UPGRADE OF THE LNS SUPERCONDUCTING CYCLOTRON FOR BEAM POWER HIGHER THAN 2-5 KW

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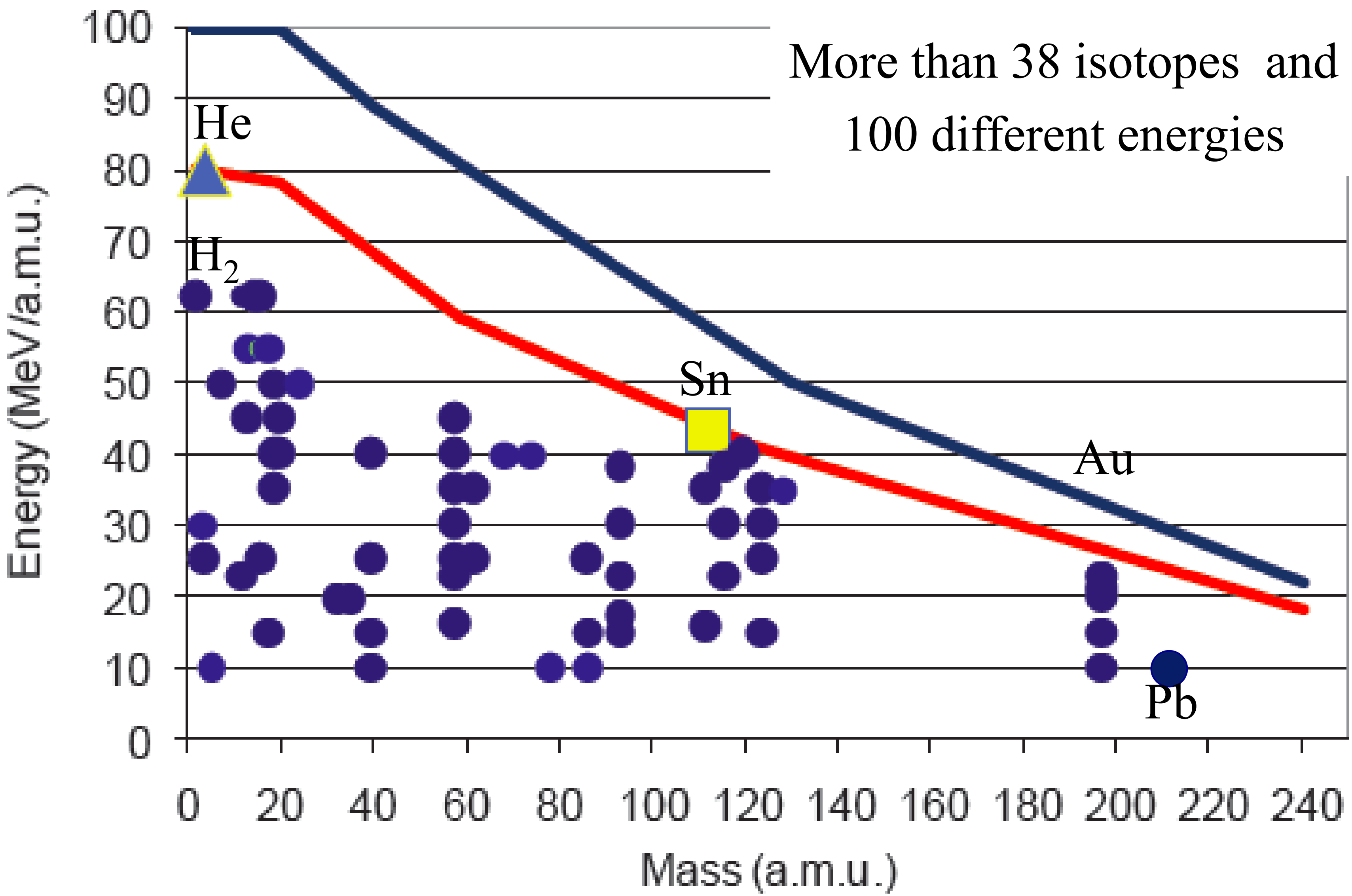
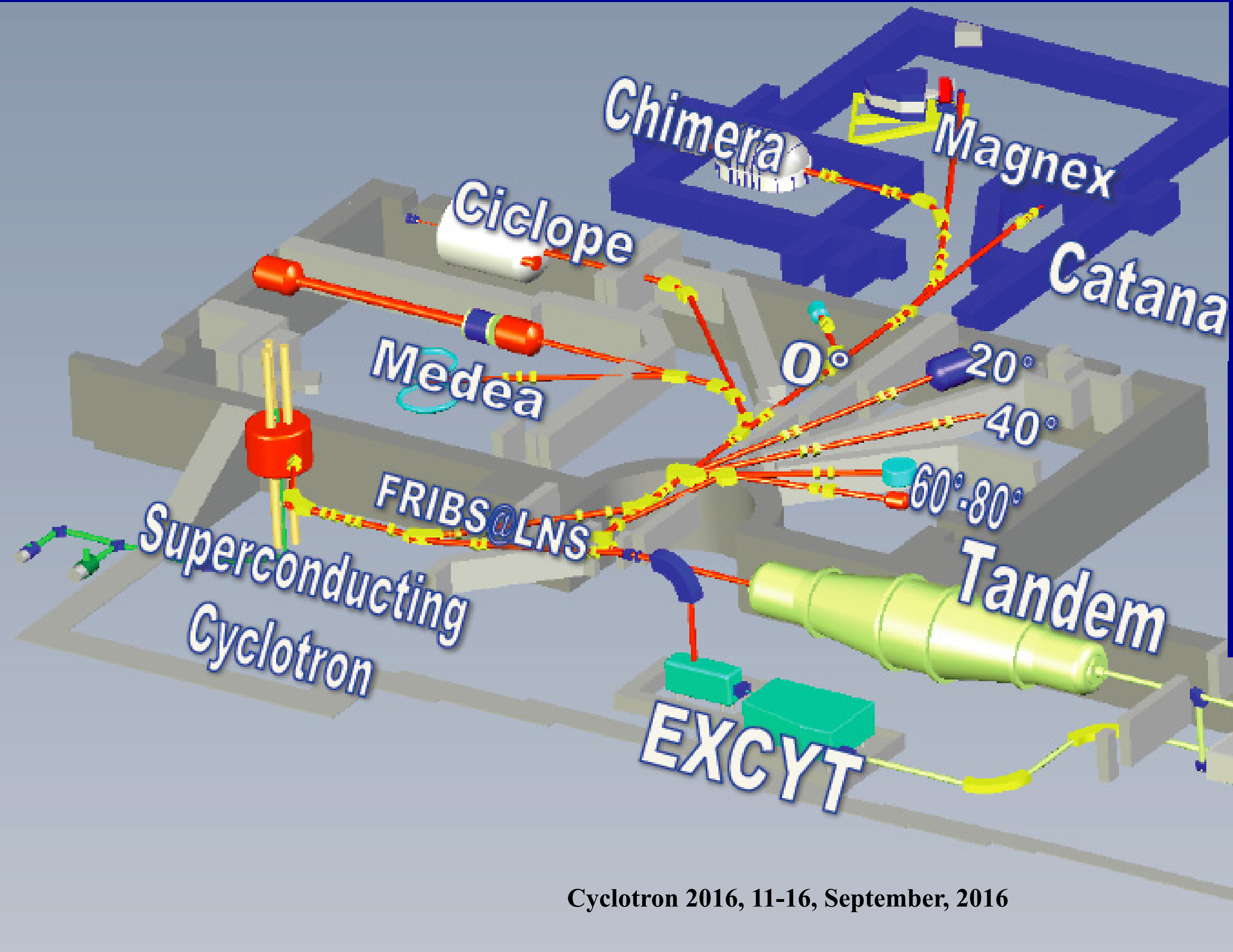
April 1995: 1st Beam delivered by our Cyclotron



Accelerators room and Experimental area of LNS - Catania

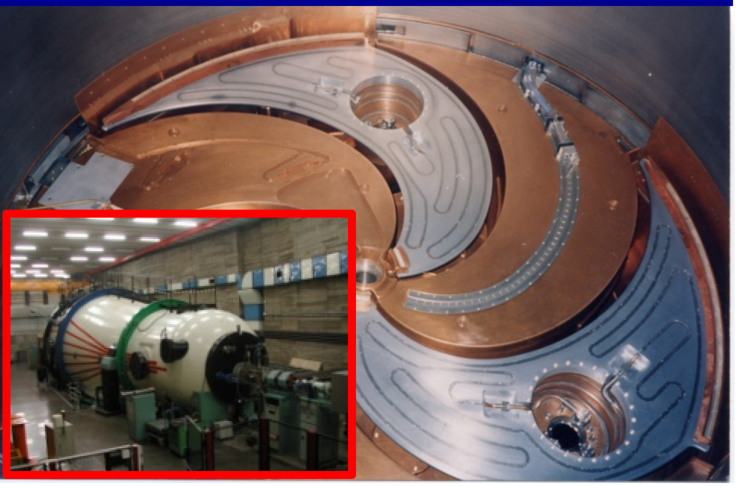


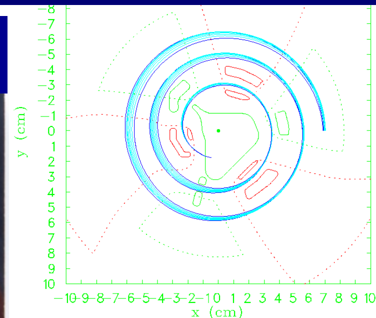
Usual beam current required by experiments <1-10 nA

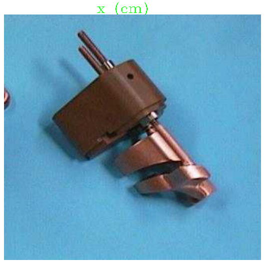
To produce radioactive ion beams power up to 100 W!

Beam current limits of our Cyclotron is mainly due to low extraction efficiency ($\varepsilon \approx 50 \div 60\%$)

1994 – CS as Tandem booster

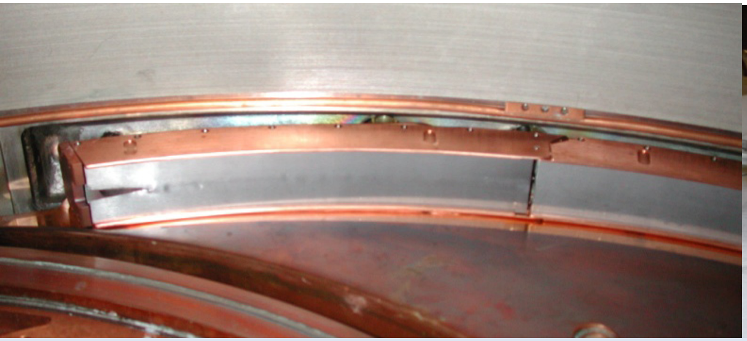


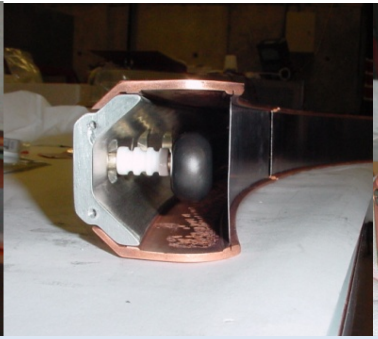




2000 – Stand alone

Separation among the turns at extraction → $\Delta R = R \cdot (\Delta E/E) \cdot (1/\nu_r^2) \cdot \gamma/(\gamma+1)$

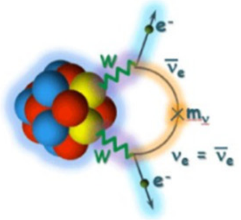




improvements: Septum W made, direct cooling, thickness 0.3 vs. 0.15 mm → Extraction efficiency 63% vs. 50%

