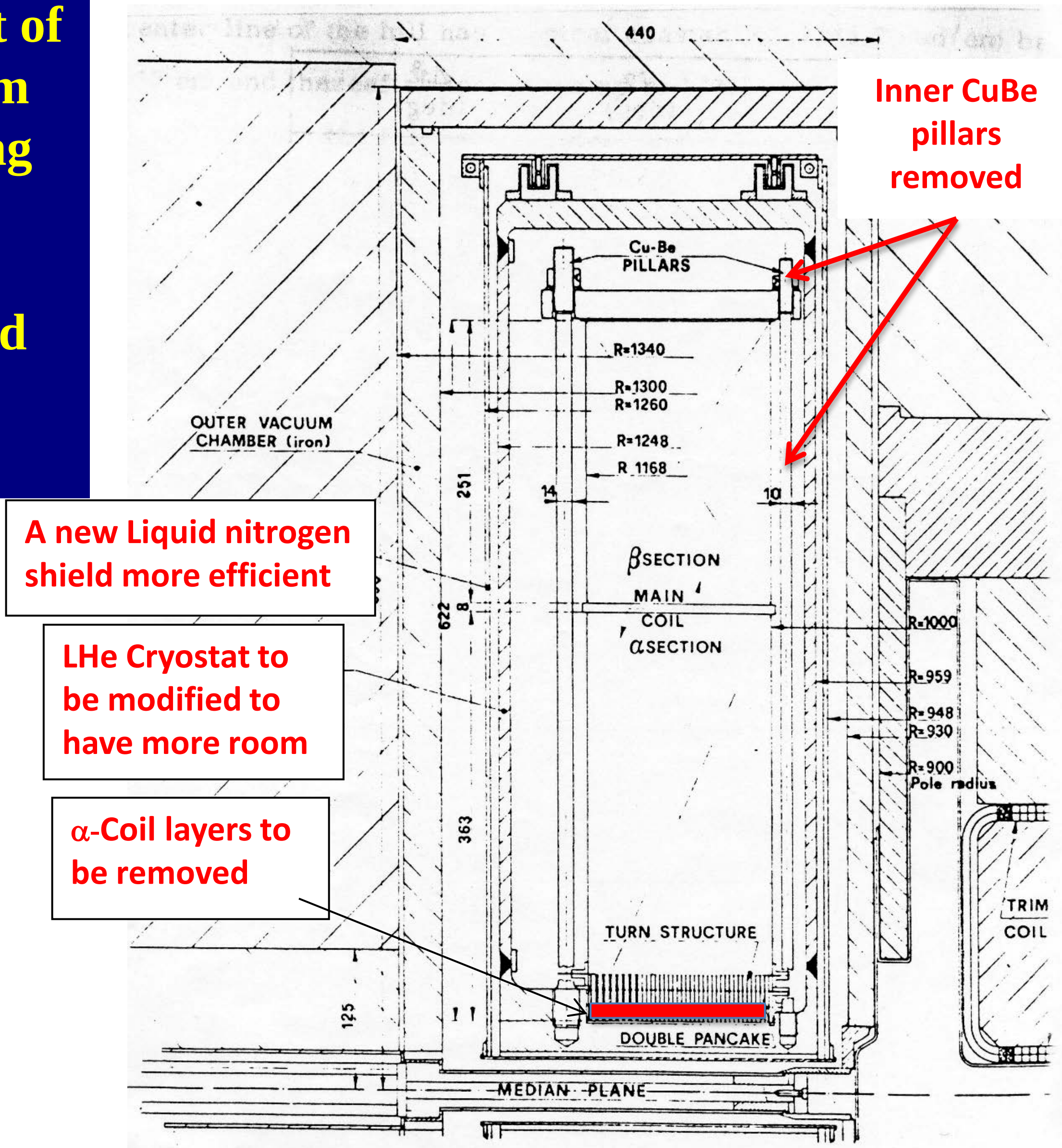
We could increase the mean life of foils, increasing the area of the beam spot on the stripper, by tilting the stripper of 45°-60°!

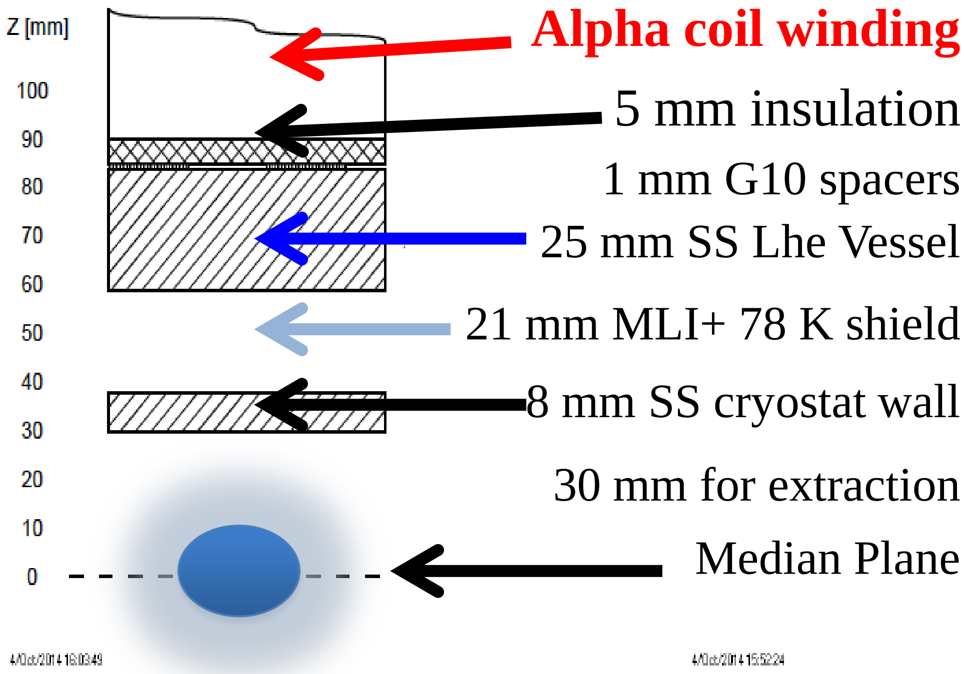
We could increase the vertical size of the beam using the Walkinshaw resonance!

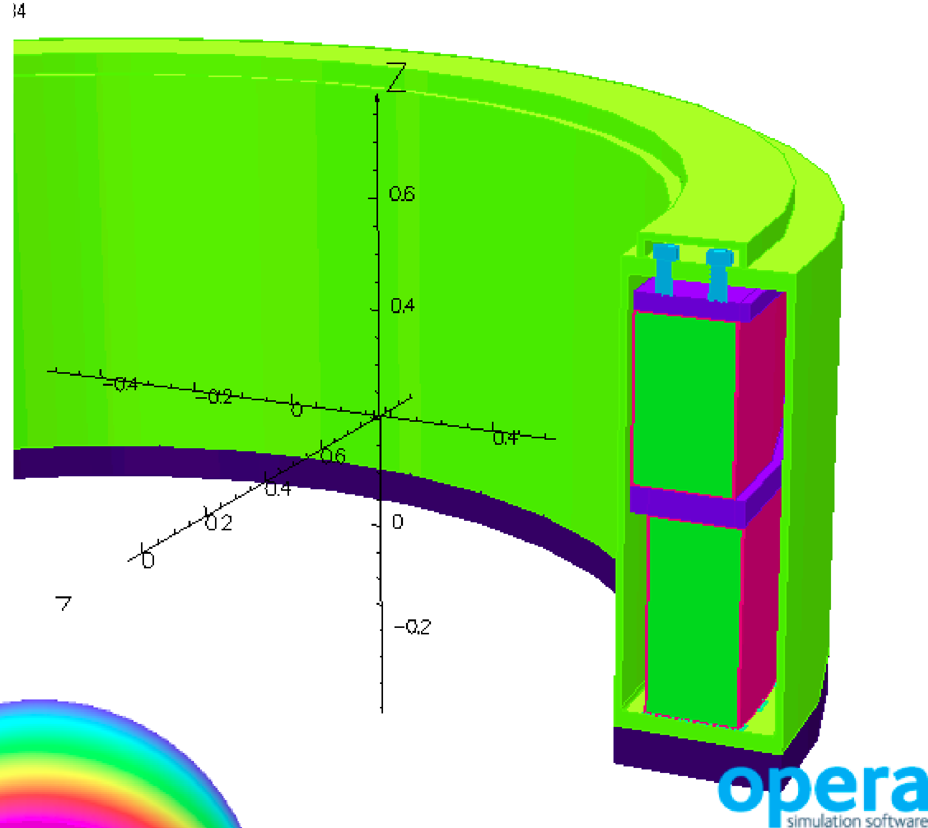
From electrostatic extraction to stripping extraction

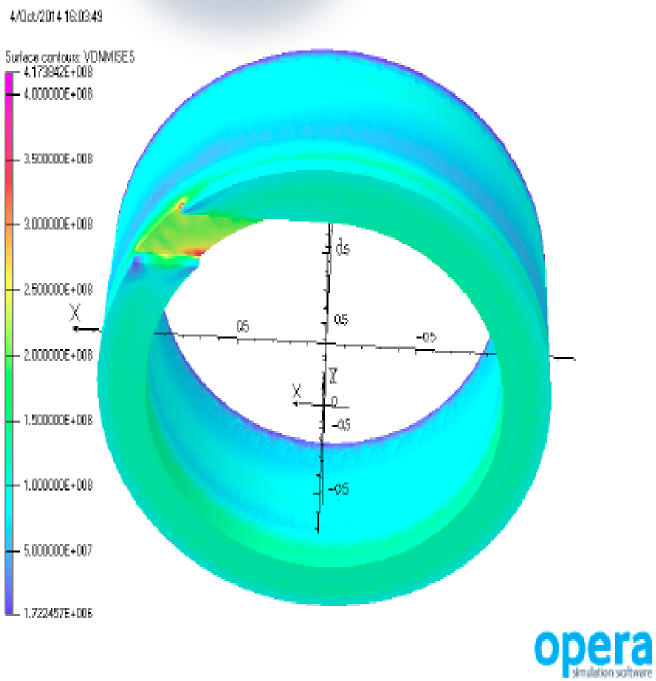
A preliminary design of a new set of superconducting coils, with form factor very similar to the existing coils, and a new cryostat were evaluated together with MIT. The current density is increased from the present 35 A/mm² to 54 A/mm²

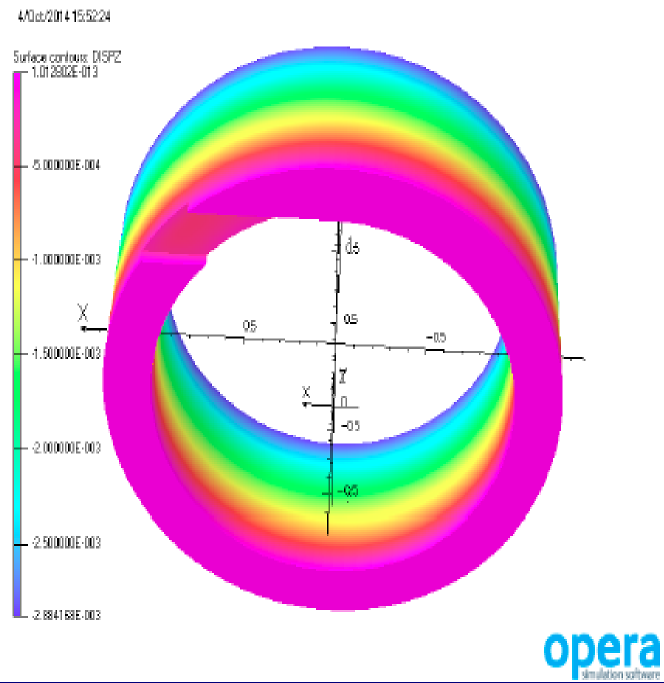
Now we are officially discussing with four companies (ASG, BABCOCK, SIGMAPHY and TESLA) to evaluate the critic items of the project and take account of their suggestion.

