GFS-2 - The New Gas-filled Separator for Super-Heavy Elements in JINR. A Guided Walk through the Genesis of the Project from First Thoughts to Completion

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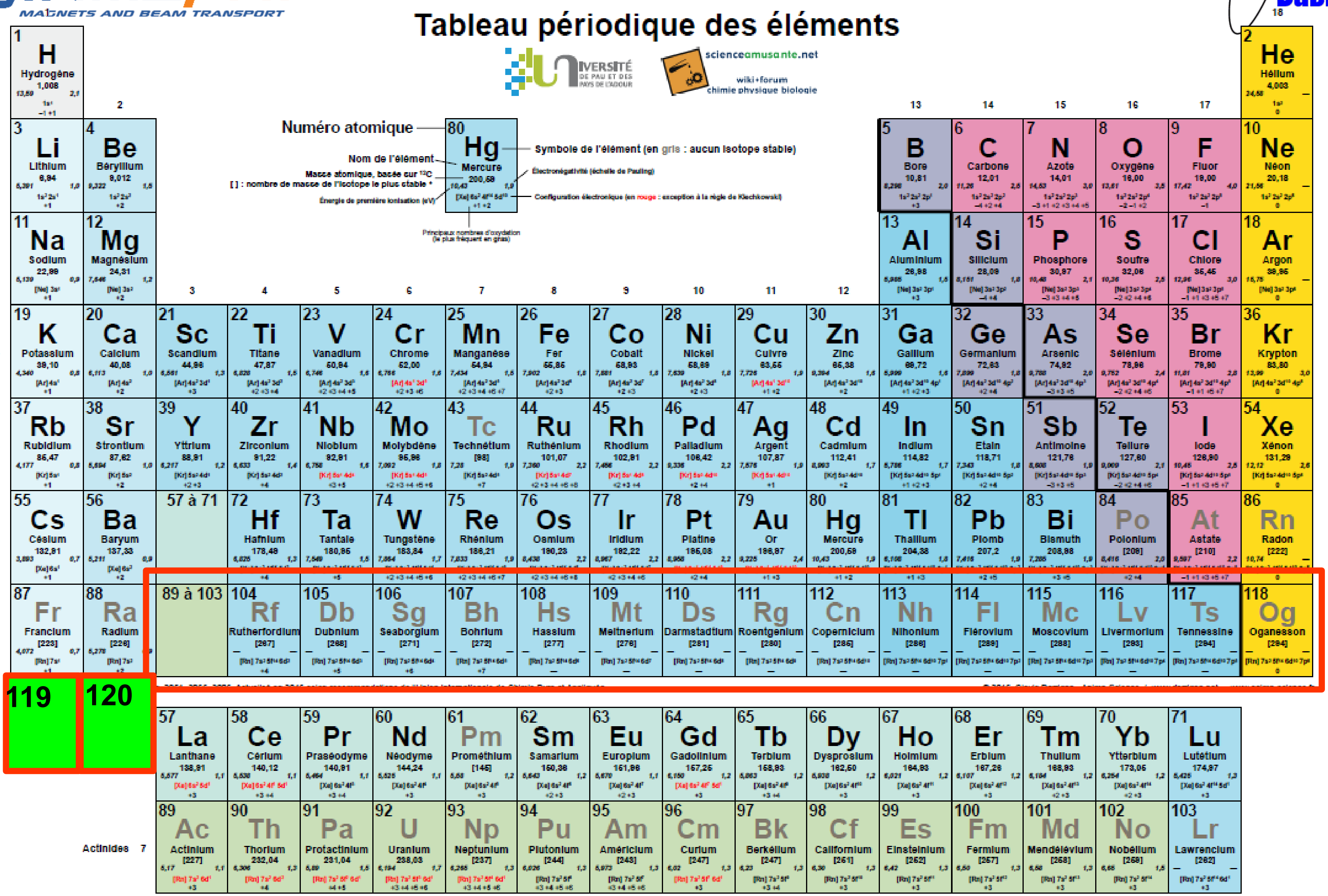
With special thanks to our co-workers from the « 100 ton » company, for their efficiency and the pleasure to work with them during the installation