$^{13}C^{4+}$ @ 45 AMeV
Pextr = 150 watt
I=1020 enA
= 1.5×10^{12} pps

The NUMEN project at INFN-LNS



$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Effective neutrino **mass**

Phase space factor

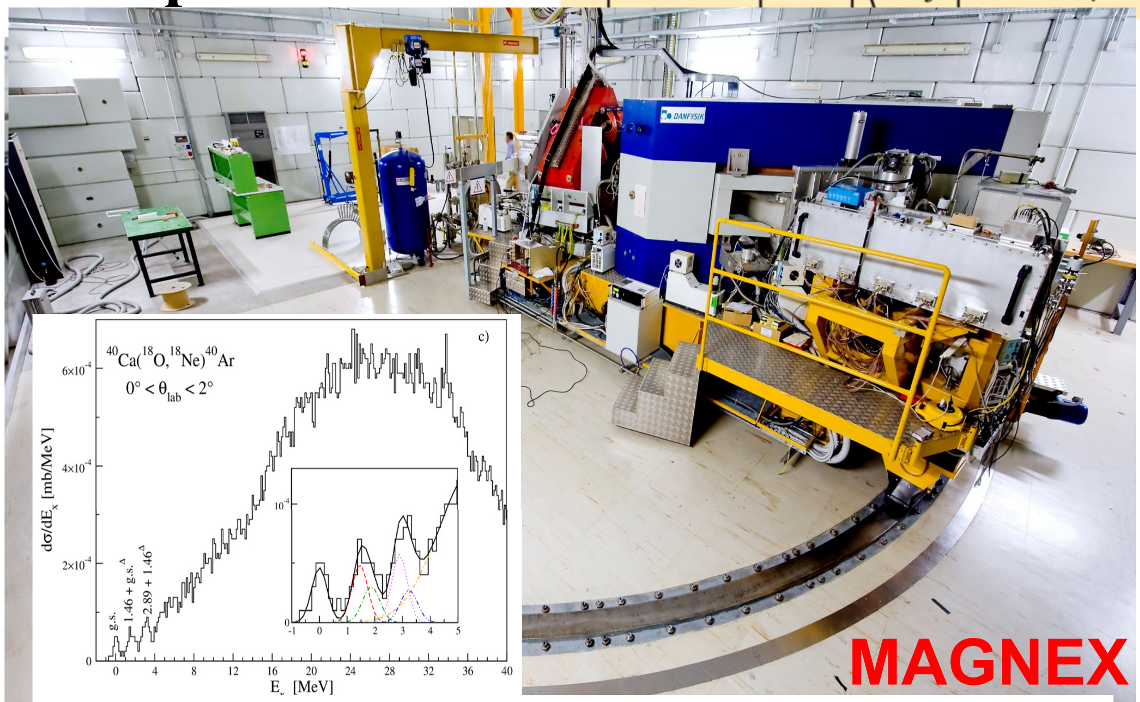
0νββ decay half-life measurement Experiment

Nuclear Matrix Element (NME)

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

Transition probability of a **nuclear** process

Nuclear physics plays a key role!



F. Cappuzzello et al., Eur. Phys. J. A (2015) 51:145

THE IDEA:
Use of Nuclear reactions, **Double Charge Exchange reactions (DCE),** to stimulate in the laboratory the same nuclear transition occurring in 0νββ

Power needed–> P ≈ kWatt

Ion & energies of interest for the NUMEN experiment are: Carbon, Oxygen and Neon

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

Carbon	E = 15 MeV/u	F(6) = 0.99917
	E = 20MeV/u	F(6) = 0.99968
Oxigen	E=15 MeV/u	F(8) = 0.9969
	E= 20 MeV/u	F(8) = 0.9987
	E = 30 MeV/u	F(8) = 0.99963
Neon	E = 15 MeV/u	F(10) = 0.9911
	E =20MeV/u	F(10) = 0.9967
	E = 30 MeV/u	F(10) = 0.9991

For light ions at these energies the percentage of stripping efficiency at q=Z is higher than >99%

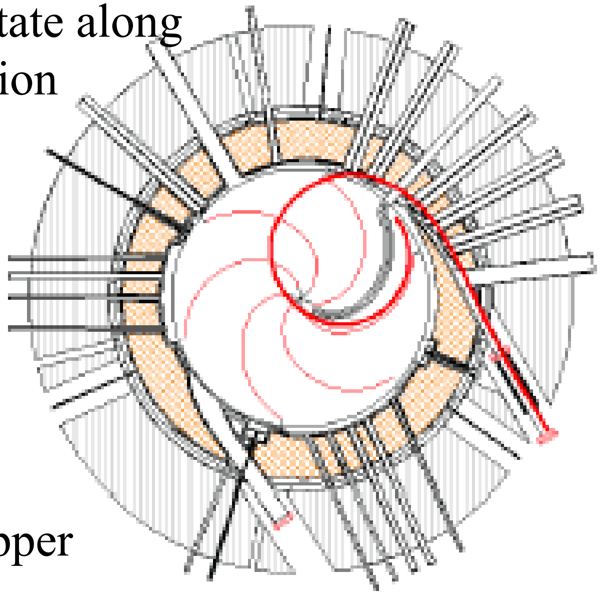
If we use the stripping extraction the expected extraction efficiency is 99%

Feasible Beam Power

Ion	Energy	Isource	Iacc	Iextr	Iextr	Pextr
	MeV/u	eμA	eμA	eμA	pps	watt
^{12}C q=4+	18	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	3240
^{12}C q=5+	30	200	30 (4+)	45 (6+)	$4.7 \cdot 10^{13}$	2700
^{12}C q=4+	45	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	8100
^{12}C q=4+	60	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	10800
^{18}O q=6+	20	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	3600
^{18}O q=6+	29	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	5220
^{18}O q=6+	45	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	8100
^{18}O q=6+	60	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	10800
^{18}O q=7+	70	200	30 (7+)	34.3 (8+)	$2.7 \cdot 10^{13}$	5400
^{20}Ne q=4+	15	600	90 (4+)	223 (10+)	$1.4 \cdot 10^{14}$	6690
^{20}Ne q=7+	28	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	4800
^{20}Ne q=7+	70	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	10280
^{40}Ar q=14+	60	400	60 (14+)	77.1 (18+)	$2.7 \cdot 10^{13}$	10280

Stripping extraction allow to achieve high efficiency > 99%

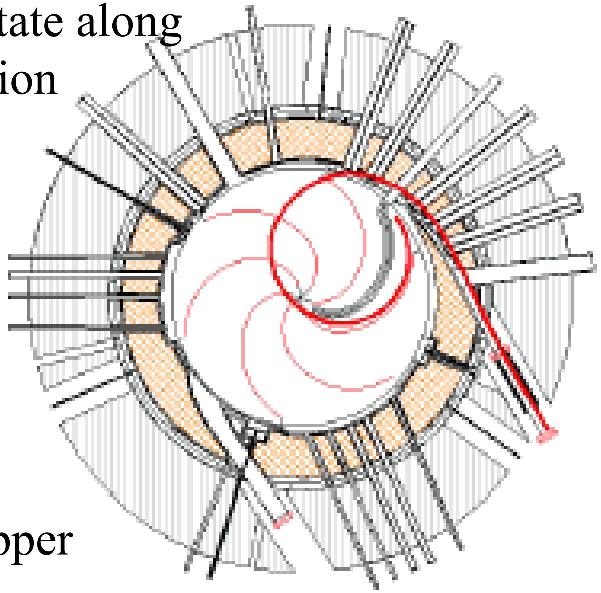
Charge state along acceleration
q=Z-2



after stripper
q=Z

Stripping extraction consists to increase the charge states of the accelerated beam of 1, 2 or more units crossing through a thin stripper foil. Then the beam magnetic rigidity is suddenly reduced and the beam trajectory escape the cyclotron pole region!

Stripping extraction allow to achieve high efficiency > 99%



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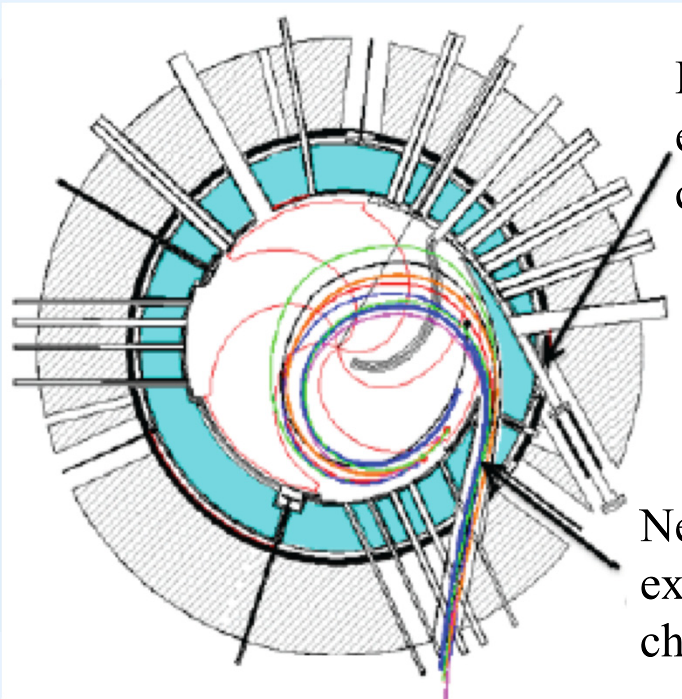
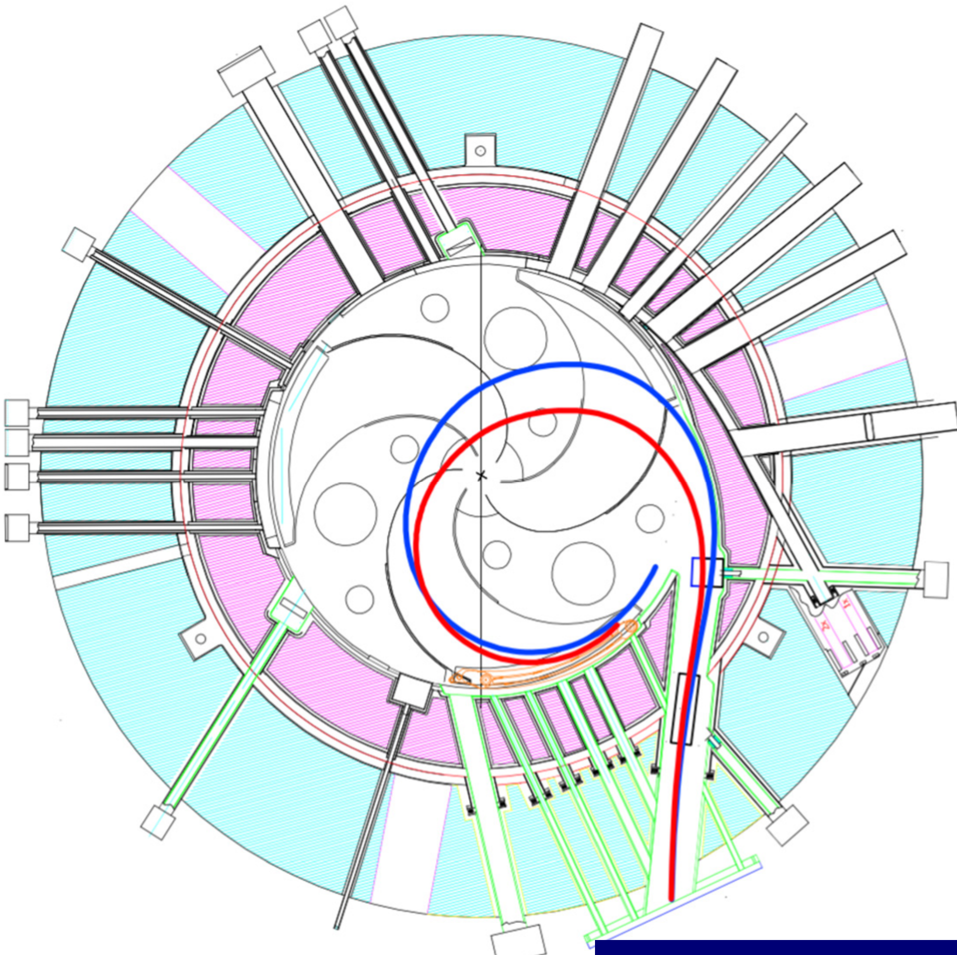
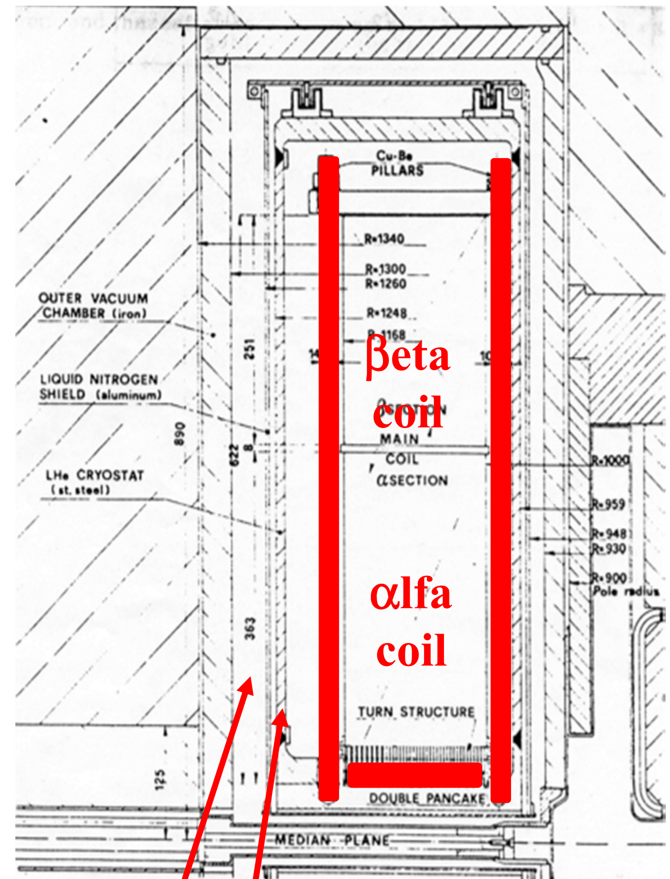