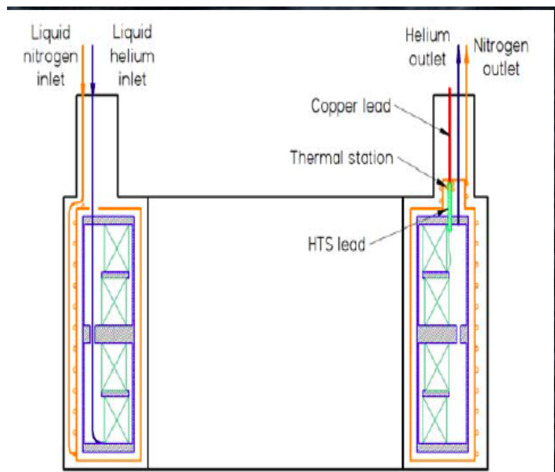



Z [mm]
100
90
80
70
60
50
40
30
20
10
0
Alpha coil winding
5 mm insulation
1 mm G10 spacers
25 mm SS Lhe Vessel
21 mm MLI+ 78 K shield
8 mm SS cryostat wall
30 mm for extraction
Median Plane


Z
0.6
0.4
−0.4
−0.2
0
0.4
0.6
0.4
0.2
0
−0.2
opera
simulation software

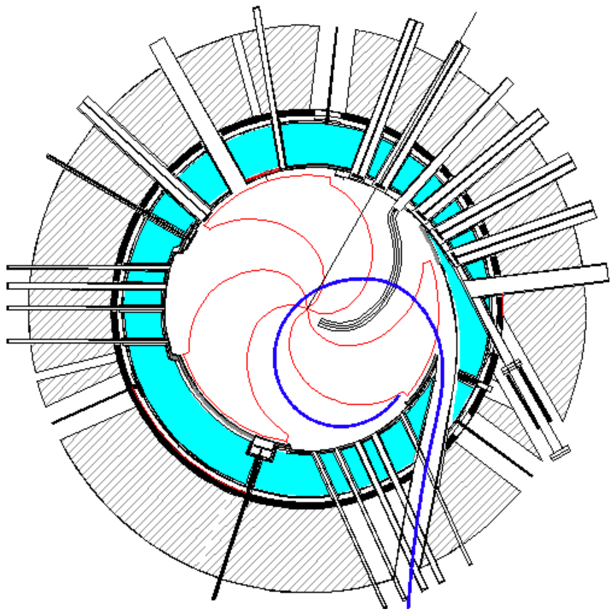

Surface contours: VONMISES
opera
simulation software

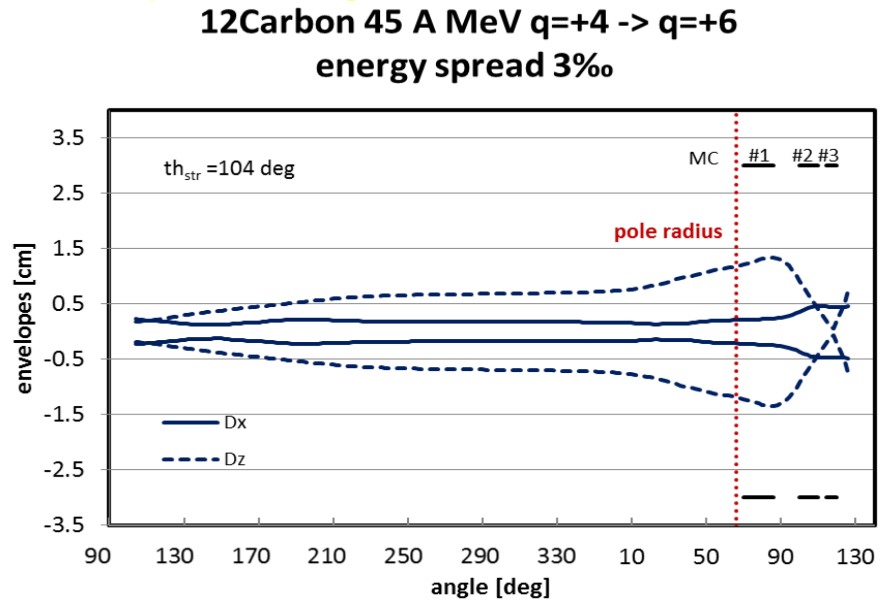

Surface contours: DISPZ
opera
simulation software

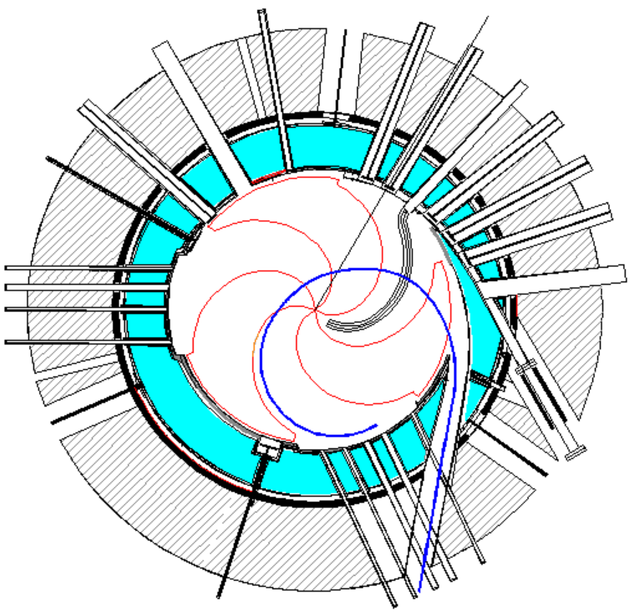

Liquid nitrogen inlet
Liquid helium inlet
Helium outlet
Nitrogen outlet
Copper lead
Thermal station
HTS lead

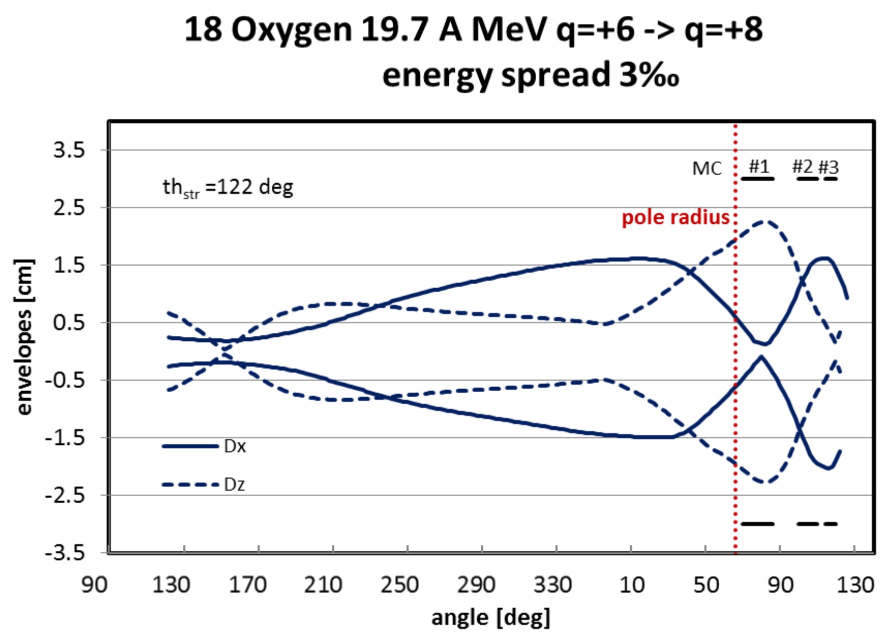
Example of beam envelope along the extraction trajectory

New Channel



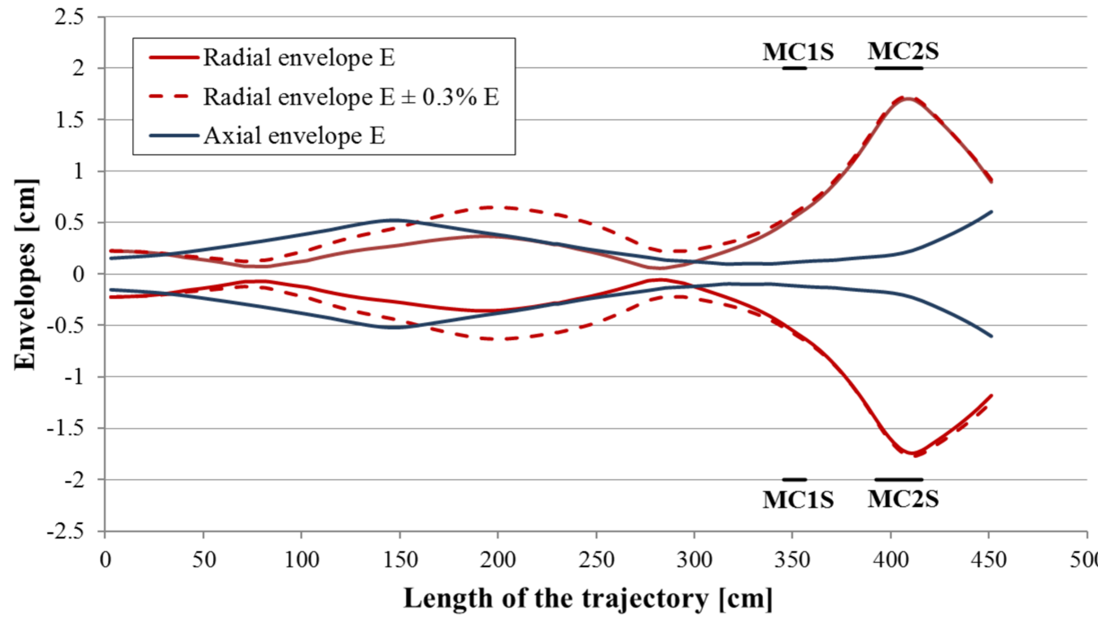




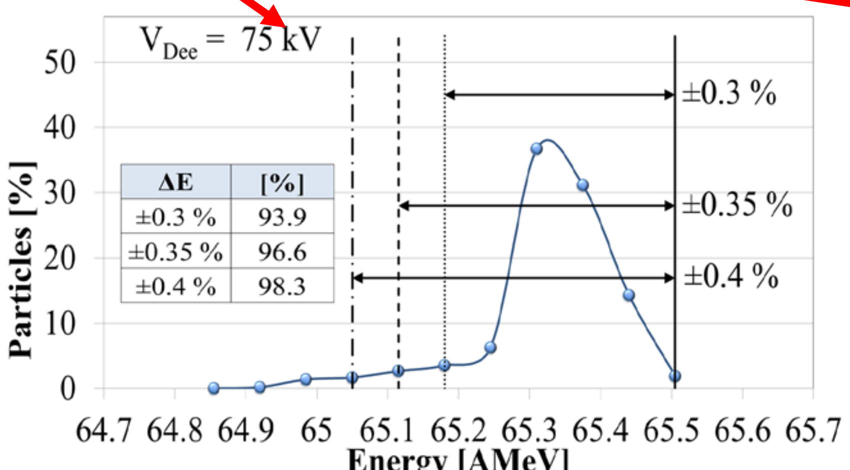


The magnetic channels stay around at 360° after the stripping position, this minimize the radial broadening effect due to the energy spread!