Layout inside SHE factory

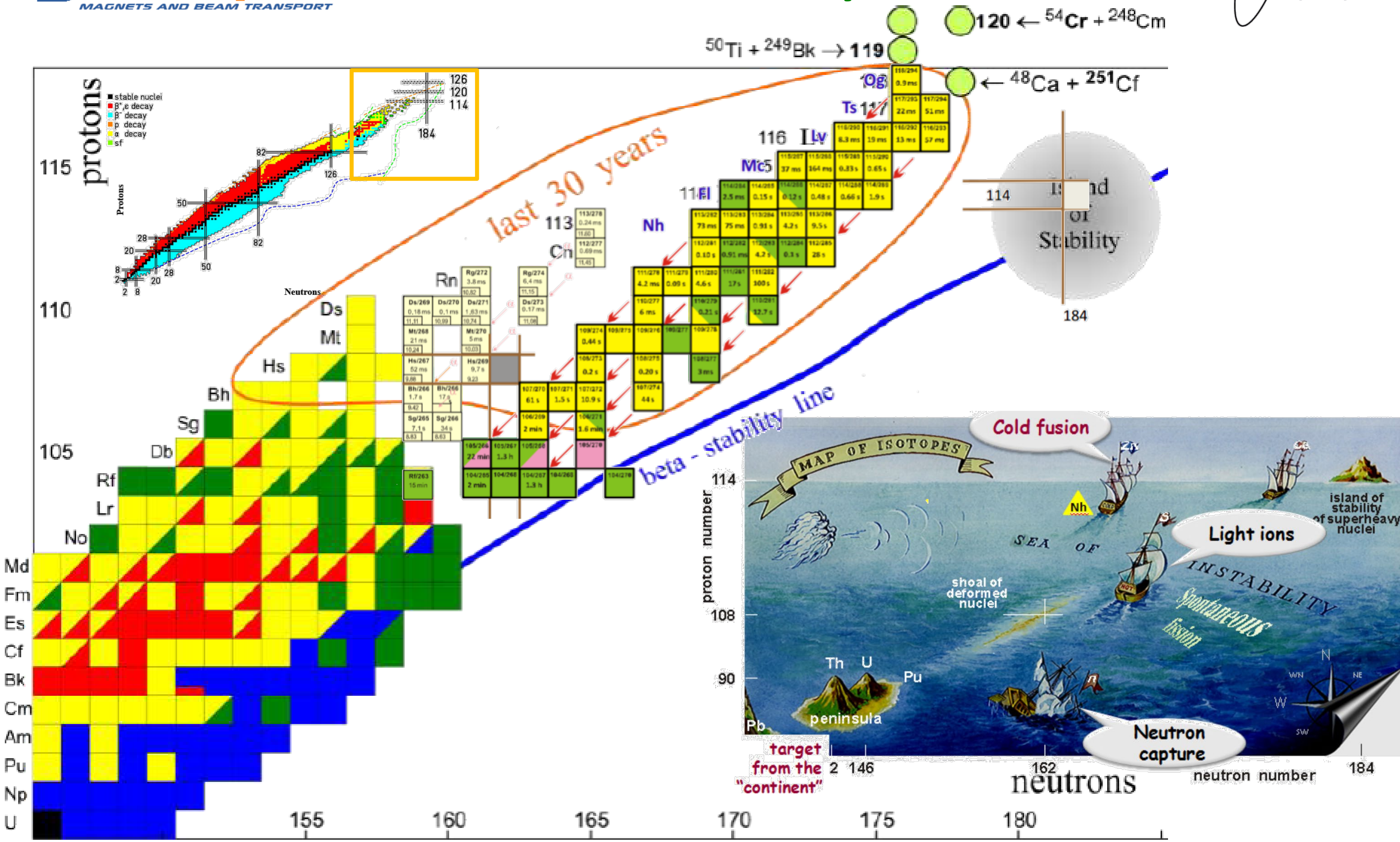
Super Heavy Elements

WHY ?

Filling in Mendeleev's



Heading towards stability



Super Heavy Elements

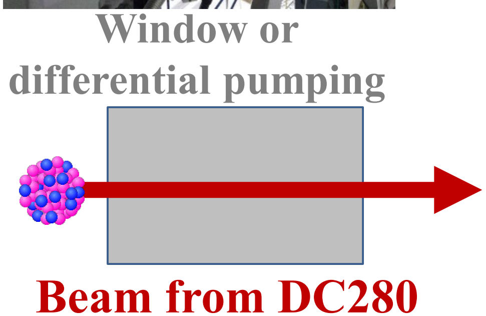
HOW ?

Schematics of a separator

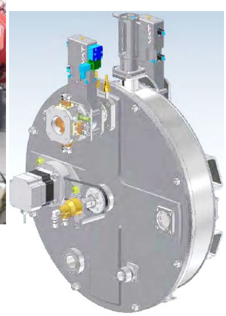
Schematics of a separator

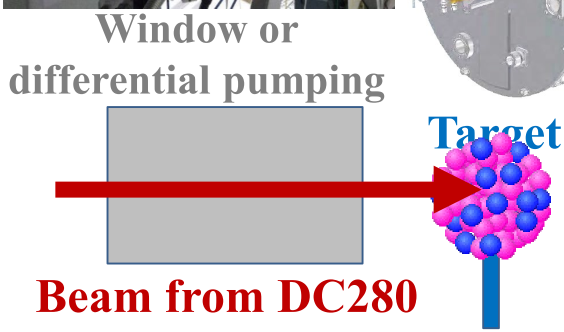
Beam from DC280

Schematics of a separator



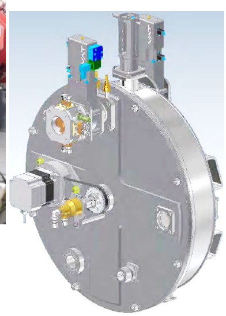
Schematics of a separator





- **Ø 480, 1500 rpm synchronous,**
- **e-beam & optical diagnostics**
- **Water & gas cooled**