Unfortunately the beam dynamic simulations shown that only for few cases is possible to match the extraction trajectories produced by stripper with the existing extraction channel. Moreover, in these cases the beams sizes are a bit too large!
Better solution is to use a new one extraction channel with higher vertical gap!

Required changes to the cryostat and magnet of LNS cyclotron

- To Drill a new channel with a vertical gap=60 mm
- Increase the vertical gap of the acceleration chamber 24 →30 mm!





Nitrogen Shield

LHe Vessel

A conceptual design study has been proposed in collaboration with the PSFC of MIT

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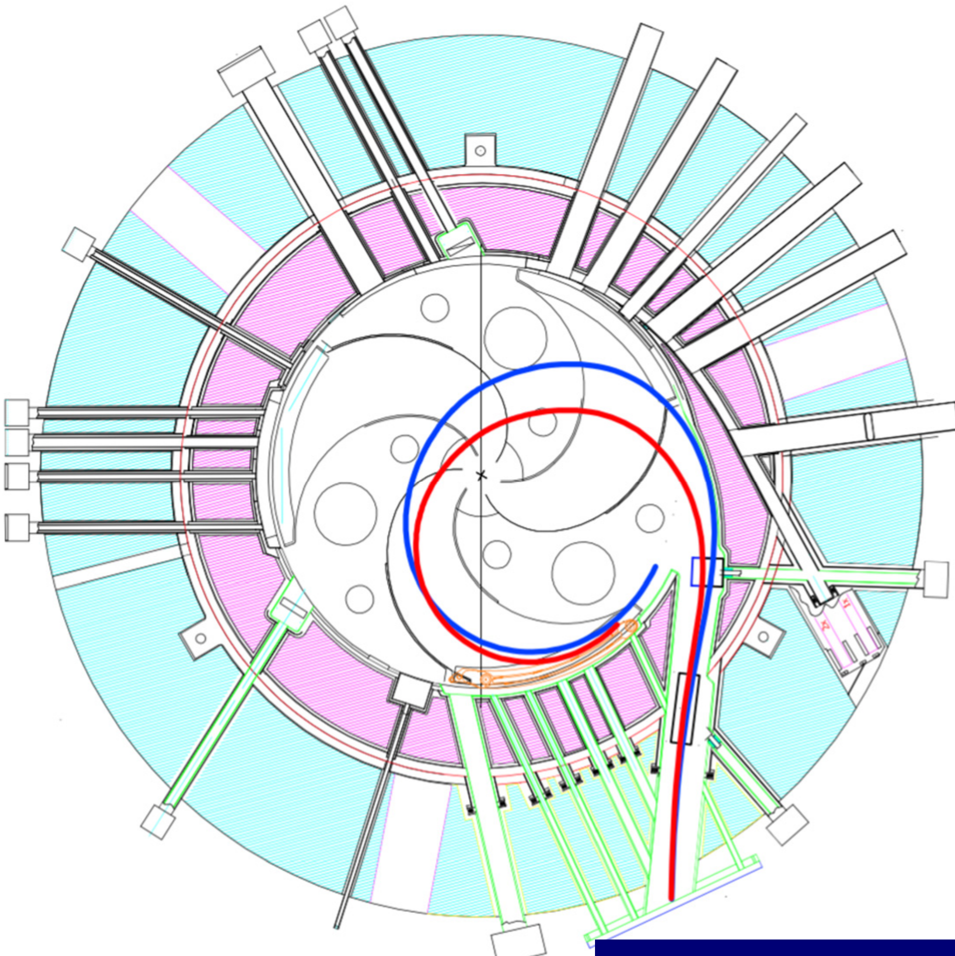
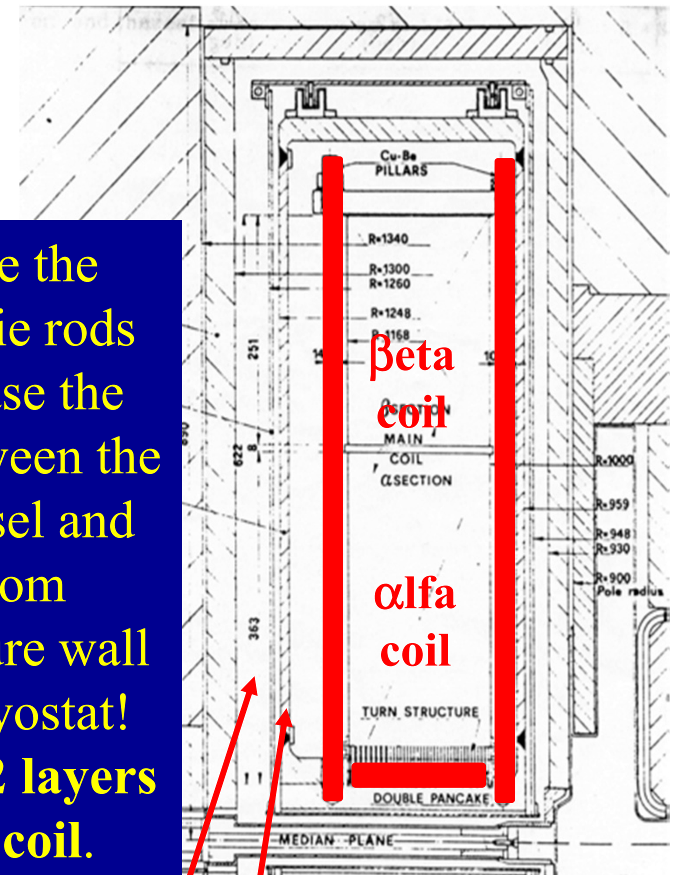


Remove the vertical tie rods to increase the room between the LHe vessel and the room temperature wall of the cryostat!
Remove 2 layers of alfa coil.



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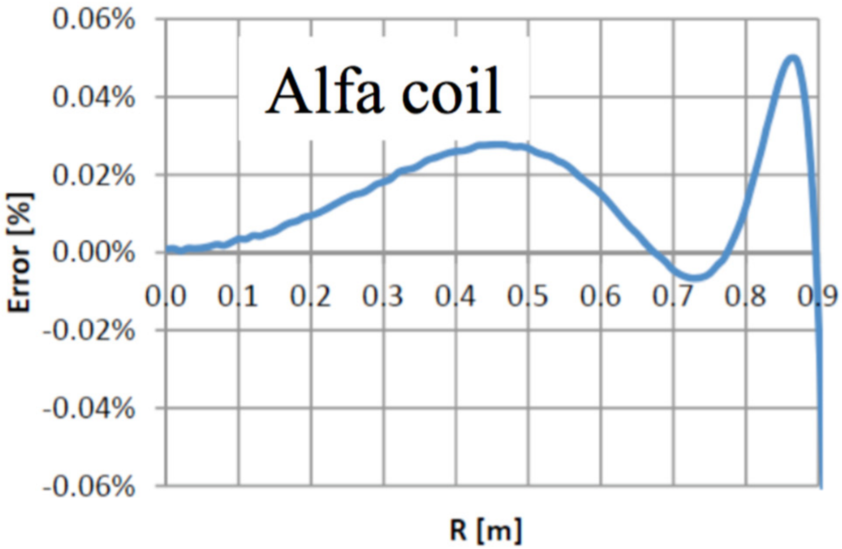
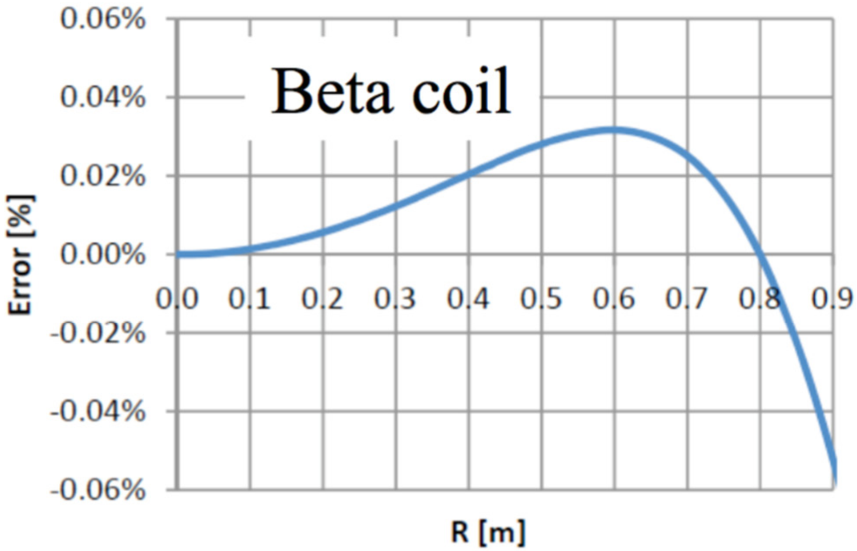
Parameter	Units	alpha-old	beta-old	alpha-new	beta-new
Rmin	m	1.000	1.000	1.027	1.000
Rmax	m	1.168	1.168	1.162	1.147
Zmin	m	0.062	0.434	0.090	0.433
Zmax	m	0.426	0.686	0.385	0.684
Mode A					
j	A/m2	3.5000E+07	3.5000E+07	5.3826E+07	3.9943E+07
NI	MA-t	2.14	1.48	2.14	1.47
w/o Iron					
B(R=Z=0)	T	2.2836	1.2044	2.2836	1.2044
Bmax	T	4.87	4.76	5.37	4.81
(RBJ)max	MPa	170.3	166.7	296.7	191.9
Sh (smeared)	MPa			85.8	62.8
Fz	MN	-21.24		-21.43	
E	MJ	46.90		48.27	
with Iron					
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

Different solution for the new superconducting coils have been evaluated. Anyway the final magnetic field produced by the superconducting coils must have form factors very near to the originals, the differences must stay below 0.1%!