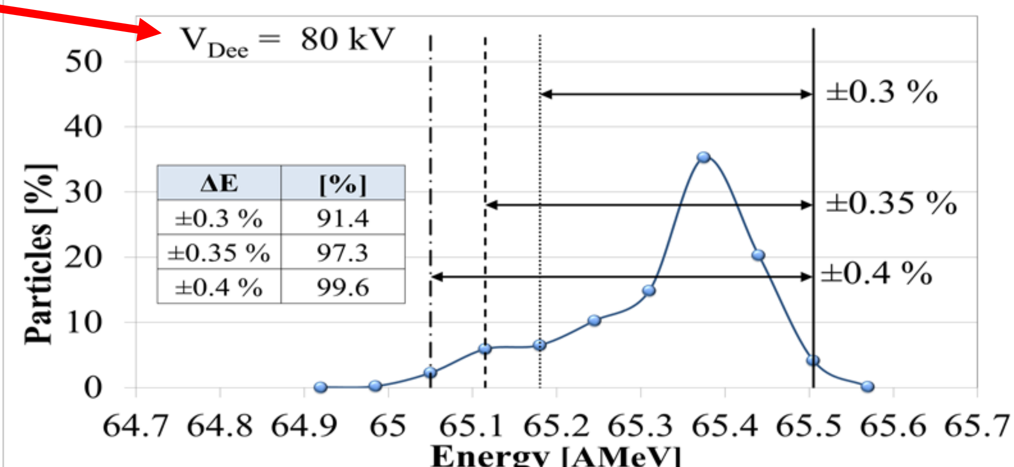
Radial and axial envelopes for the ion beam 18O at stripping energy equal to 65 AMeV along the stripping trajectory. The effect of energy spread 0.3% is also shown.



The effect of the accelerating voltage (75 kv & 80 kV) on the energy spread of the accelerated beam is not serious! The bunch length used in the simulations are of 26° and 32° for the 75 kV and 80 kV respectively



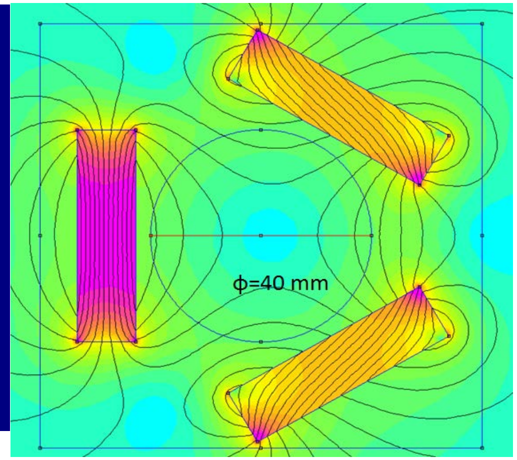
Distribution at stripper position

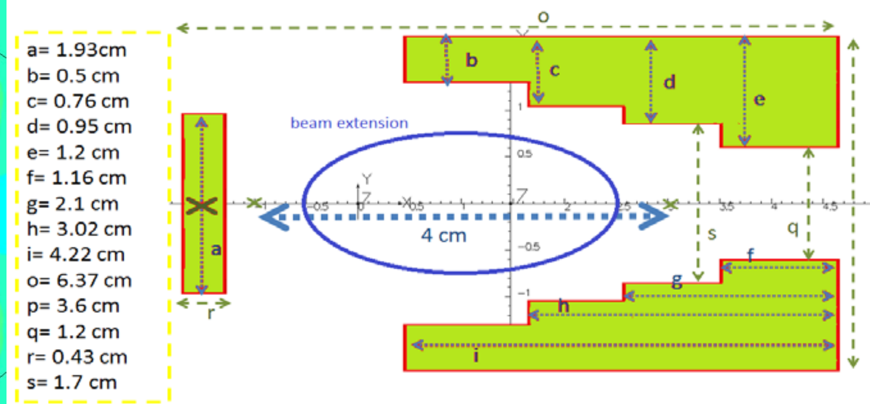


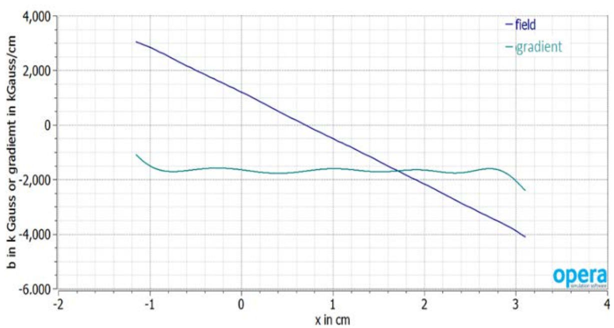
Distribution at stripper position

New and larger magnetic channel to control the beam sizes along the extraction trajectories

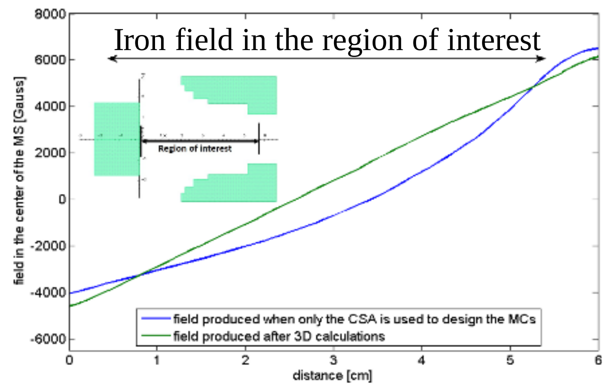
Design of the magnetic channel using the Current Sheet Approximation could be misleading if the field lines are not perpendicular to the device

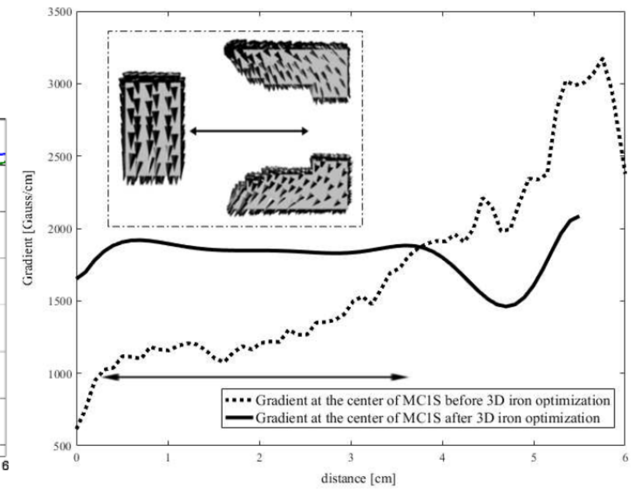






Result of the C.S.A. assuming external field perpendicular to the median plane



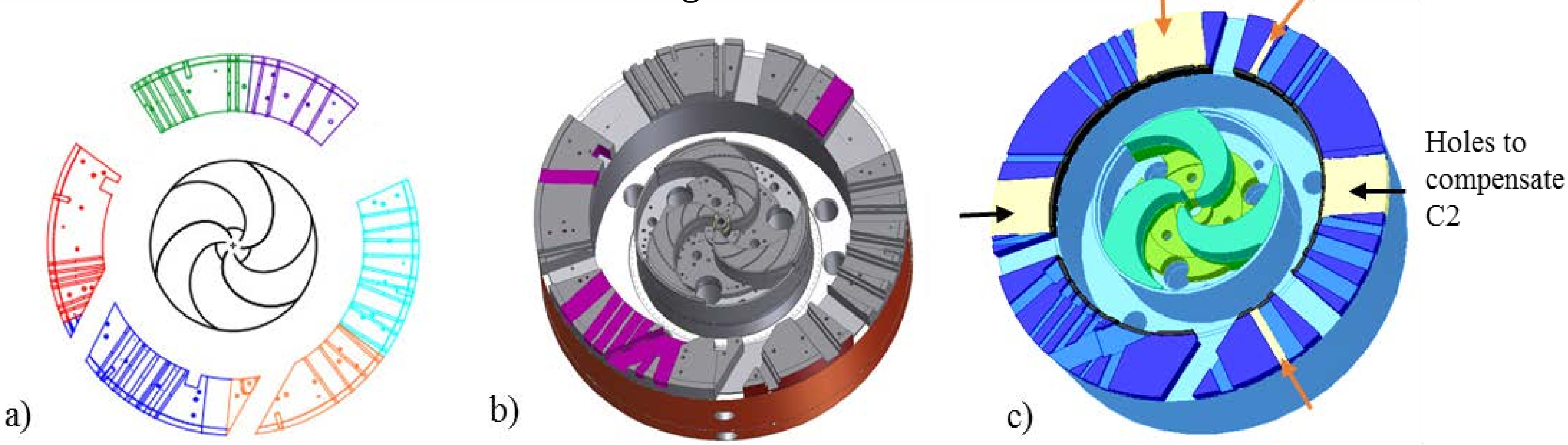


The blue line is the result of 3D simulations of the Magnetic Channel in the cyclotron true magnetic field, fine optimization were necessary to achieve the green lines