Schematics of a separator



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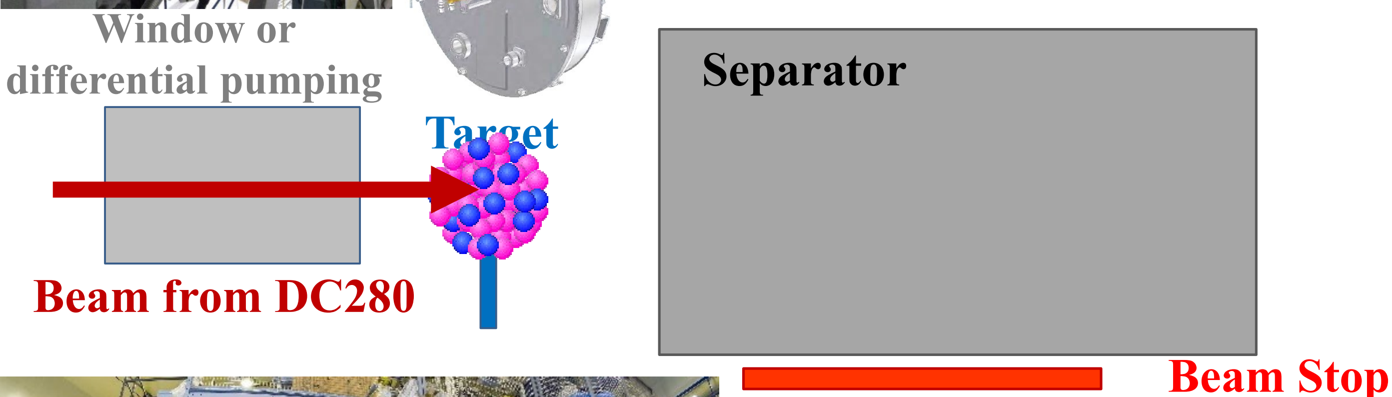
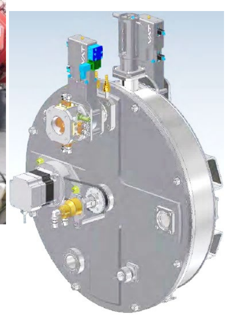


Schematics of a separator



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Schematics of a separator

48×128 strips
6144 pixels

128×128 strips
16384 pixels

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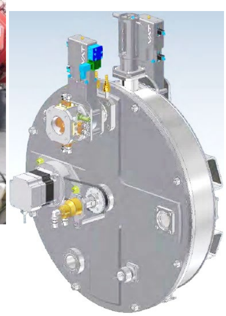
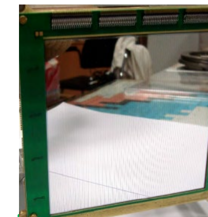
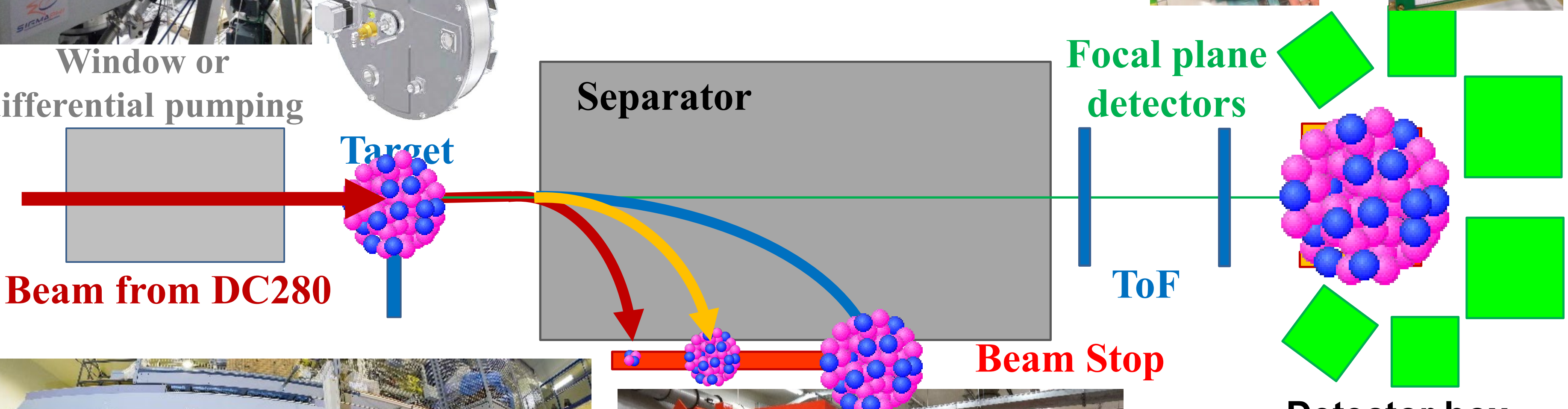
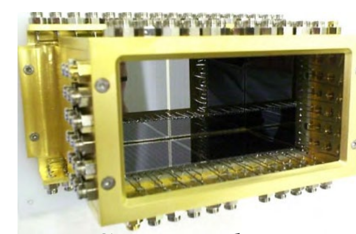


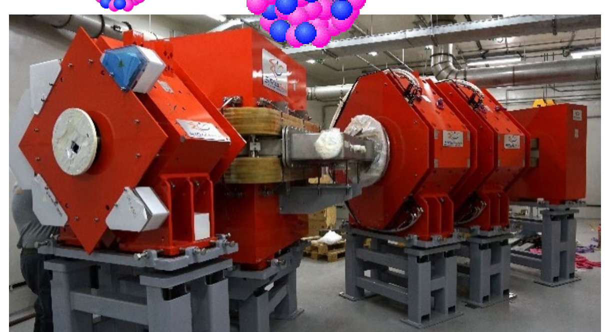
Window or differential pumping





Detector box





Micron Semiconductors, UK

What are we fighting for?