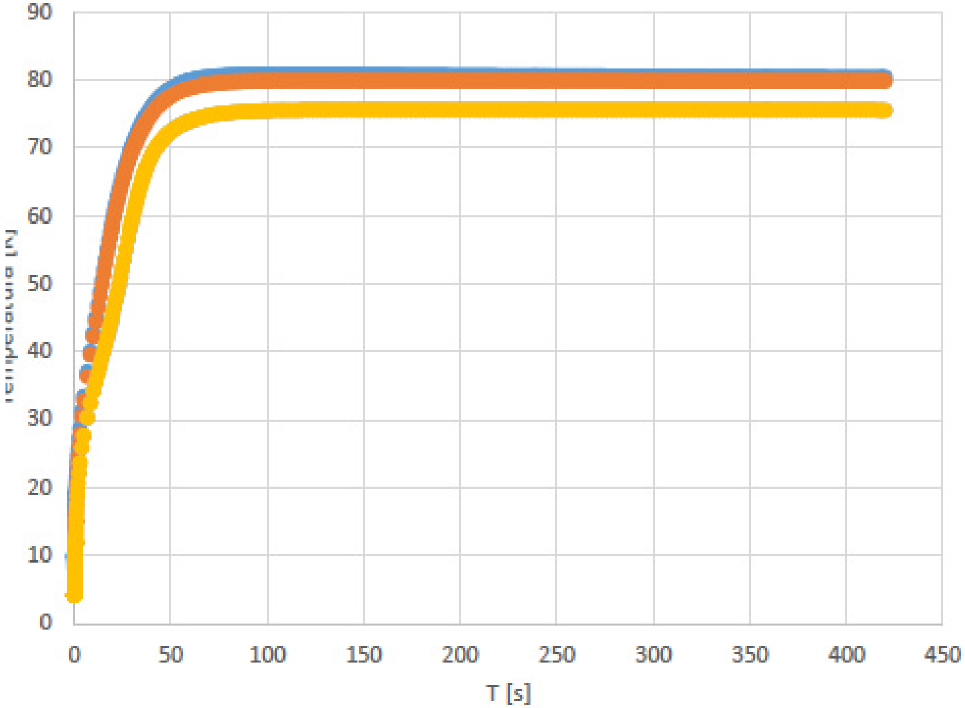
Form factors of alfa and beta coils almost unchanged!

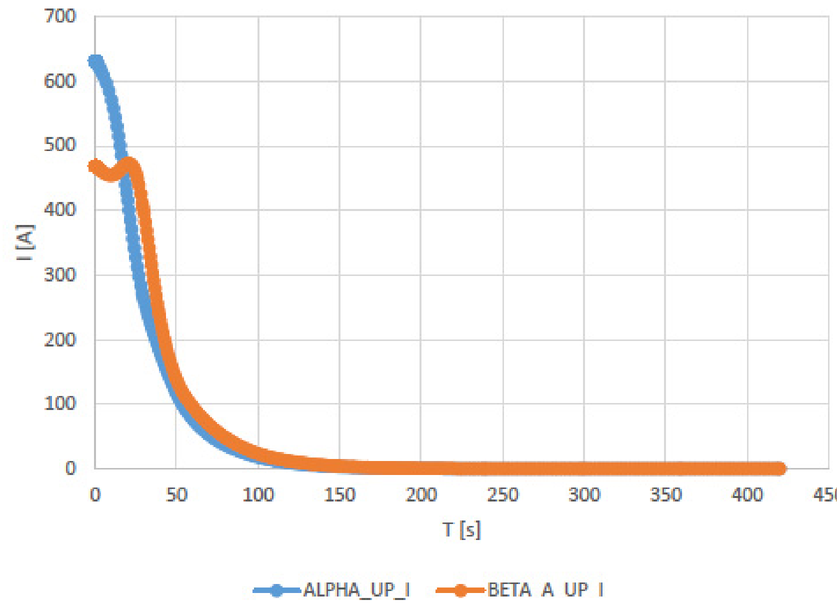




Percentage difference between the new alfa and beta coils form factors vs. the form factor of the existing coils

Here a solution with a commercial cable feed with maximum current of 670 A Coils is shown.
The coils are epoxy impregnated and maximum temperature of the coils in case of quench should stay below 85 K!



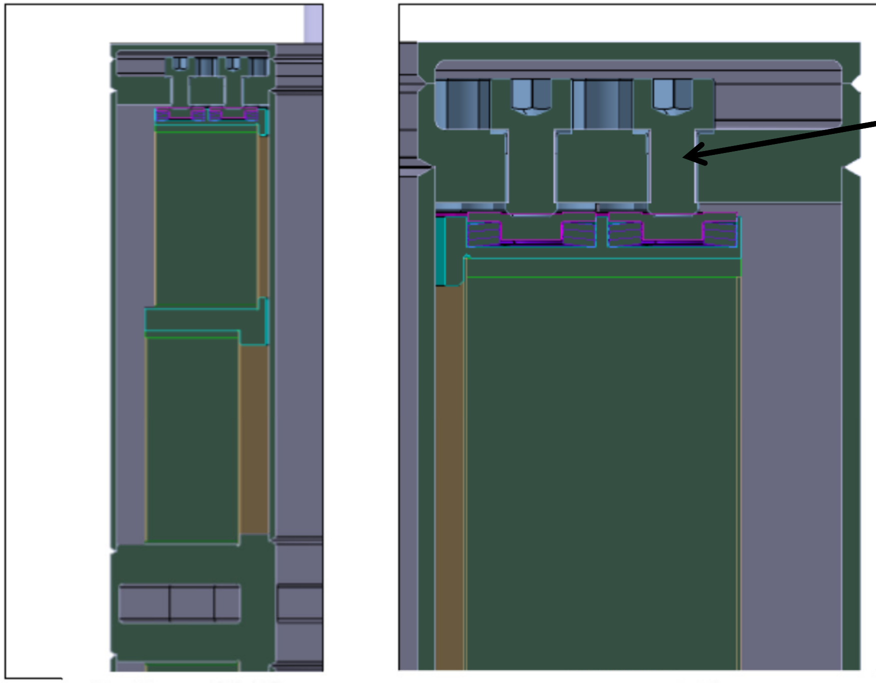


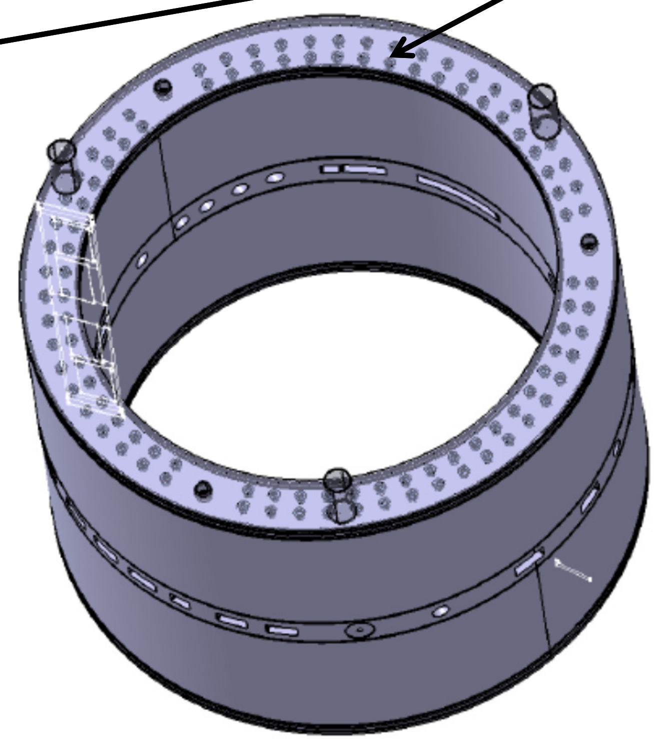
Courtesy of ASG

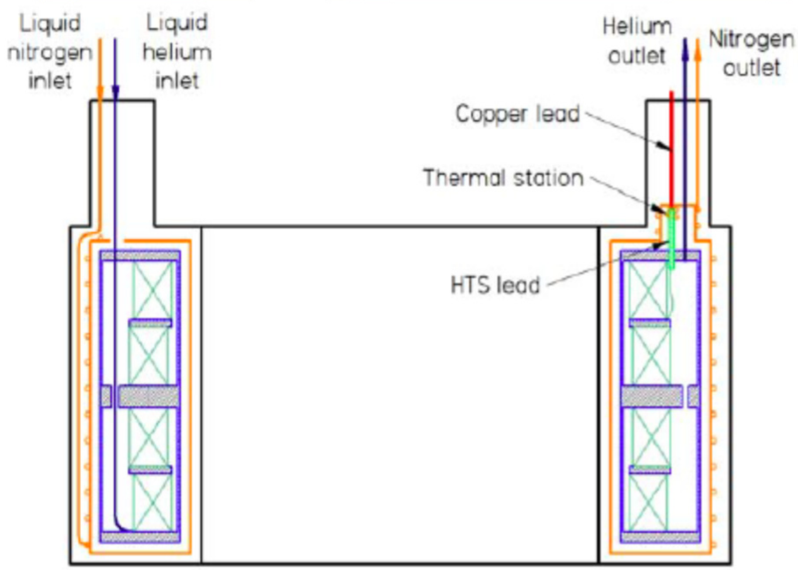
The use of a small cable need to use a much longer cable. The inductance is higher and this increase the rump-up time, 1.5 hour! The use of a cable able to be feed with 2000 A is more similar to the present solution but cable cost is higher!