See poster 7

See poster 7

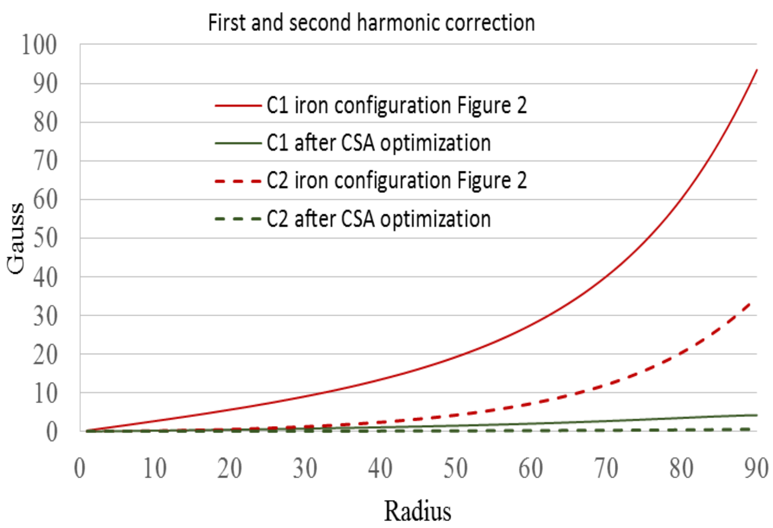
Height of the holes ± 12.5 cm



The existing iron yoke of our cyclotron

The holes for the new extraction channel and for the radial tie rods

Additional holes for 1st and 2nd harmonics compensatation

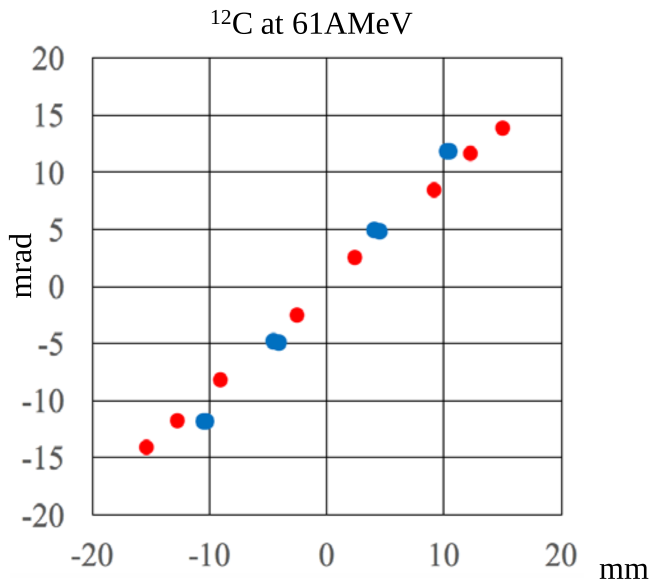


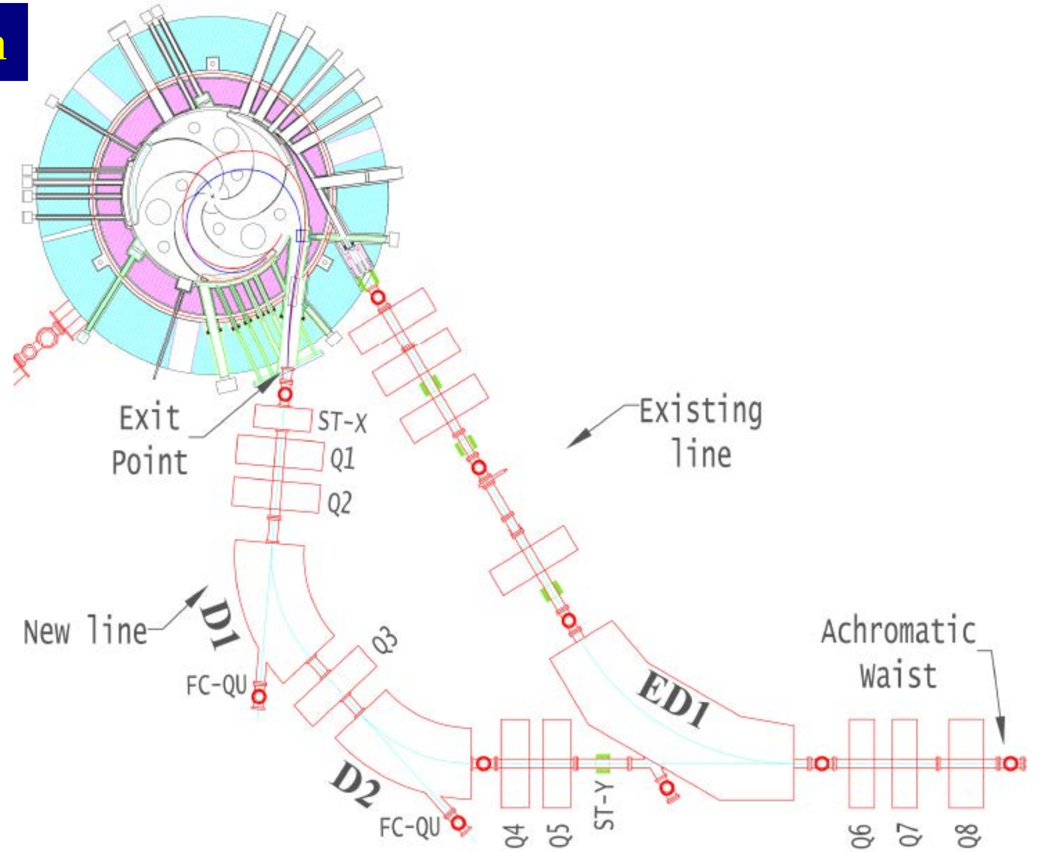
1st and 2nd harmonic contributions before and after the compensation

See poster 7

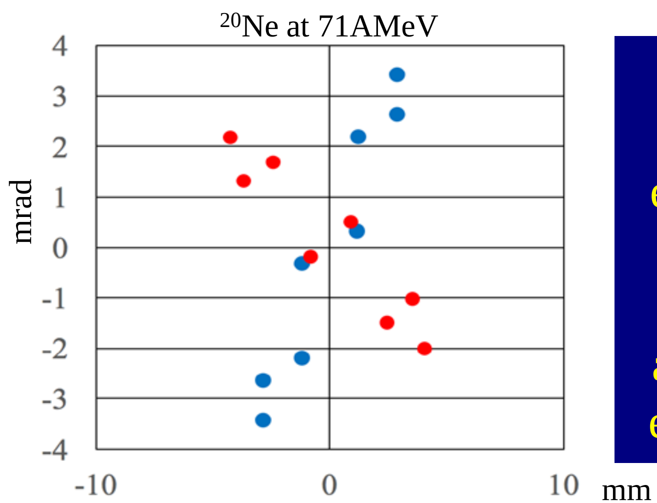
See poster 7

The new extraction line for the 10 kW beam

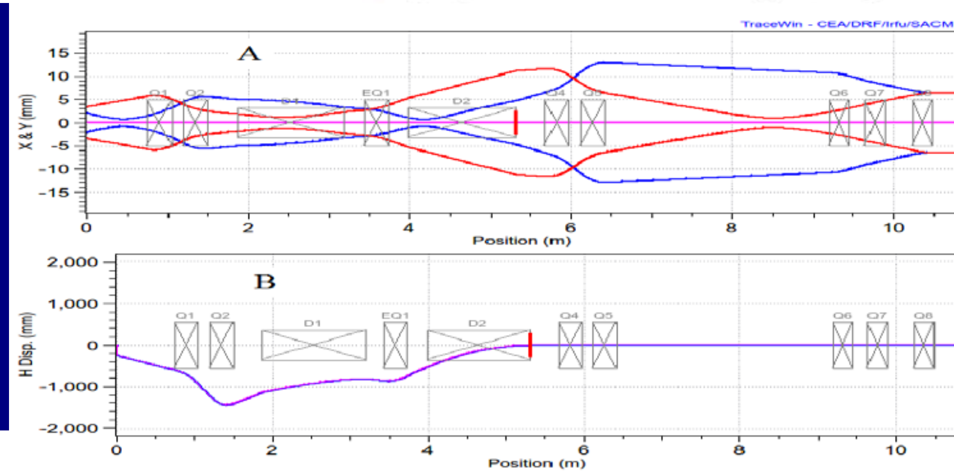




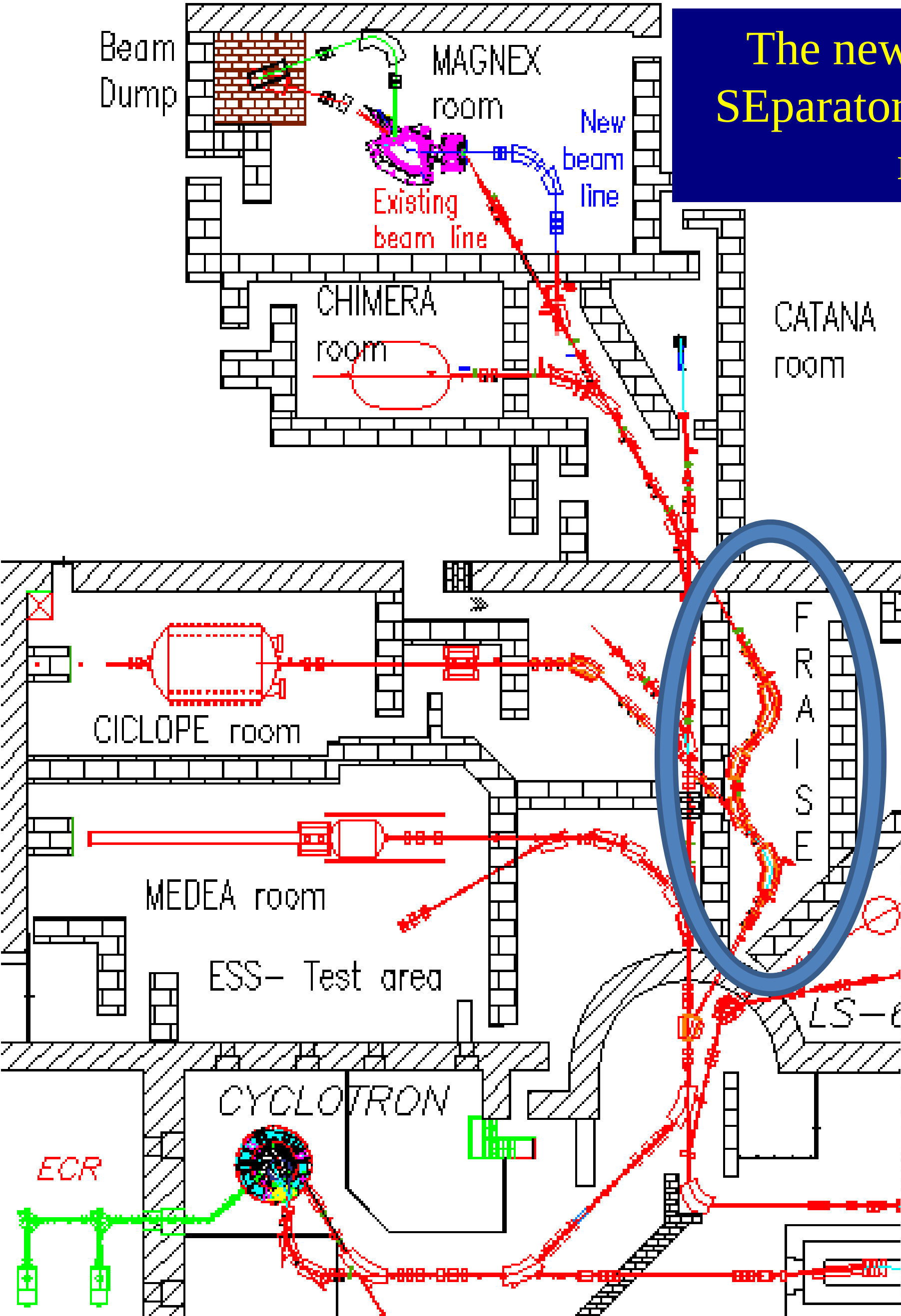
Examples of emittance orientation at the exit point for two ions