Reaction products in magnetic separator suffer from

Contamination

Many charge states

Large emission angle

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Improve rejection

Bending angle

dispersion

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Separator

What are we fighting for?

Reaction products in magnetic separator suffer from

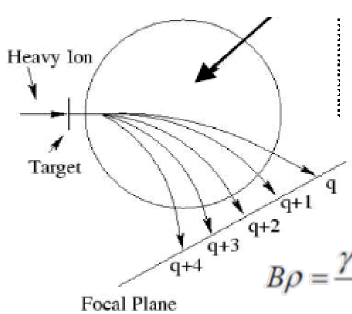
Contamination	Many charge states	Large emission angle
Improve rejection Bending angle dispersion **Separator**	Promote mechanisms that narrow the charge state distribution	

What are we fighting for?

Reaction products in magnetic separator suffer from

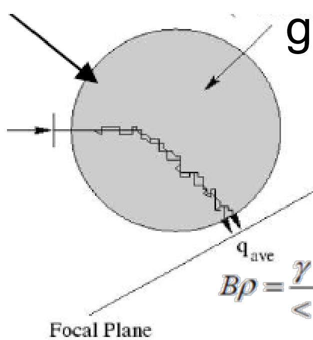
Contamination	Many charge states	Large emission angle
Improve rejection Bending angle dispersion	Promote mechanisms that narrow the charge state distribution	
Separator	**Gas-filled Separator**	

dipole



$$B\rho = \frac{\gamma m v}{q}$$

gas

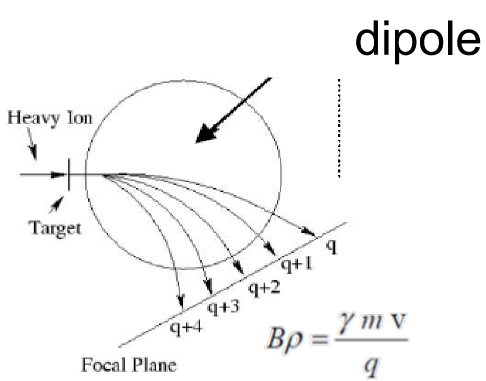


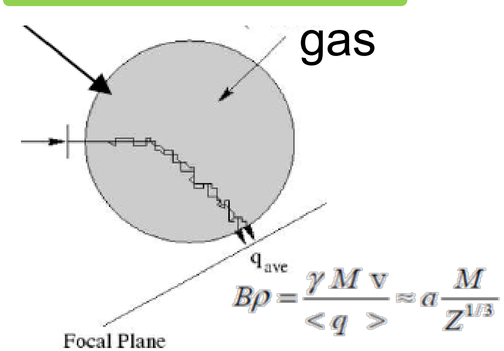
$$B\rho = \frac{\gamma M v}{<q>} \approx a\frac{M}{Z^{1/3}}$$

What are we fighting for?

Reaction products in magnetic separator suffer from

Contamination	Many charge states	Large emission angle
Improve rejection Bending angle dispersion	Promote mechanisms that narrow the charge state distribution	Increase acceptance/transmission Optics Large apertures Focusing Optimized chambers
Separator	**Gas-filled Separator**	





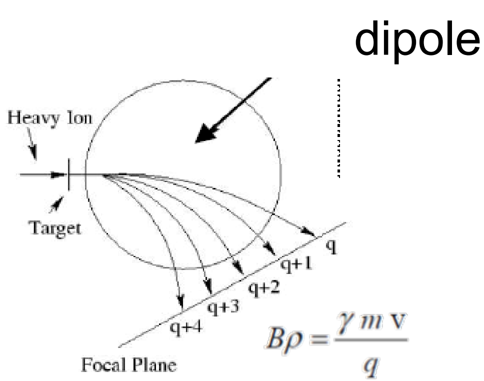
SIGMAPHI
MAGNETS AND BEAM TRANSPORT

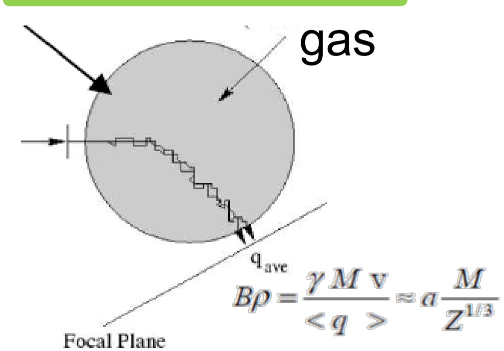
What are we fighting for?