Preliminary details of the new cryostat

Preloading springs, that will replace the BeCu tie rods







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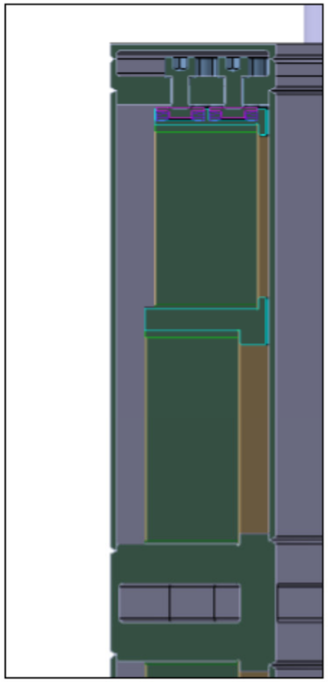
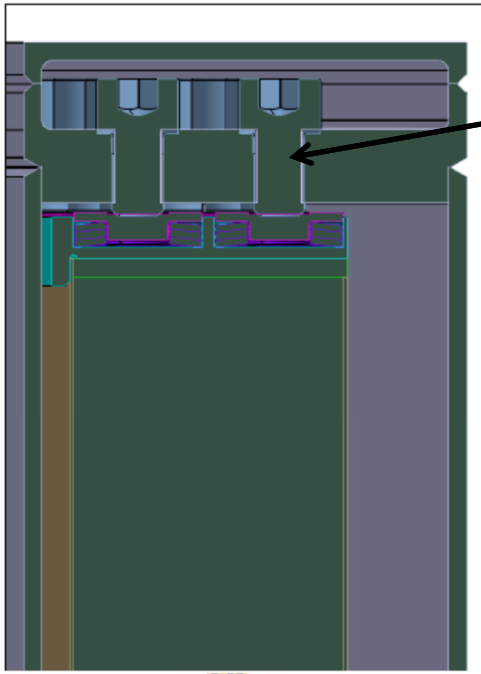
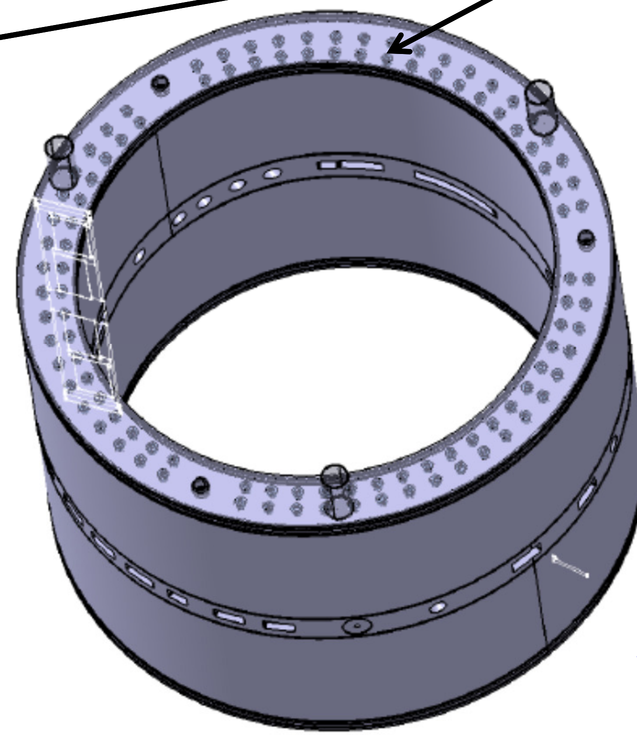
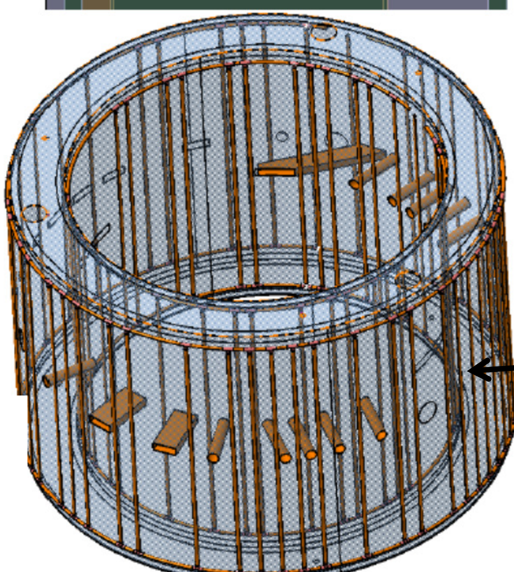






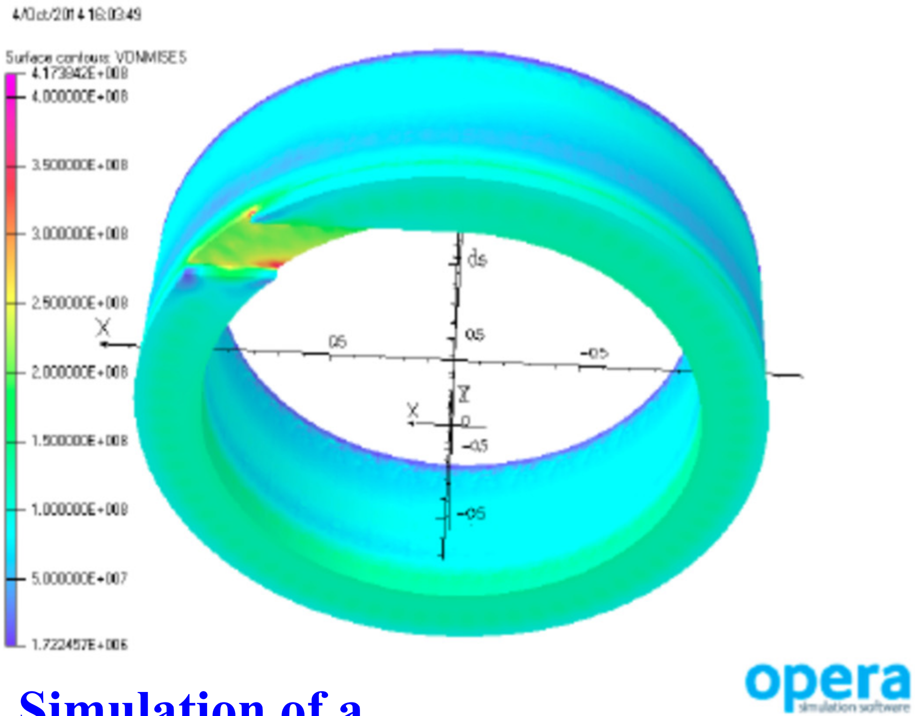
The existing 3 Liquid Nitrogen shields have problems. The internal shield is closed and the outer shield one time per year has to be closed to allow to recover the vacuum in the cryostat.

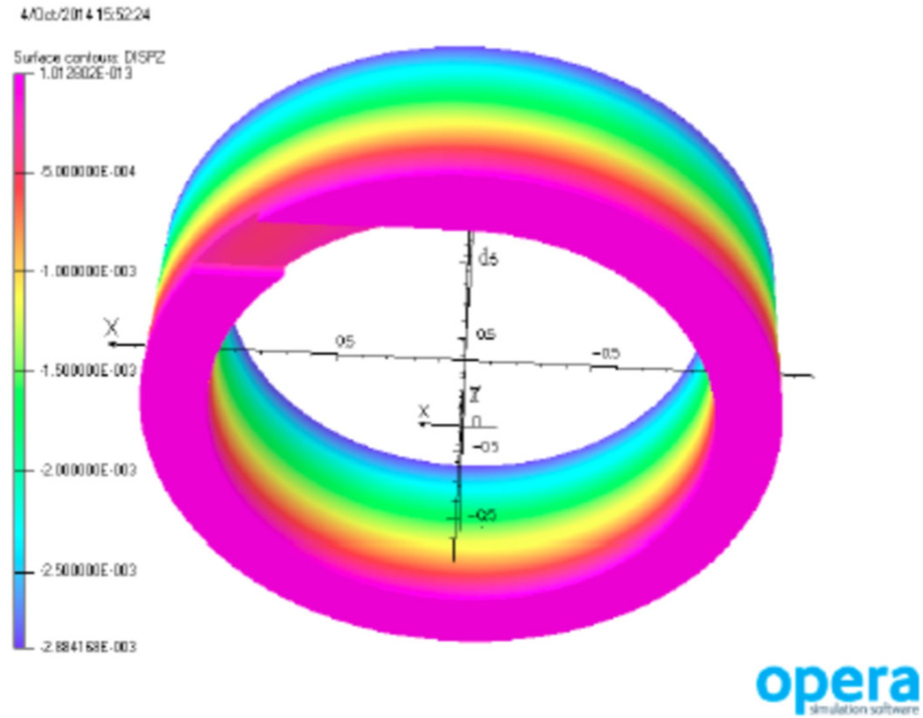


A much more robust Liquid Nitrogen shield flow with natural convection to replace the forced flow

Courtesy of ASG

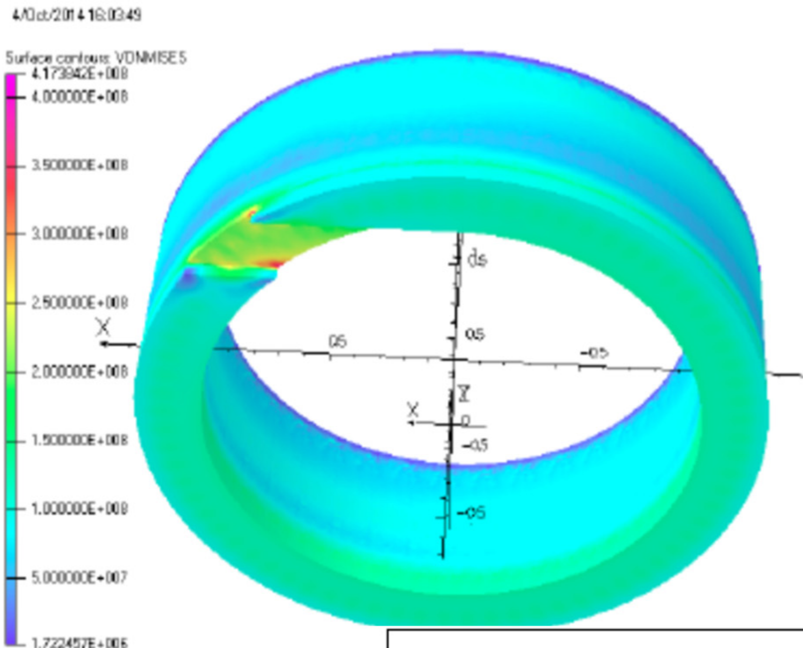
Von Mises stress and axial deformation of Helium Vessel

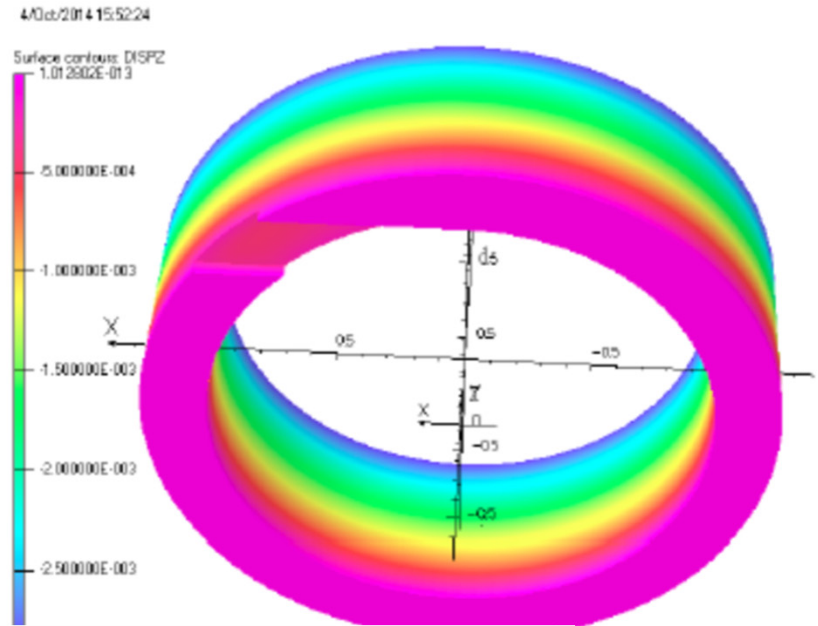




Simulation of a 118 x 260 mm hole drilled through. For the extraction channel being 60 mm gap and 200 mm width.