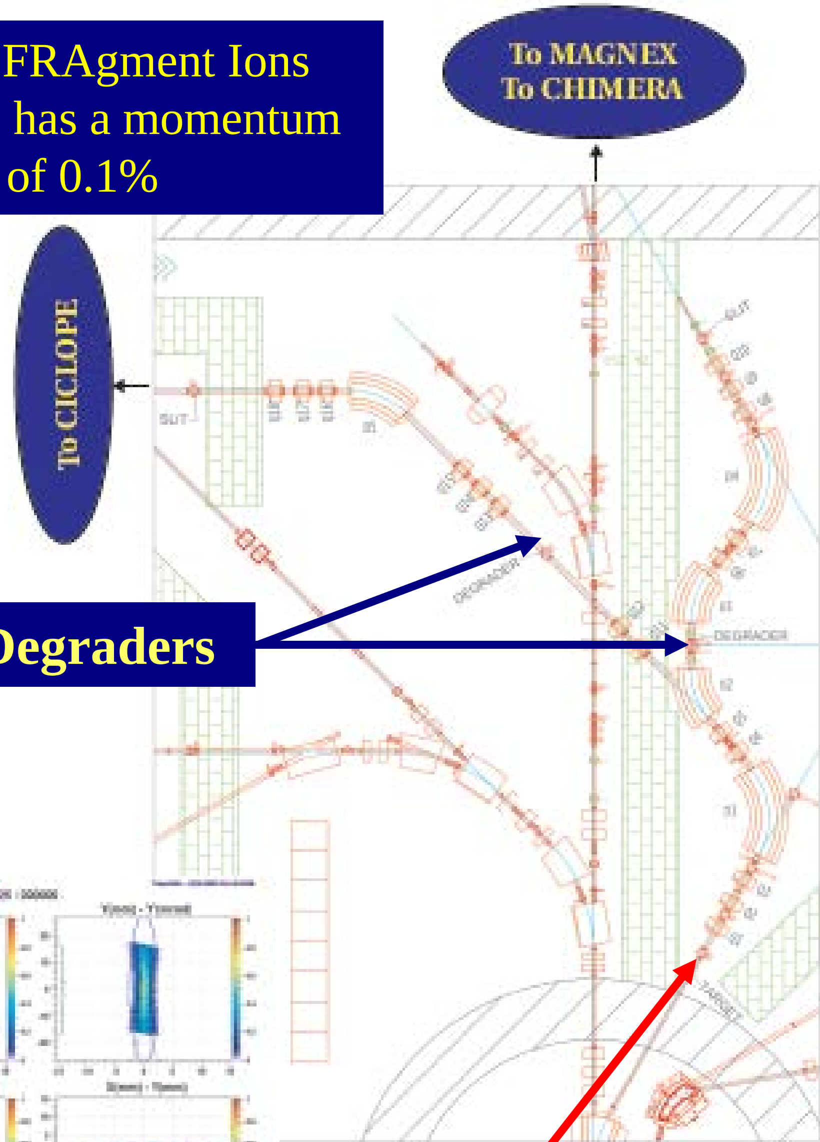


Example of beam envelopes and radial dispersion along the new extraction line

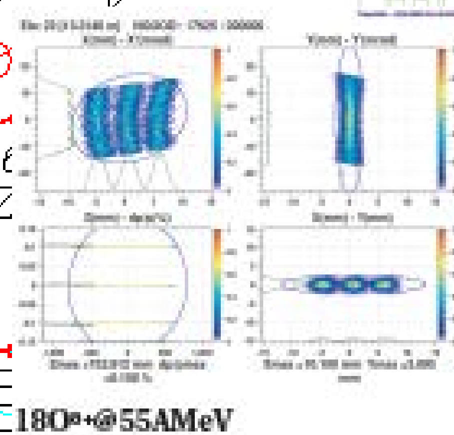


The new In-flight FRAgment Ions SEparator FRAISE has a momentum resolution of 0.1%



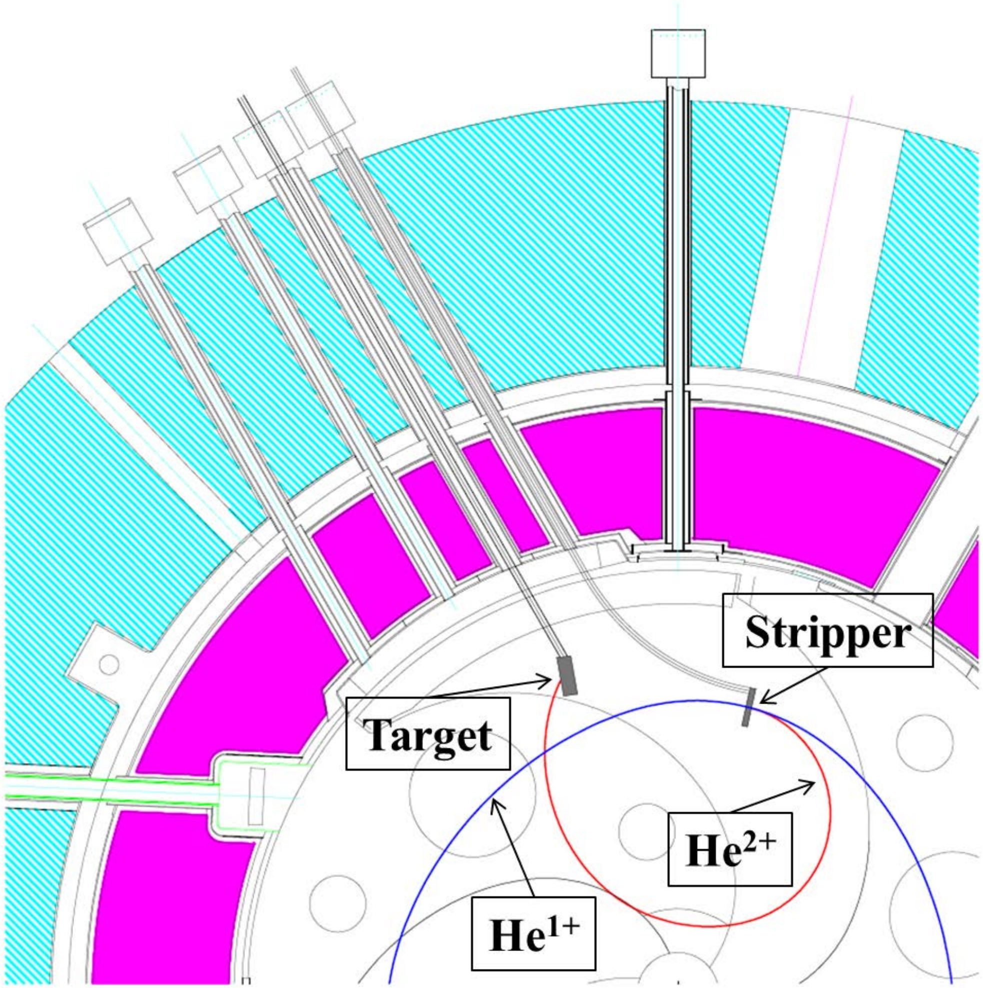


Degraders



Rotation Target for 2 kW incident beam

See poster 8



Production of At-211 by internal target

At211 is an alpha emitter that is accessible through the reaction Bi209 (alpha, 2n) At211 and could be used as a therapy radionuclide. The maximum energy for alpha beam must be limited at about 28 MeV to avoid the production of the contaminant, Po 210!
(by private lesson of Dick Johnson)

Unfortunately the stripper extraction don't allow to extract helium beam from our cyclotron.
But it is possible to irradiate a Bismuth internal target.

The cyclotron can be set to accelerate He^{1+} at 28 MeV energy at the orbit with R=700 mm. A beam power in excess of 500 W (18 pmicroA @ 28 MeV) will be available for the target irradiation. A production of At-211 in excess of 200 mCi it is expected after an irradiation of 8 h.

Main items of the upgrading program managed by Danilo Rifuggiato

Looking for intensity

- <u>New s.c. magnet: cryostat with coils</u>
- <u>Stripper system in progress</u>
- <u>Magnetic channels in progress</u>
- <u>New liner</u>
- <u>Ions Sources-Cyclotron matching</u>
- <u>Cyclotron-Magnex beam line</u>

Looking for reliability

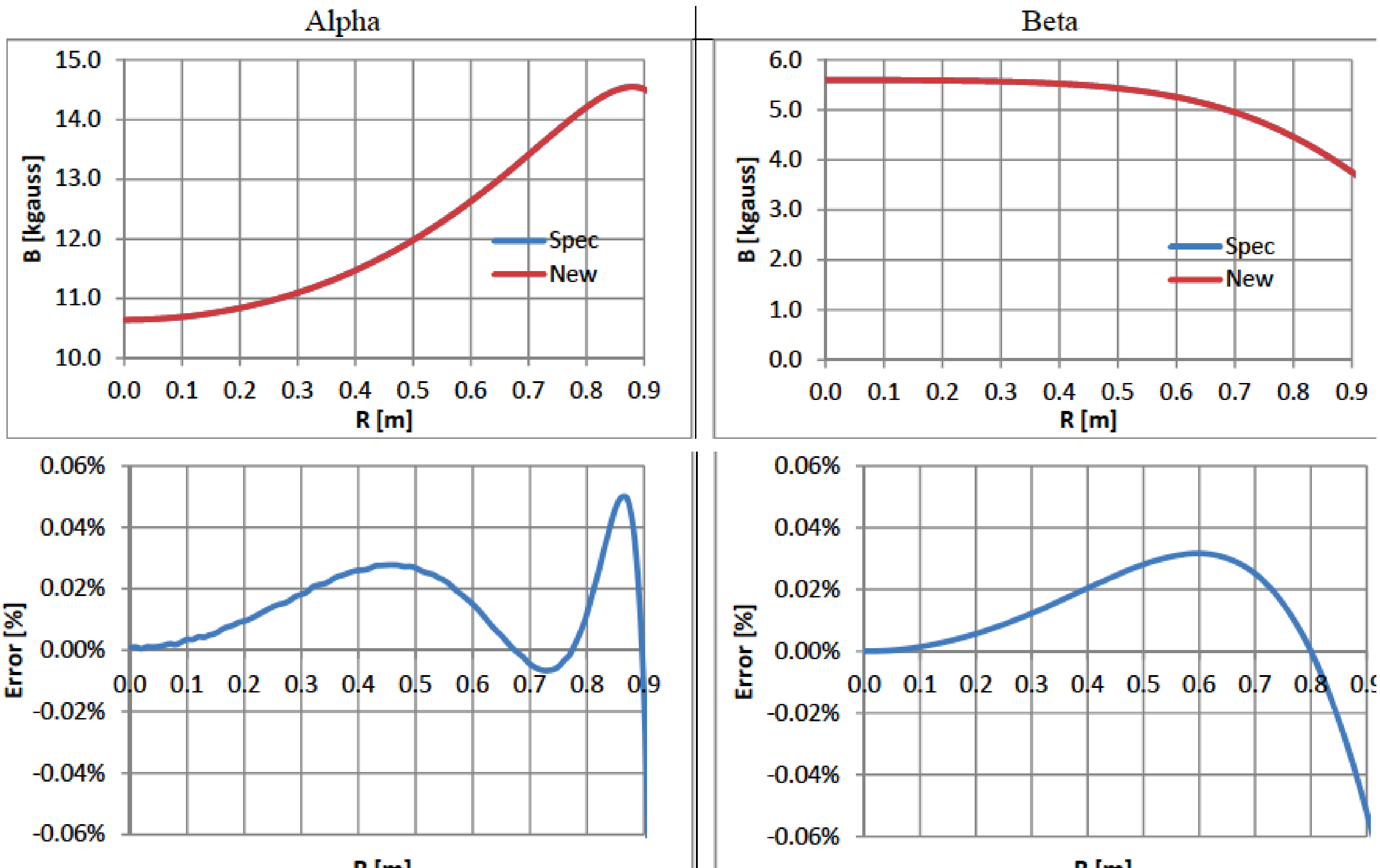
- New trim coils ?
- RF cavities insulators ?
- New power supplies ?
- ~~New Helium liquefier or small reliquefiers~~

Thanks for your attention!