JINR
114 Flerovium
FLNR
Dubna

Reaction products in magnetic separator suffer from

Contamination	Many charge states	Large emission angle
Improve rejection Bending angle dispersion	Promote mechanisms that narrow the charge state distribution	Increase acceptance/transmission Optics Large apertures Focusing Optimized chambers
Separator	**Gas-filled Separator**	**Large acceptance Gas-filled Separator**





… and last but not least BE PATIENT

Formation of SHE is a very rare event (**pb**)

At 1pμA of ^{48}Ca

1nb -> 100 events/h

1pb -> 1 event/week

1fb -> 1 event/20 years

"On 9 October 2006, the researchers announced that they had indirectly detected a total of 3 (possibly 4) nuclei of oganesson-294 (1 or 2 in 2002 and 2 more in 2005) produced via collisions of californium-249 atoms and calcium-48 ions"

Excerpt from the Wikipedia webpage on Oganesson
https://en.wikipedia.org/wiki/Oganesson

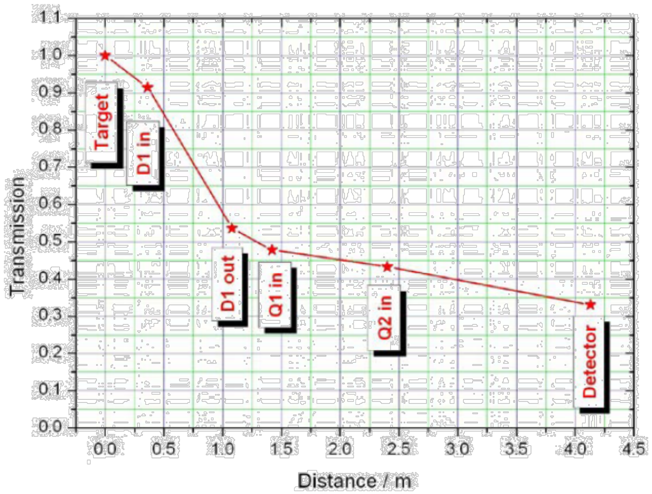
Expectations

Rationale for new layout

Rationale for new layout

Losses for $^{243}Am(^{48}Ca,4n)^{286}Mc$ in existing DGFRS

DQ_hQ_v layout : dipole gap 58mm, quad diameter 100mm



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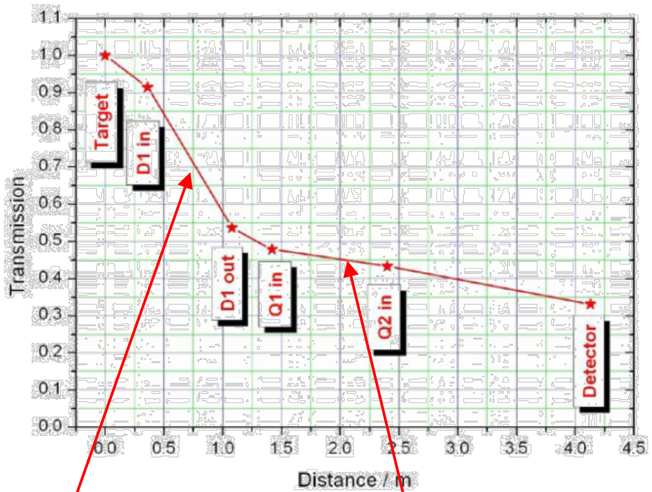

40% loss in dipole

15% loss in quads

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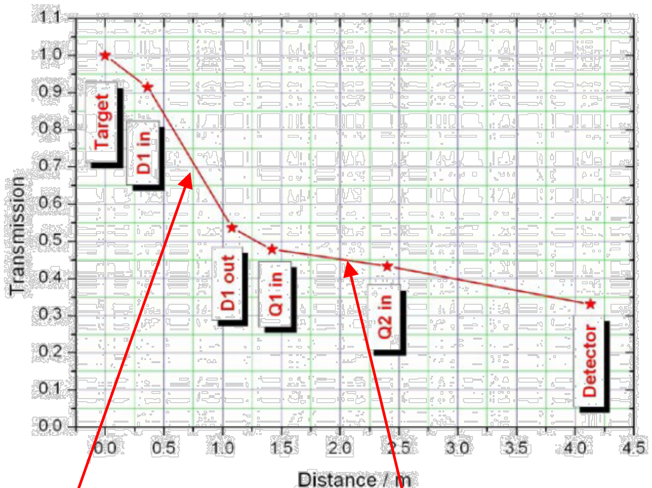

40% loss in dipole

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MUST IMPROVE TRANSMISSION

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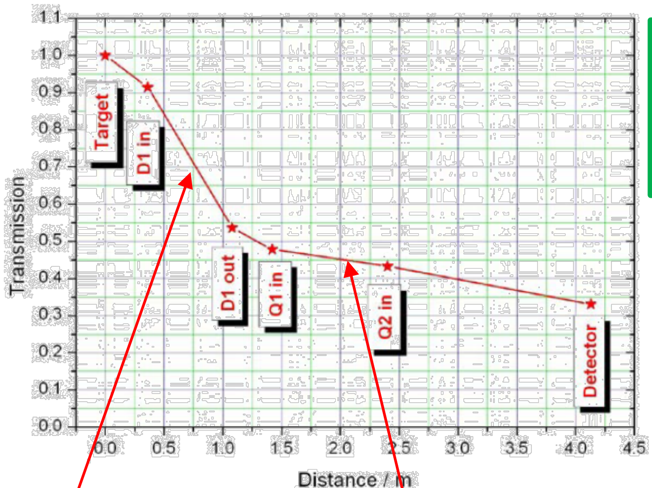