Von Mises stress and axial deformation of Helium Vessel





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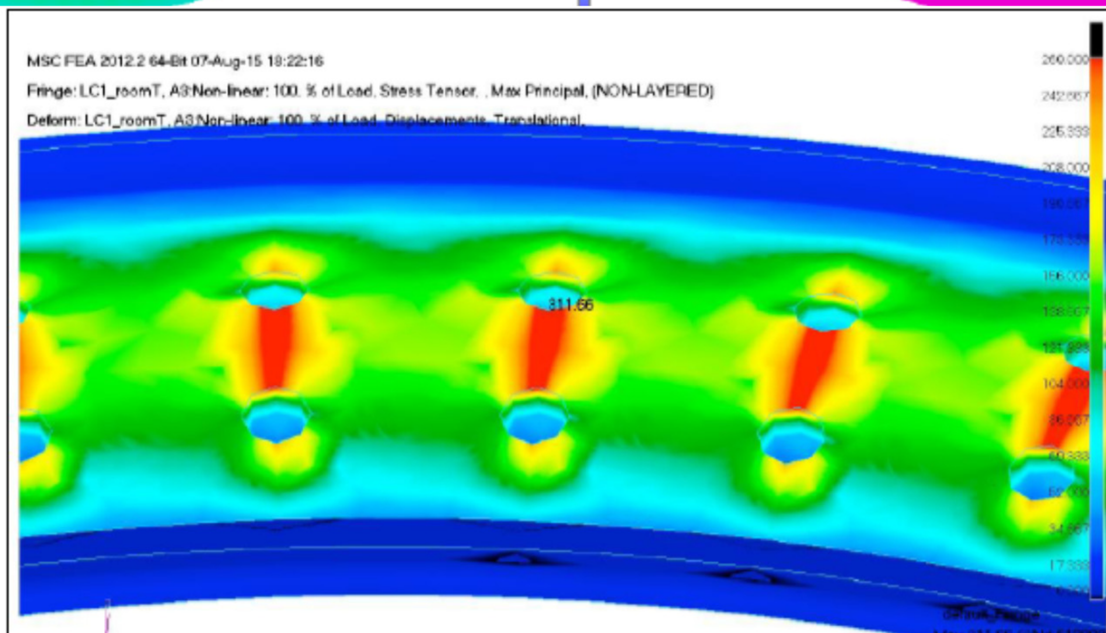
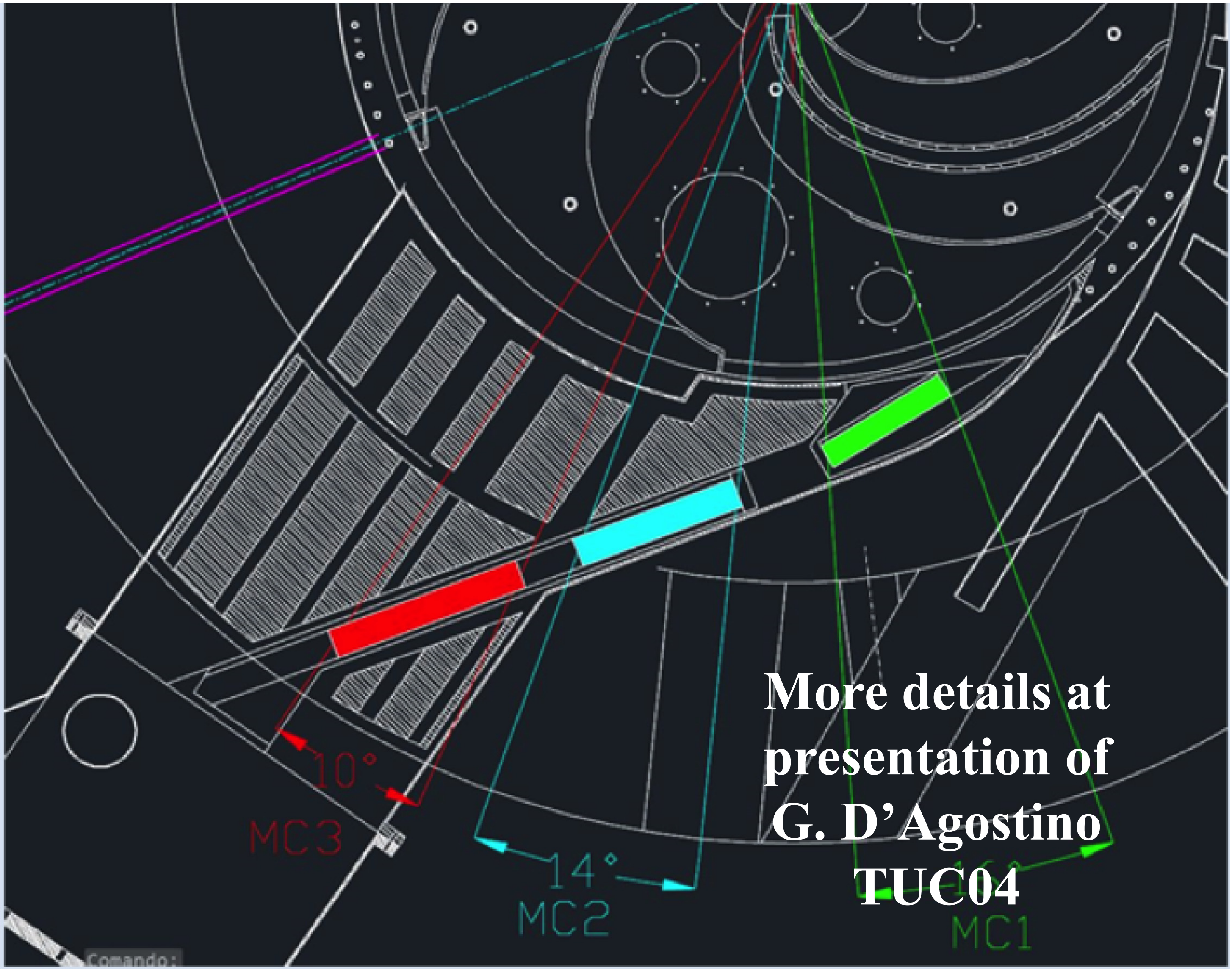


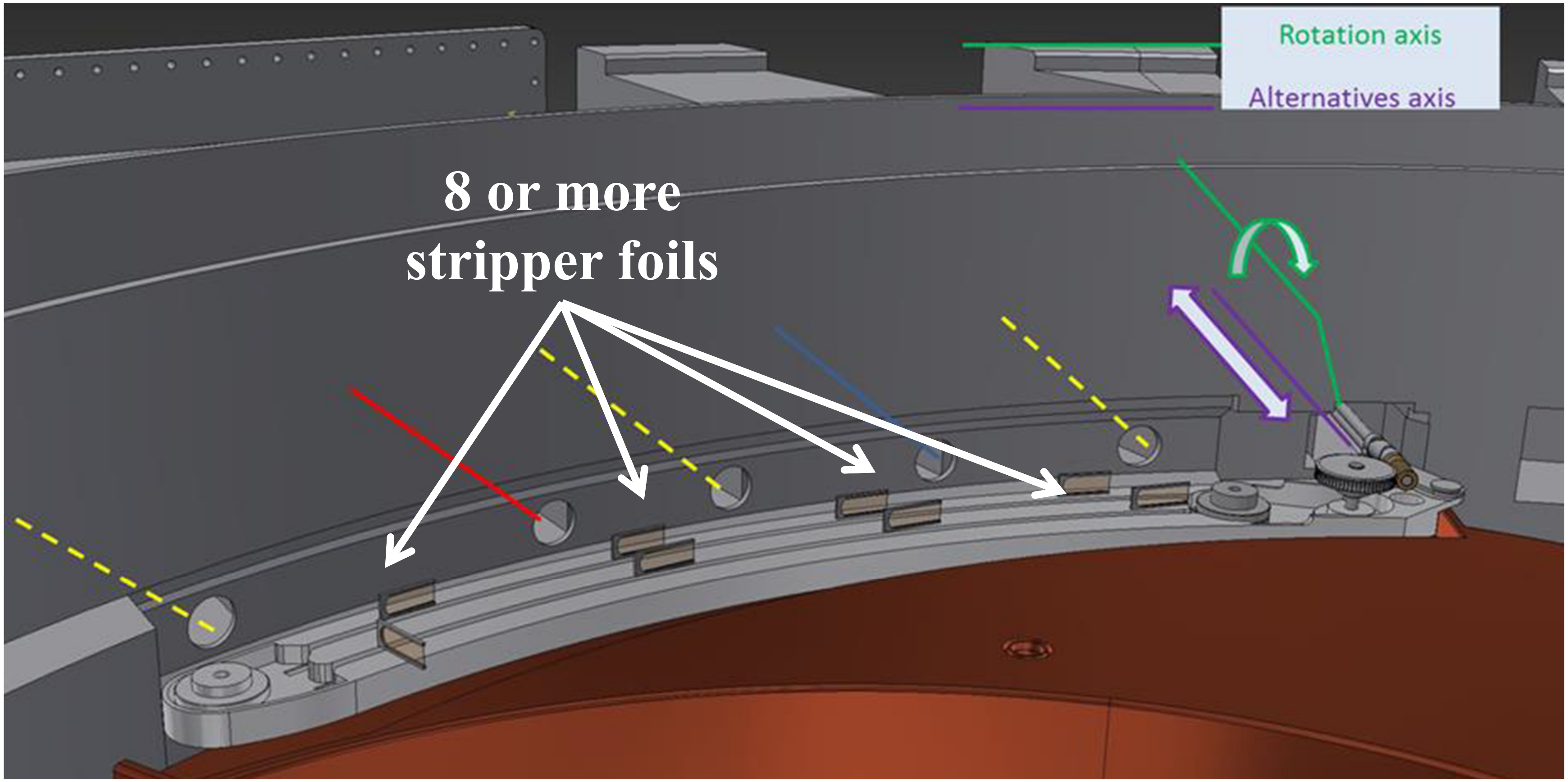
Stress analysis on the Lhe Vessel. Particular of the compression flange, top side.

Preliminary layout of the New Extraction channel and of the three Magnetic channels, final solution with only 2 channels



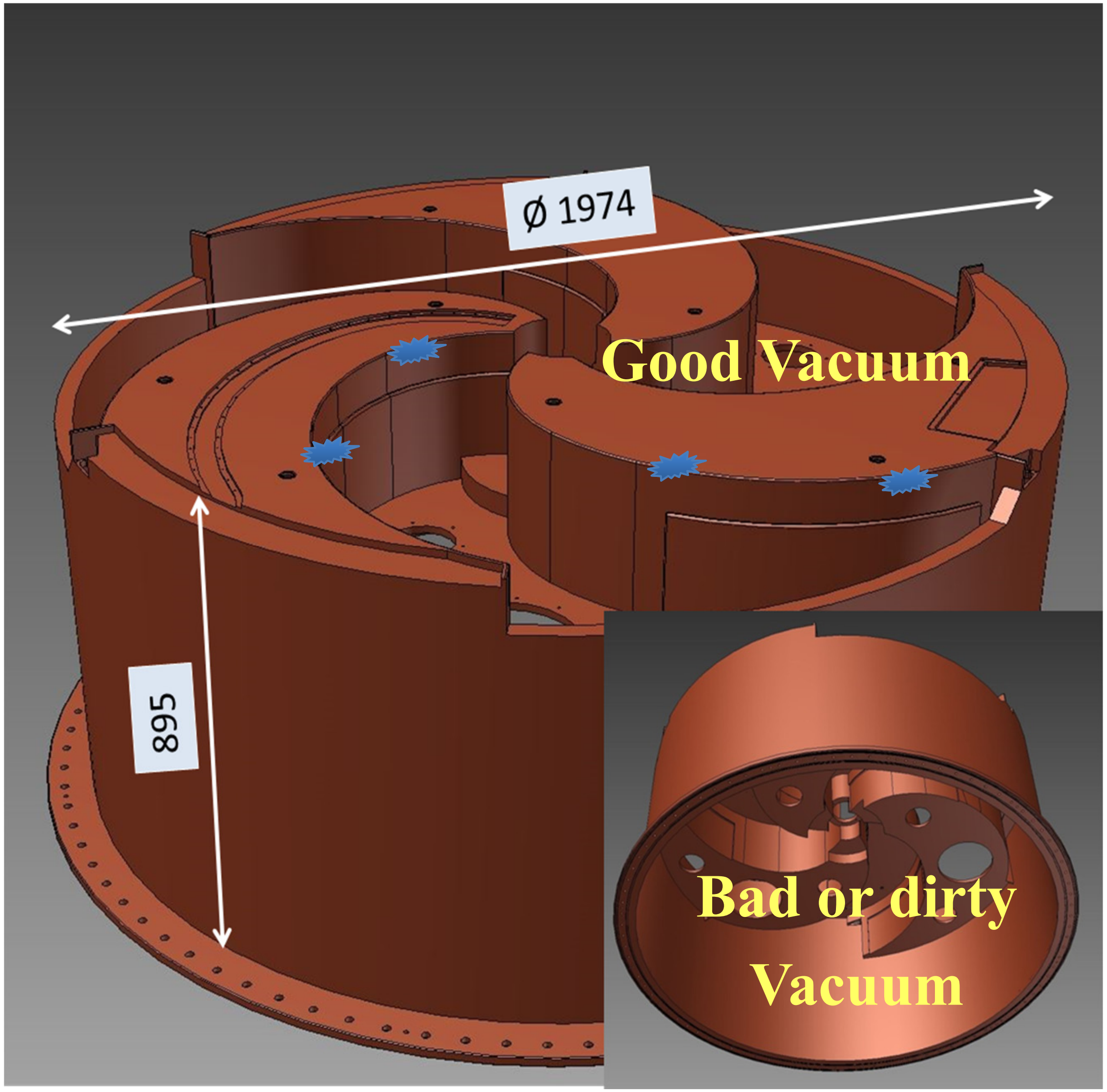
More details at presentation of G. D'Agostino TUC04