Parameters of the existing coil and of the new proposed coils

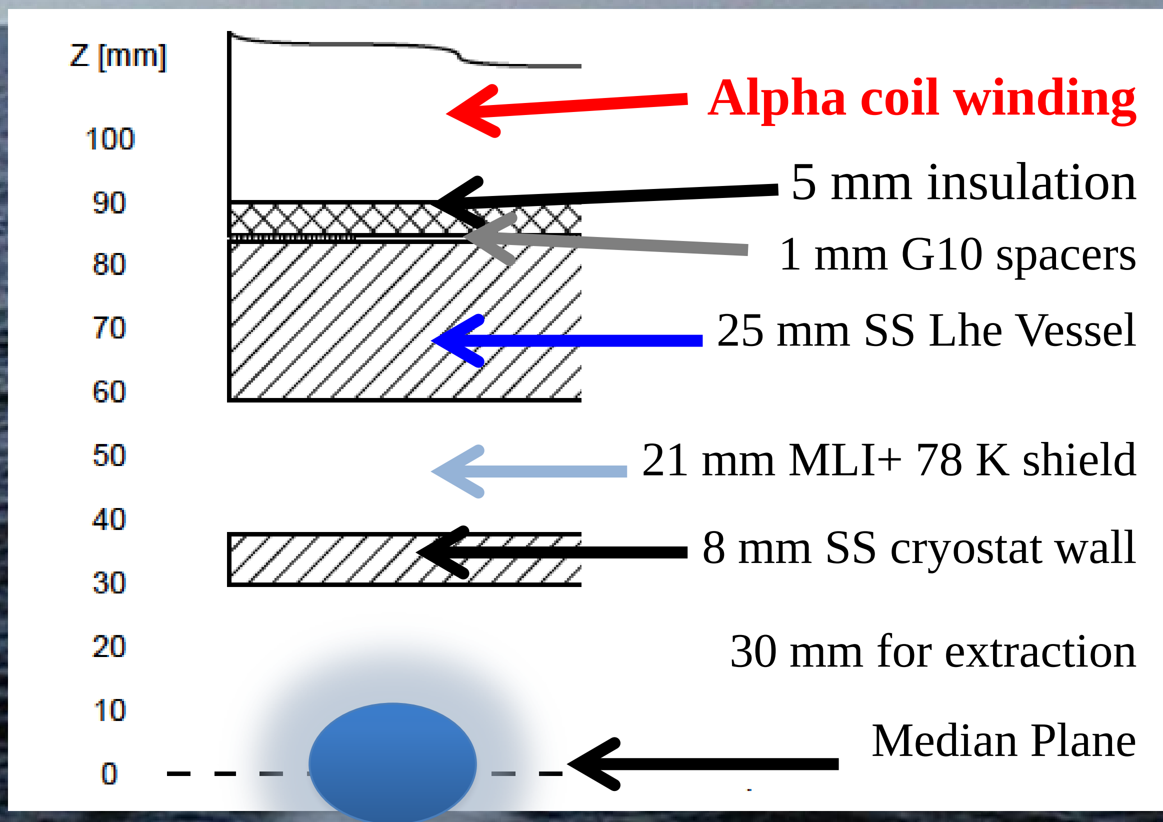
Parameter	Units	alpha-old	beta-old	alpha-new	beta-new
Rmin	m	1.000	1.000	1.027	1.000
Rmax	m	1.168	1.168	1.162	1.147
Zmin	m	0.062	0.434	0.090	0.433
Zmax	m	0.426	0.686	0.385	0.684

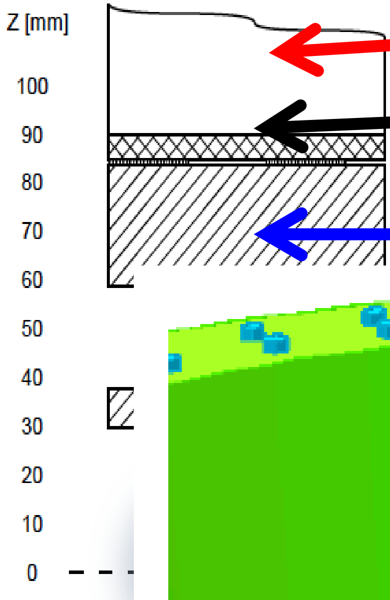
Current density
Old New
35 → 54
[A/mm^2]



Form factors dei vecchi e nuovi coils.

La differenza è al massimo di 0.6 per mille!


Z [mm]
100
90
80
70
60
50
40
30
20
10
0
Alpha coil winding
5 mm insulation
1 mm G10 spacers
25 mm SS Lhe Vessel
21 mm MLI+ 78 K shield
8 mm SS cryostat wall
30 mm for extraction
Median Plane