Increase dipole gap

40% loss in dipole

15% loss in quads

MUST IMPROVE TRANSMISSION

Rationale for new layout

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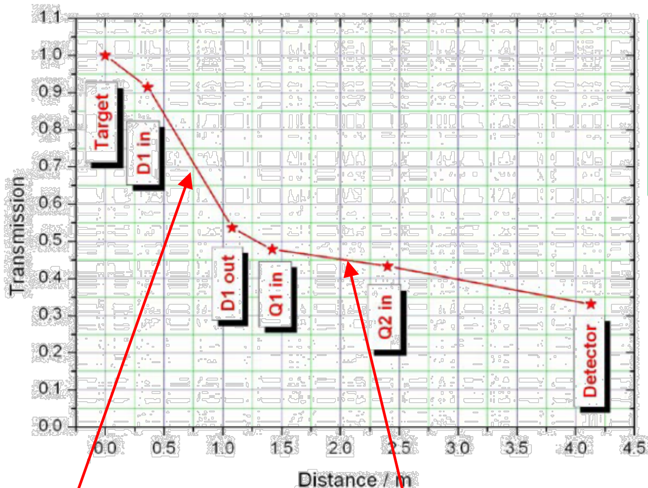

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MUST IMPROVE TRANSMISSION

Increase dipole gap

Q_1 V to enter dipole

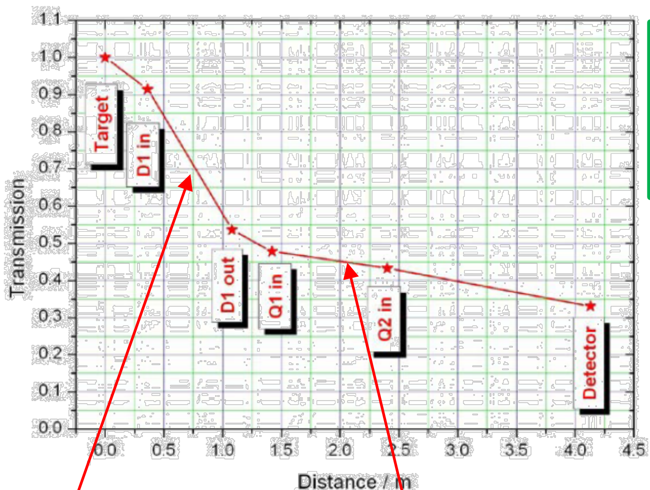
Refocus H asap

Large exit pole edge angle

Rationale for new layout

Losses for $^{243}Am(^{48}Ca,4n)^{286}Mc$ in existing DGFRS

DQ_hQ_v layout : dipole gap 58mm, quad diameter 100mm



Increase dipole gap

Q_1 V to enter dipole

Large aperture quads

Refocus H asap

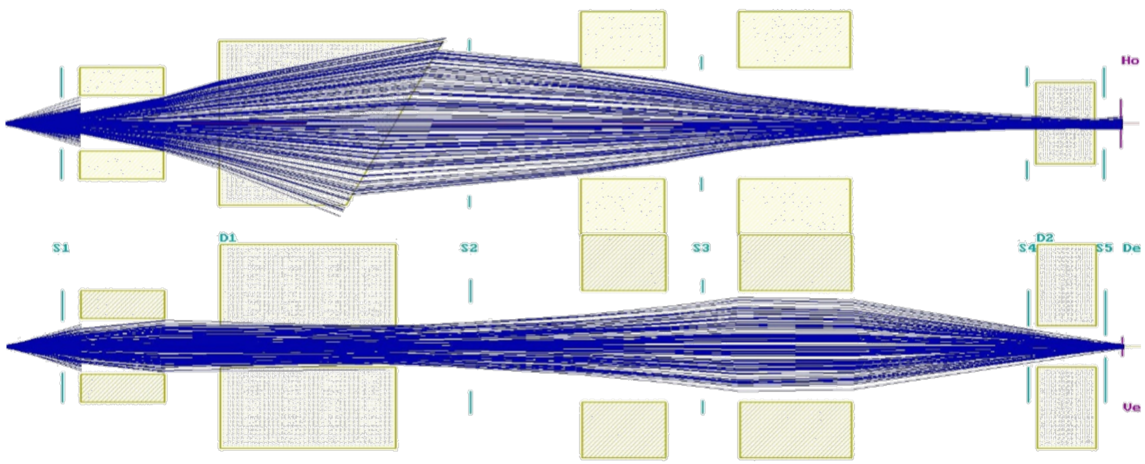
Large exit pole edge angle

40% loss in dipole

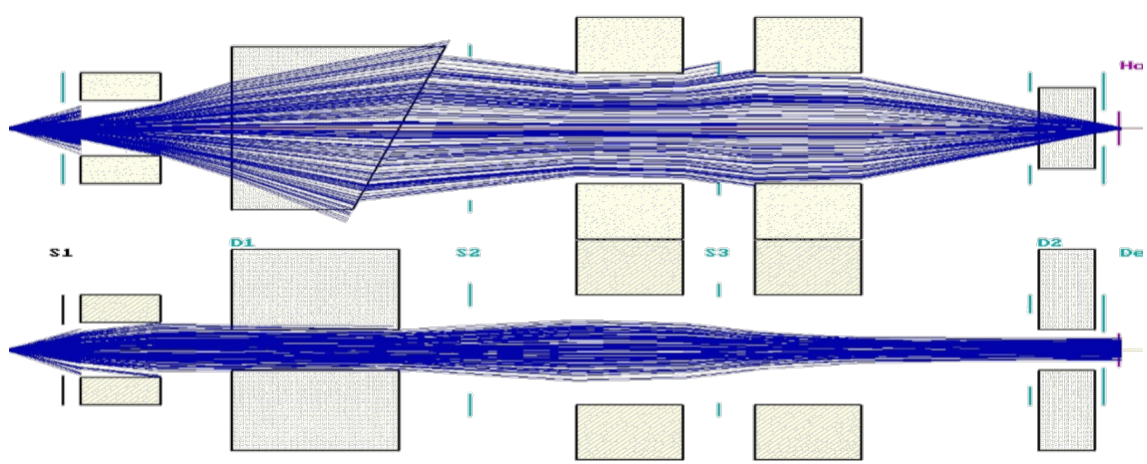
MUST IMPROVE TRANSMISSION

15% loss in quads

Transmission or Resolution ?



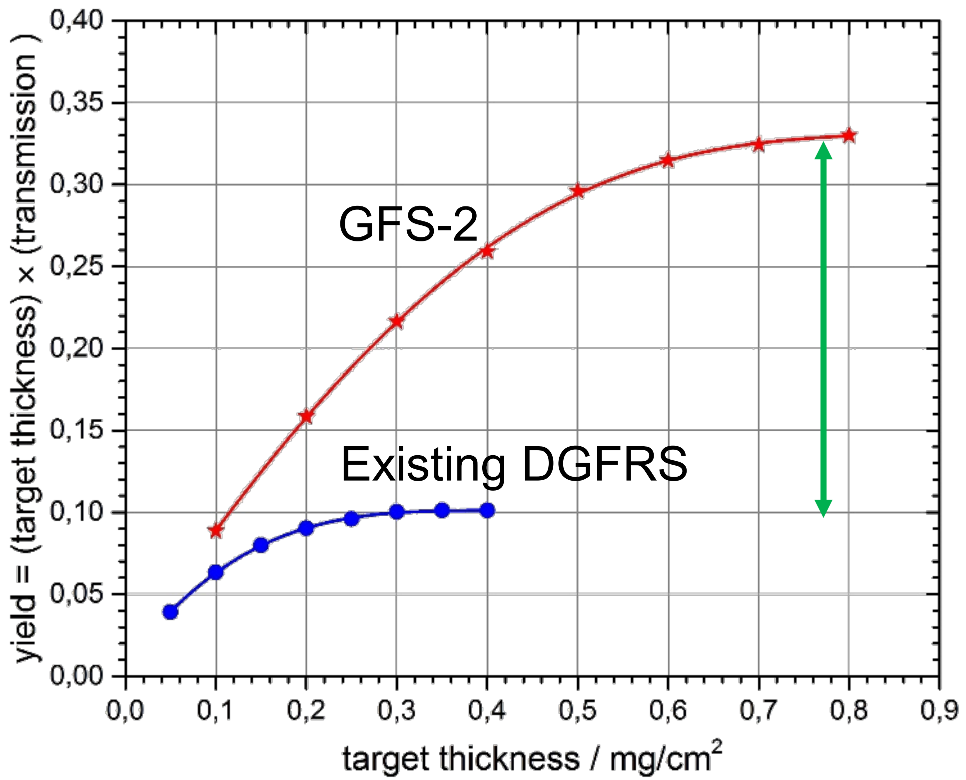
VHHV
Transmission +
Resolution -
Separator



VHVH