Preliminary layout of moving and positioning stripper foils



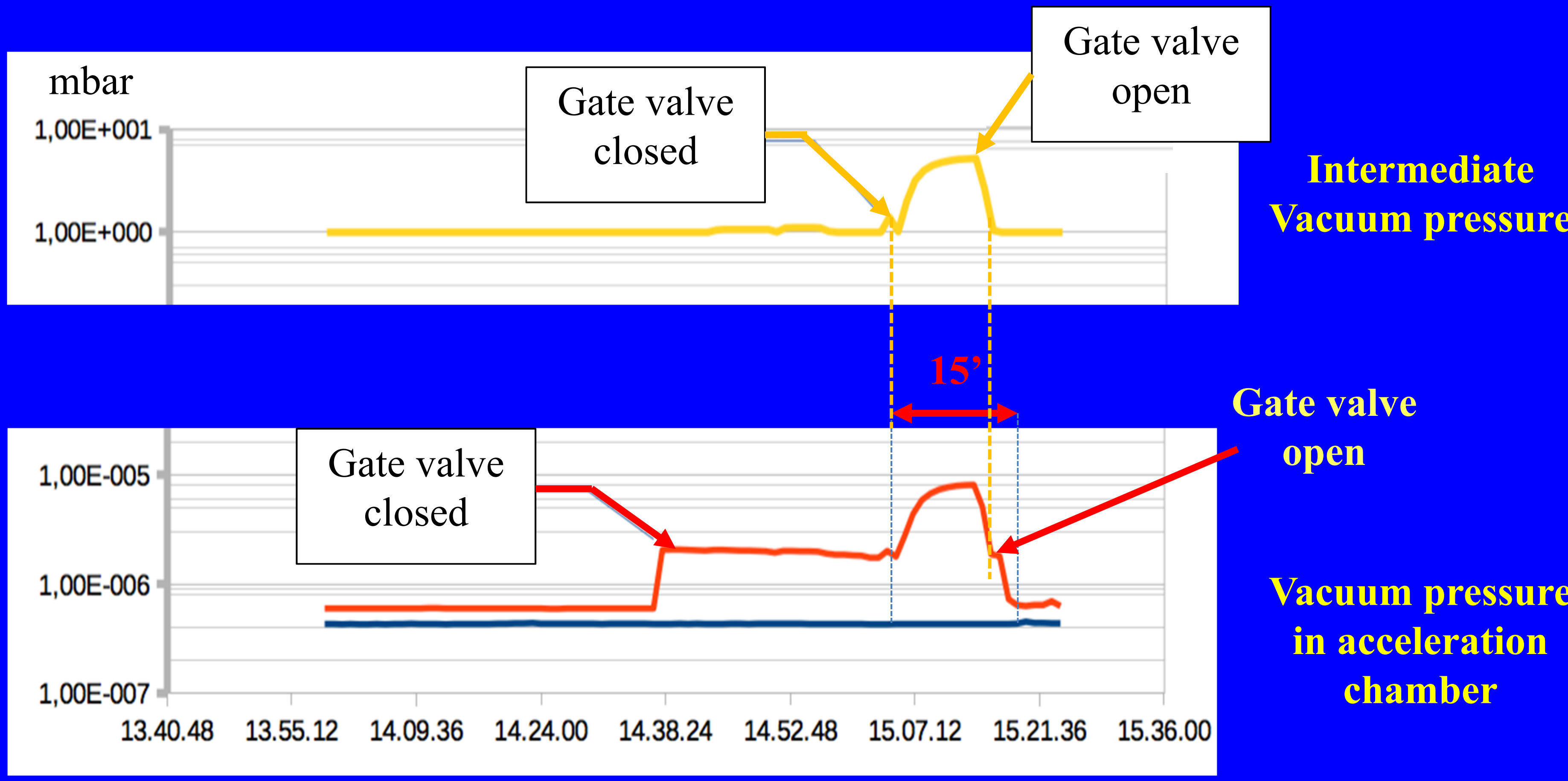
The mean life of stripper foils used in commercial cyclotron with H^- @30 MeV is 20-30 mAh. For a Oxigen beam of 60 μA, and at 60 MeV/n (10 kW), the expected mean life for each stripper is 330-470 hours, equivalent to 14-21 days!

We plan to build a couple of new “LINERS”



We will use the existing technical drawings, but the wall thickness will be increased from 3 to 5 mm, to avoid the existing vacuum leaks. We will use better welding procedure.

Vacuum pressure in acceleration chamber
Effect of the pressure of "dirty vacuum"



We plan to build also a new set of 120 Trim Coils (TC)!

We plan to use the same construction procedure already used for the existing trim coils but using a cable with a smaller cross section to have more room for the "Liner wall thickness".

Existing cable 6,35 x 6,35 mm, new cable 6,35 x 5 mm

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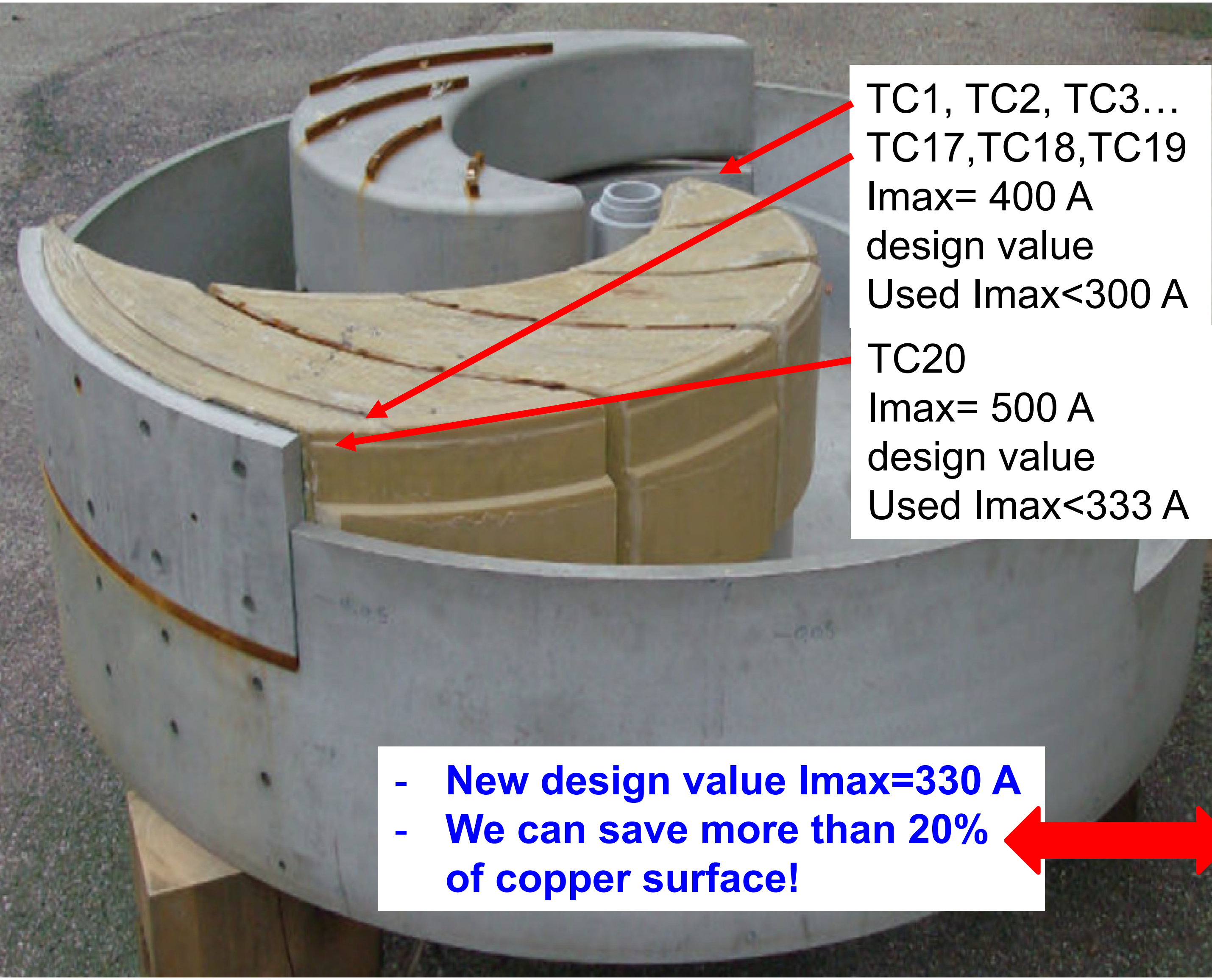

- New design value Imax=330 A
- We can save more than 20% of copper surface!