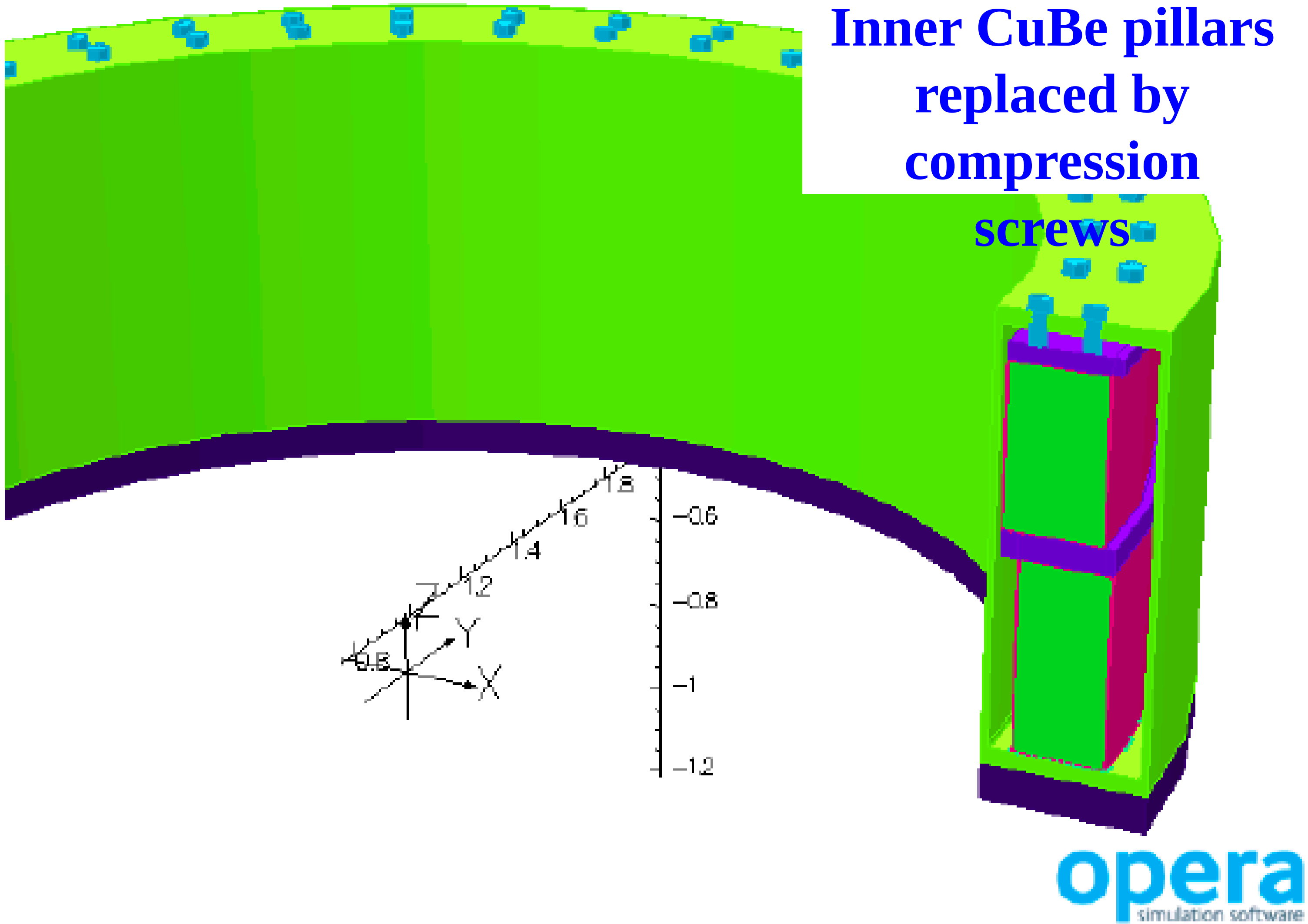


Alpha coil winding

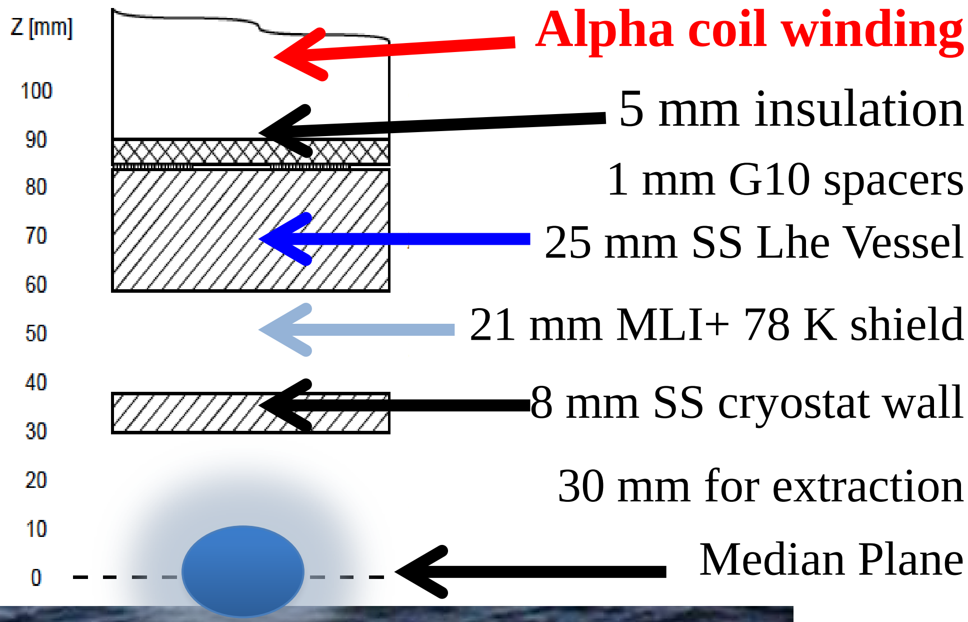
5 mm insulation

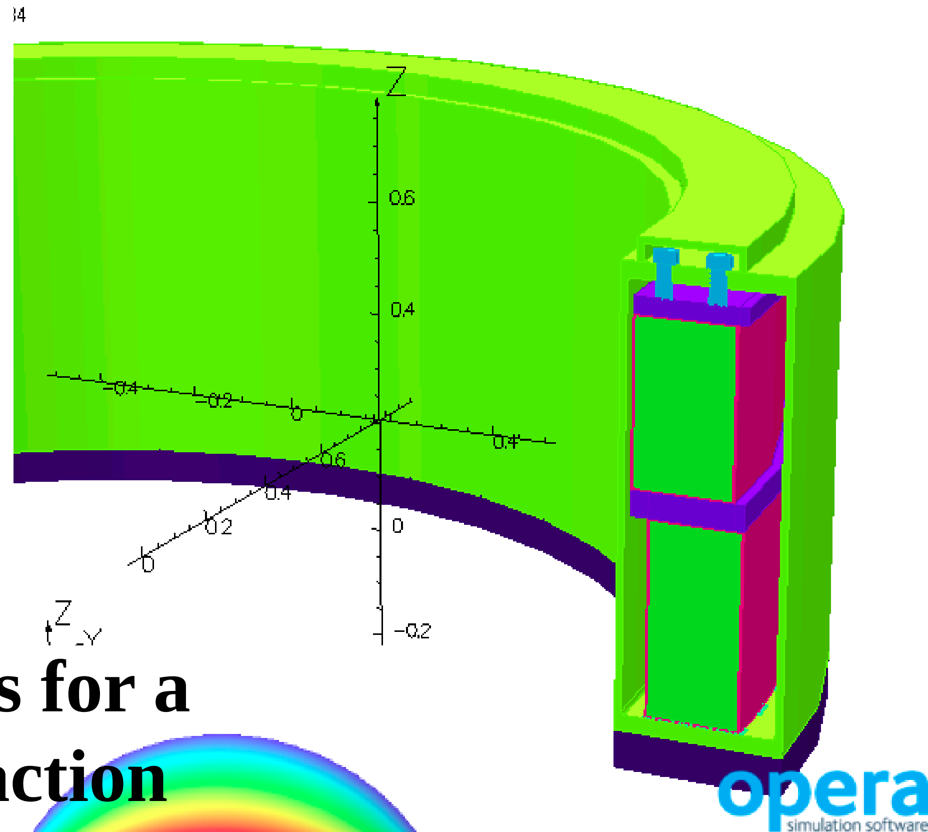
1 mm G10 spacers

25 mm SS Lhe Vessel

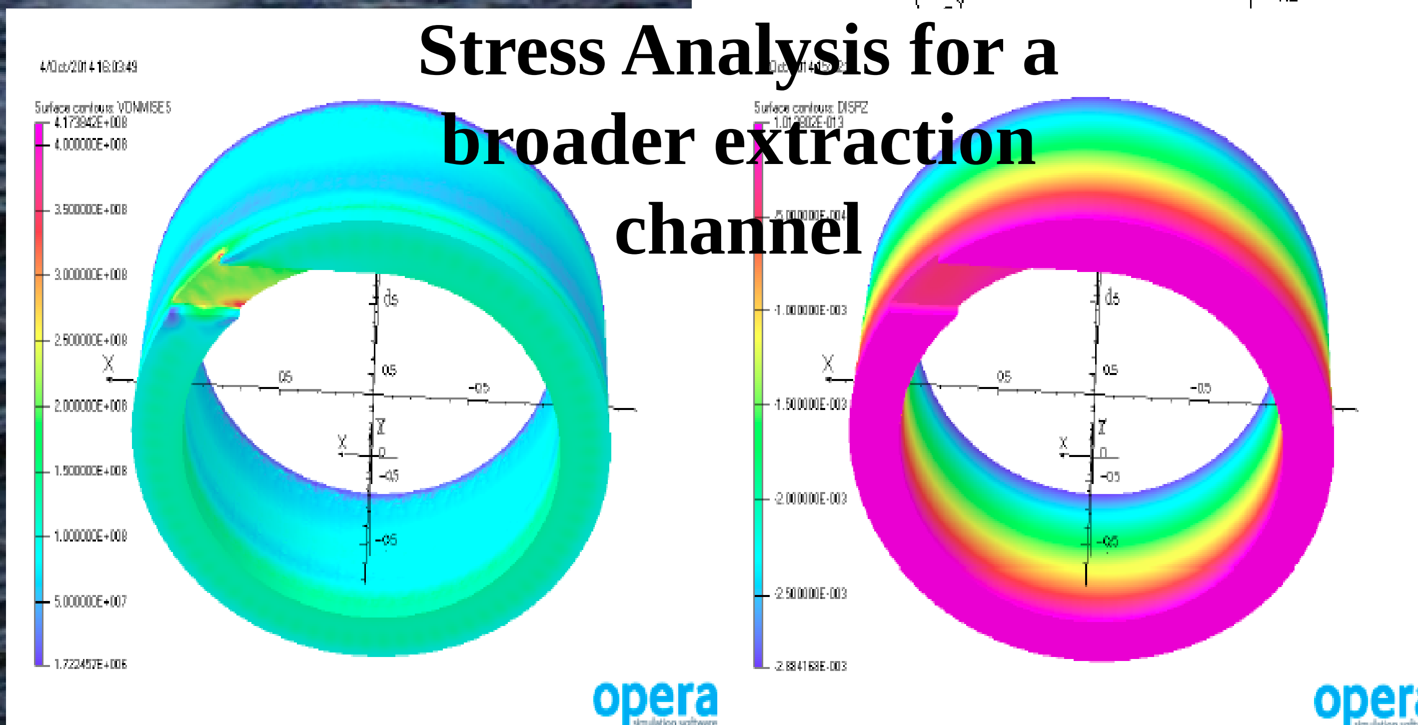


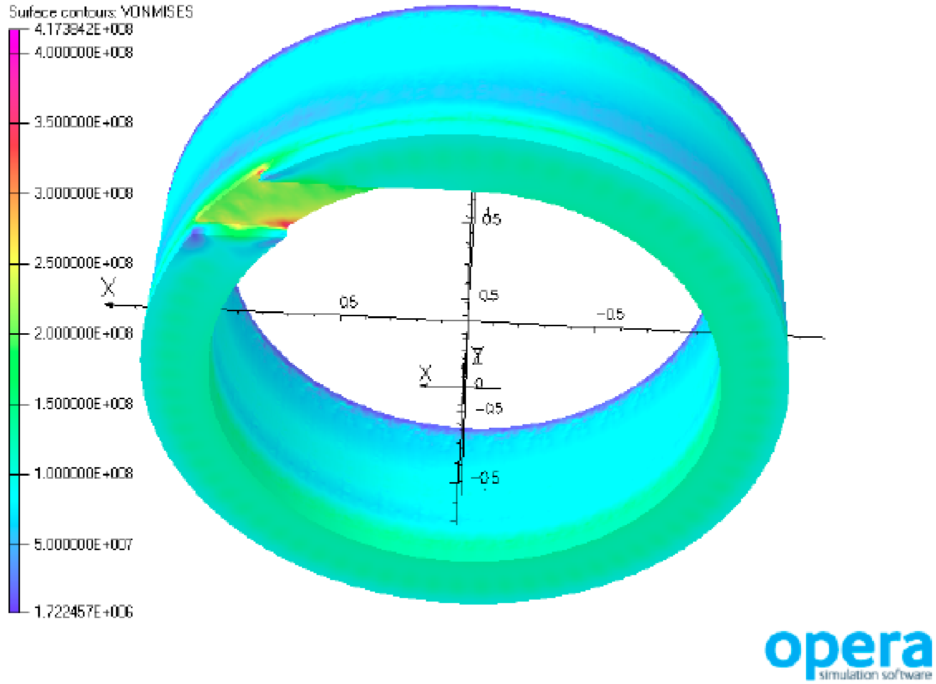
Inner CuBe pillars replaced by compression screws