Transmission –
Resolution +
Spectrometer

Expected gain

Reaction	Transmission
$^{244}Pu(^{48}Ca,3n)^{289}Fl$	60 %
$^{244}Pu(^{58}Fe,4n)^{298}120$	75 %



$^{244}Pu(^{48}Ca,4n)^{288}Fl$

Over 3 times more !!

GFS2 among some gas-filled separators

Separator	DGFRS	GARIS-II	RITU	BGS	TASCA	SHANS	GFS-II
Location	FLNR Dubna Russia	RIKEN Wakô Japan	JYFL Jyväskylä Finland	LBNL Berkeley USA	GSI Darmstadt Germany	IMP Lanzhou China	FLNR Dubna Russia
Configuration	DQ_hQ_v	$Q_vDQ_hQ_vD$	$Q_vDQ_hQ_v$	Q_vD_hD	DQ_hQ_v	$Q_vDQ_vQ_h$	$Q_vDQ_hQ_vD$
Deflection angle	23º	30º+7º	25º	25°+45º	30º	52º	30º+10º
Bρ (max/T·m)	3.1	2.46	2.2	2.5	2.4	2.88	2.25
Length (m)	4	5.06	4.8	4.6	3.5	6.5	6.3
Dispersion (mm/% Bρ)	7.5	19.3	10	20	9	7.3	9.7
					High Transmission Mode	High Resolution Mode	

From initial spec to final layout through various iterations

Living with constraints

gives rise to important questions

It is desirable but is it technically feasible ?