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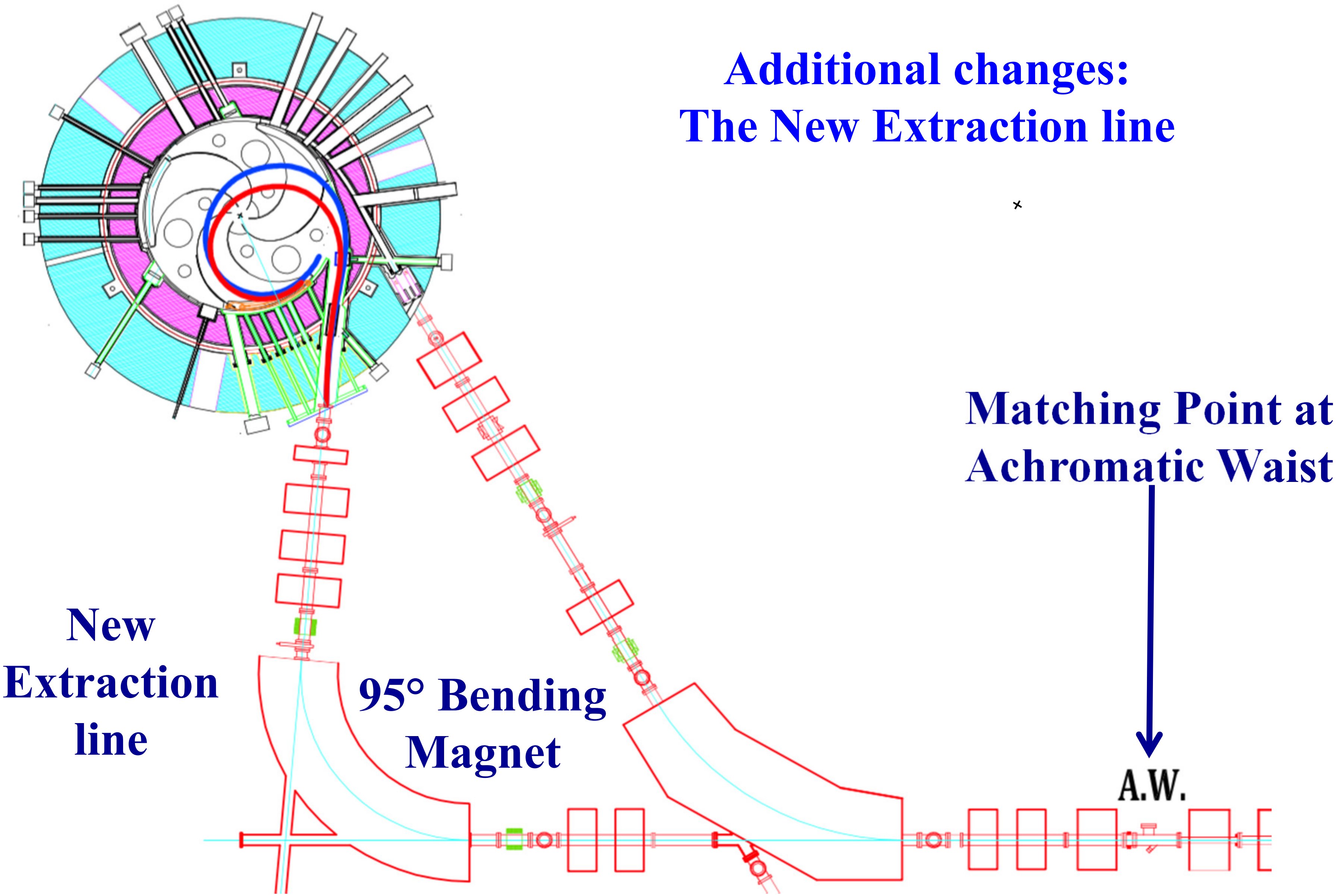
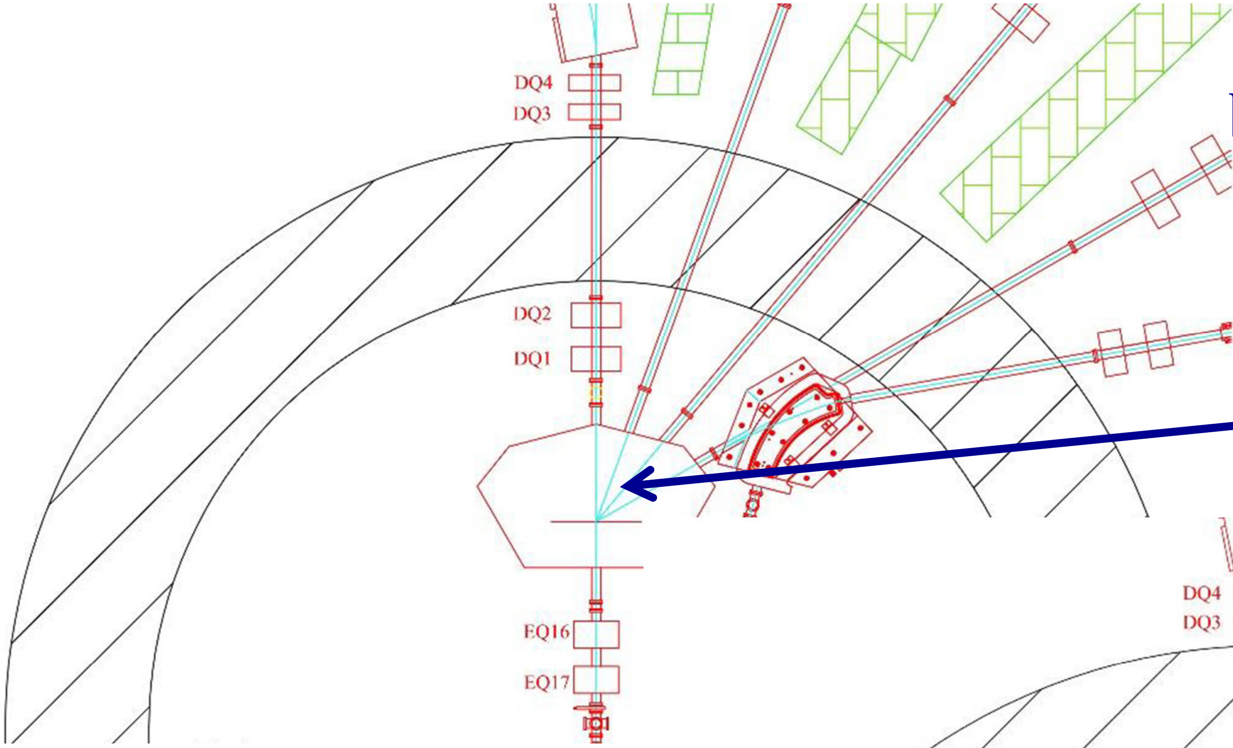
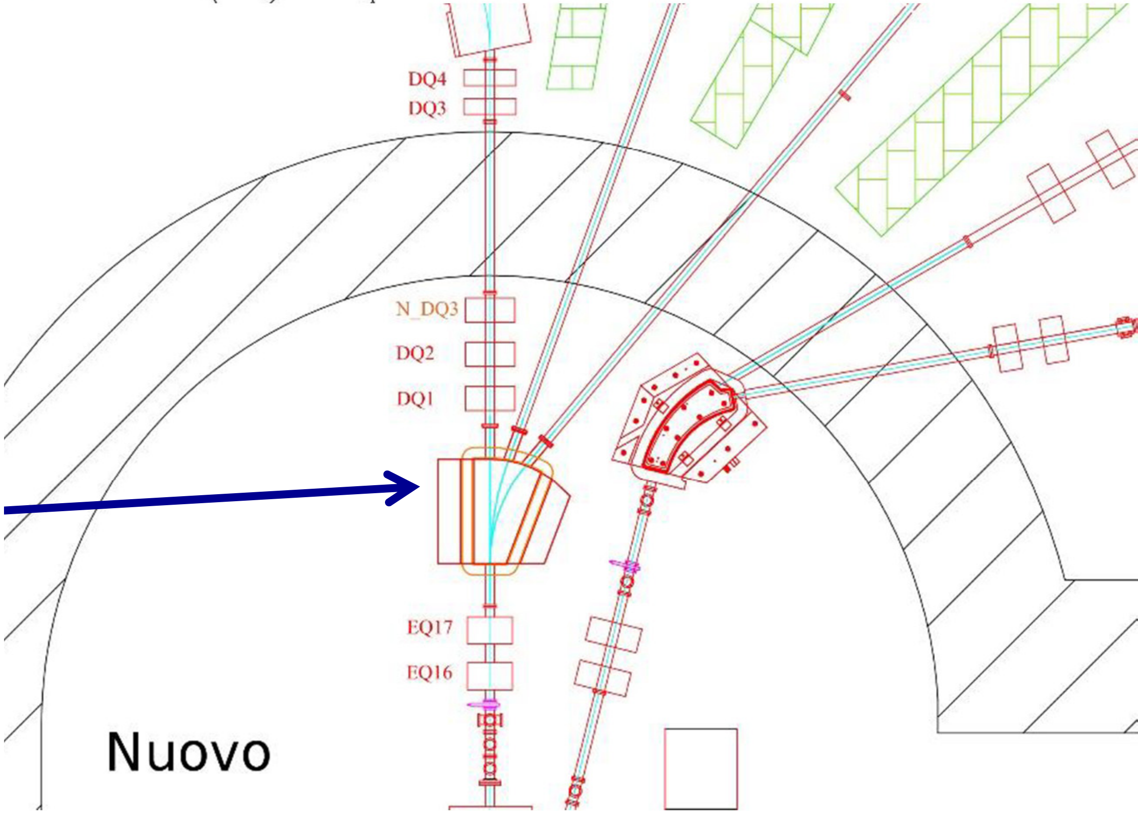
Additional changes:
The New Extraction line





This area is critical for beam losses. This is due to the small gap (25 mm) of the switching magnet and of its sizes.

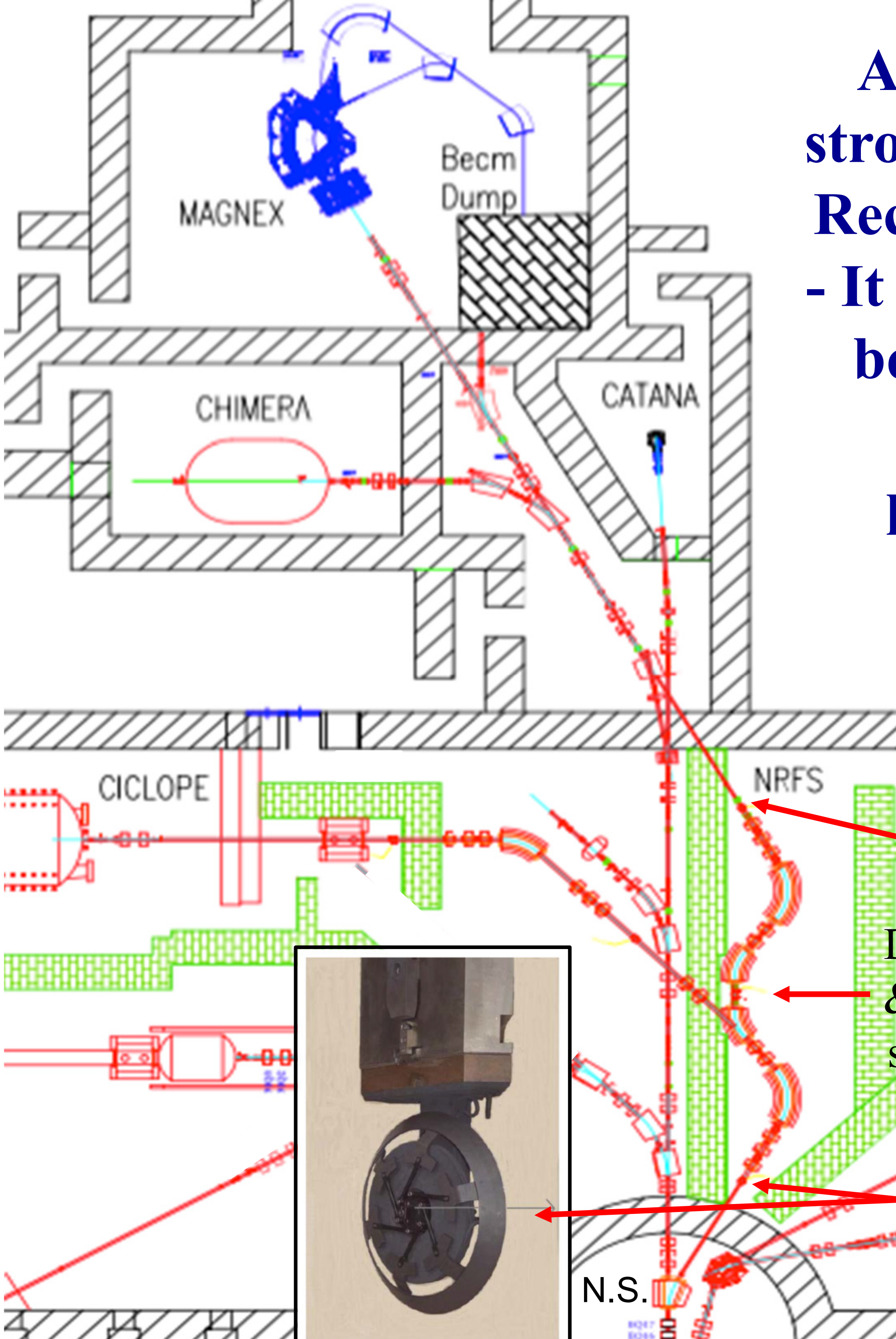
We plan to replace with a new switching magnet with 70 mm gap (just 60 mm for the beam). The new magnet has minor sizes and allows the insertion of an extra quad.



A section of the beam line will be strongly changed to became our New Recoil Fragment Separator (NRFS).

- It will be able to deliver radioactive beam to three experimental area.

- The maximum power of the primary beam must be limited at 2 kW!



The NRFS can be used as energy selector to deliver beam with energy spread lower than ± 0.1% to MAGNEX Spectrometer

Thanks for your attention