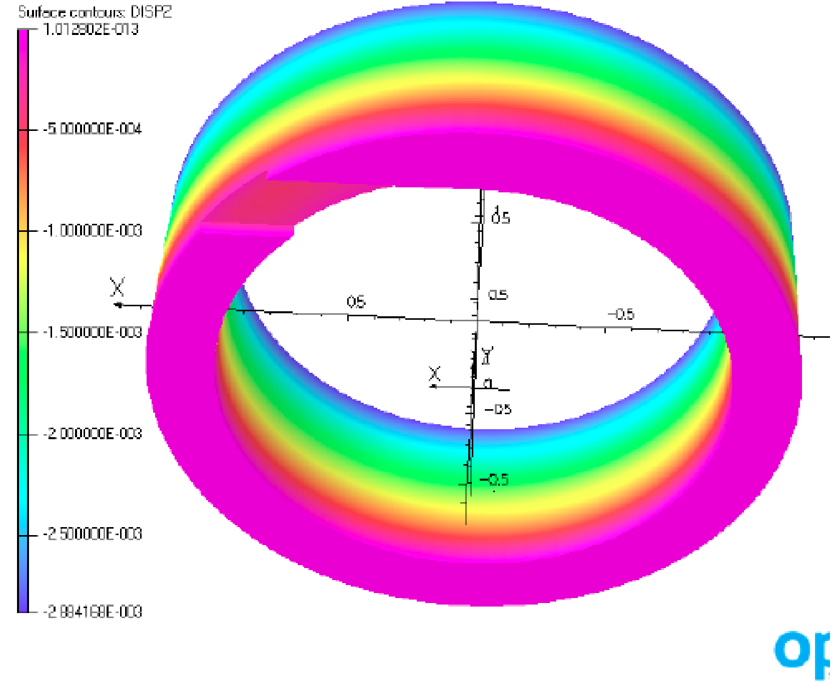


Stress Analysis for a broader extraction channel

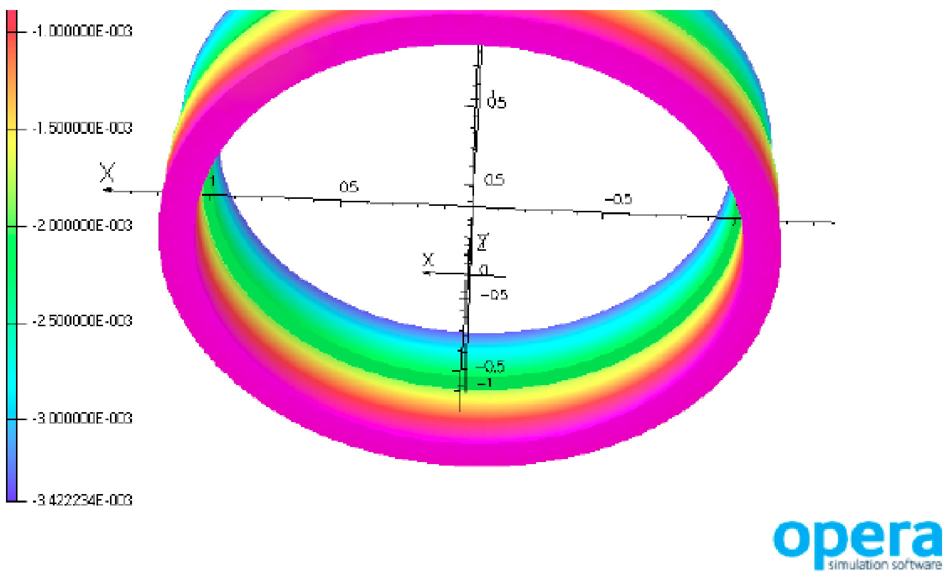




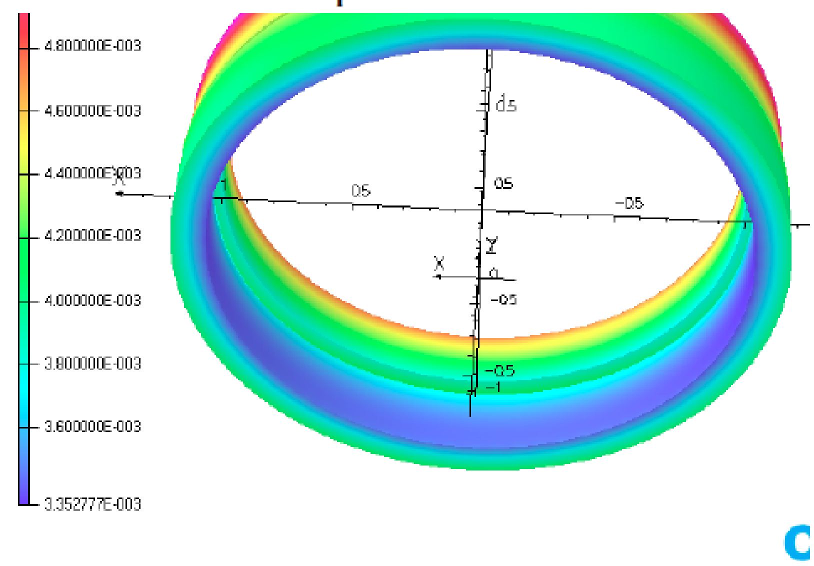
Von Mises Stress around the Cutout



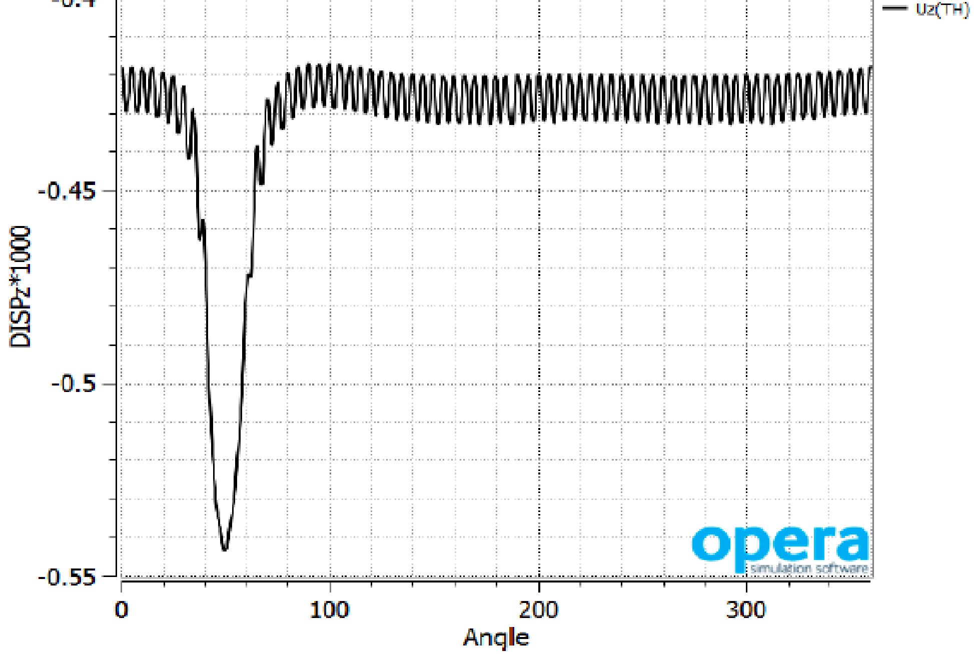
Axial Displacements in the He can



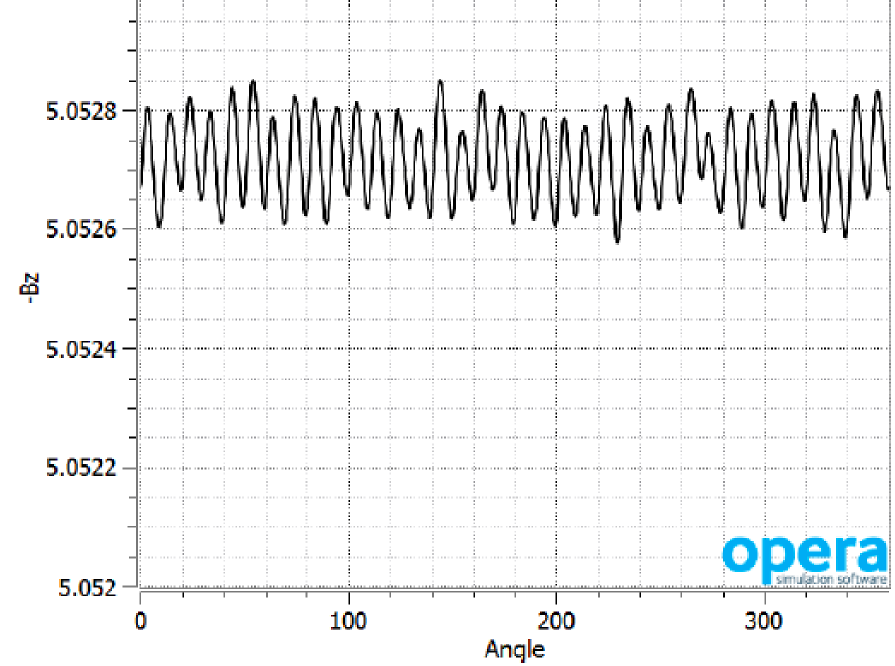
Axial Displacements in the Coils



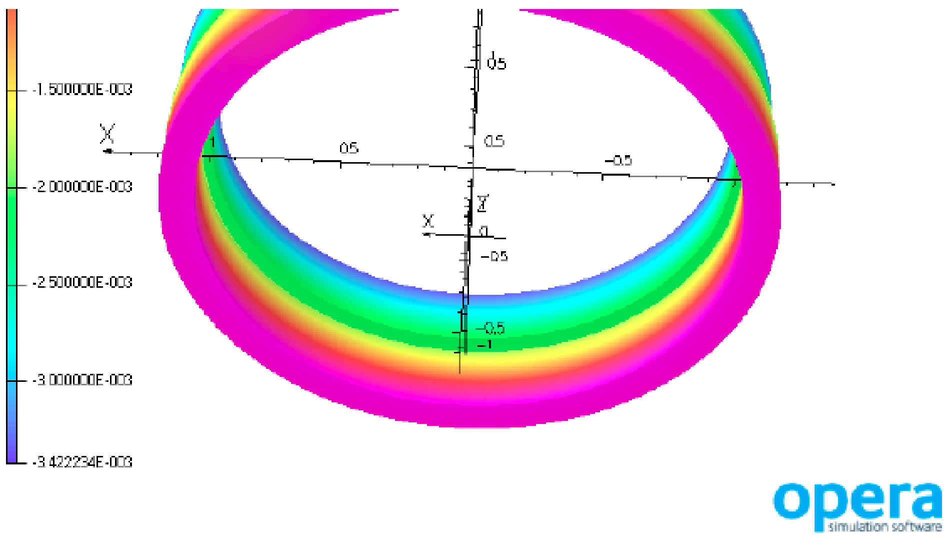
Full Displacements in the Coils



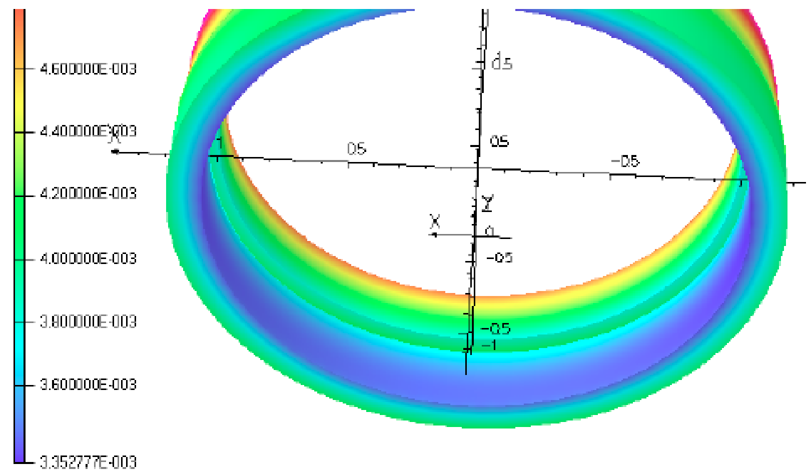
Axial Displacements at the bottom of alpha coil



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

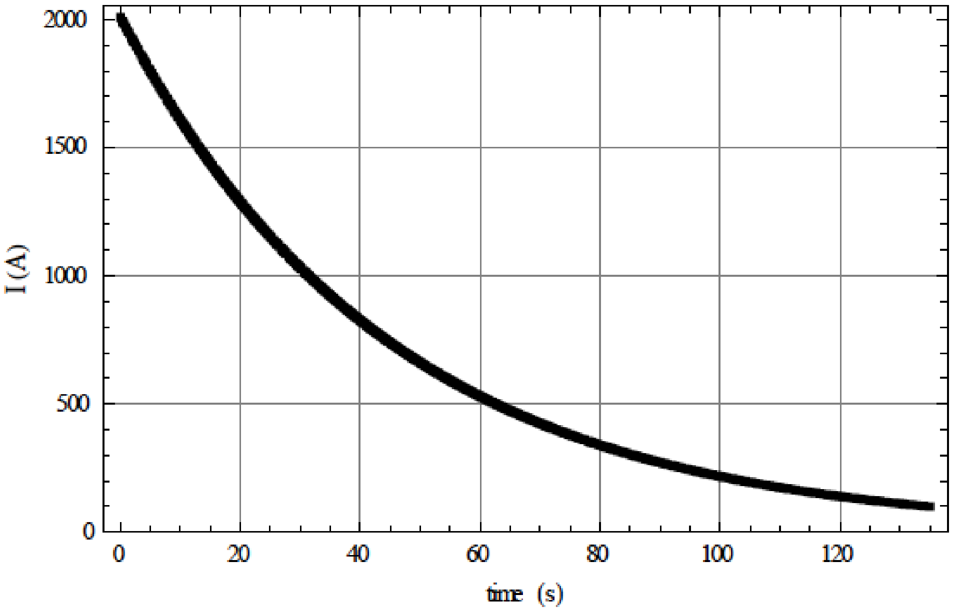


Axial Displacements in the Coils

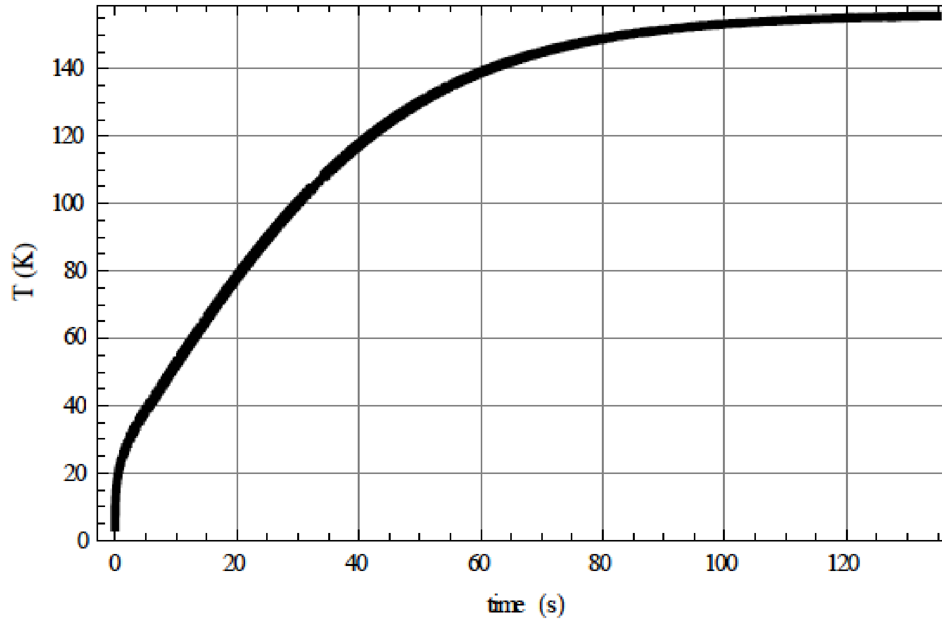


Full Displacements in the Coils

Quench Analysis Assuming a cable feed with 2000 A



Current Decay



Hot Spot Adiabatic Temperature Rise

A study of coil made by a smaller cable powered with about 600 A is in progress and the hot spot should stay below120 K