Is it economically OK ?

Investment costs AND running costs

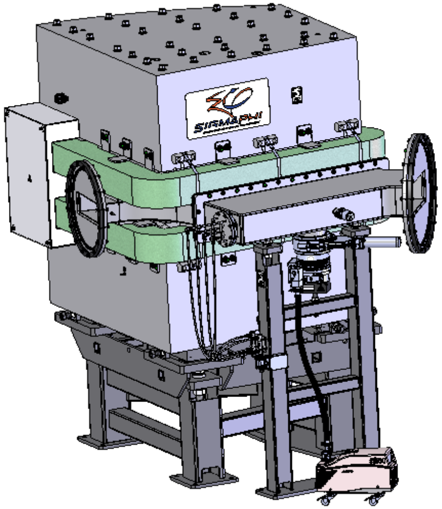
Can I trade this for that ?

I can improve. Is it worth ?

…

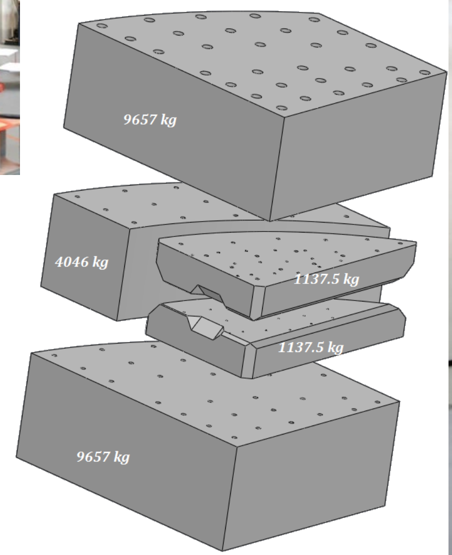
The big guy – 30° D1

D1 General

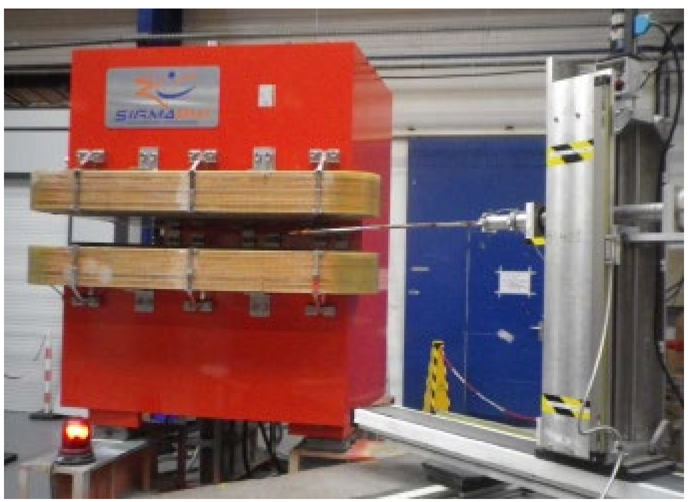


Factory assembly

Assembly on site



Each part must be less than 10 tons



Hall probe measurement

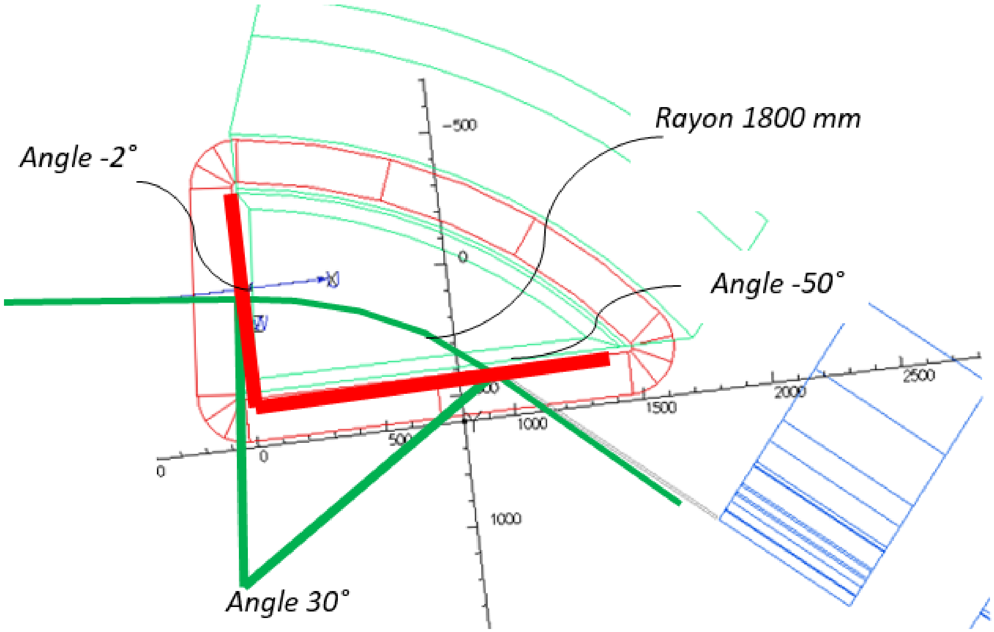
D1 parameters

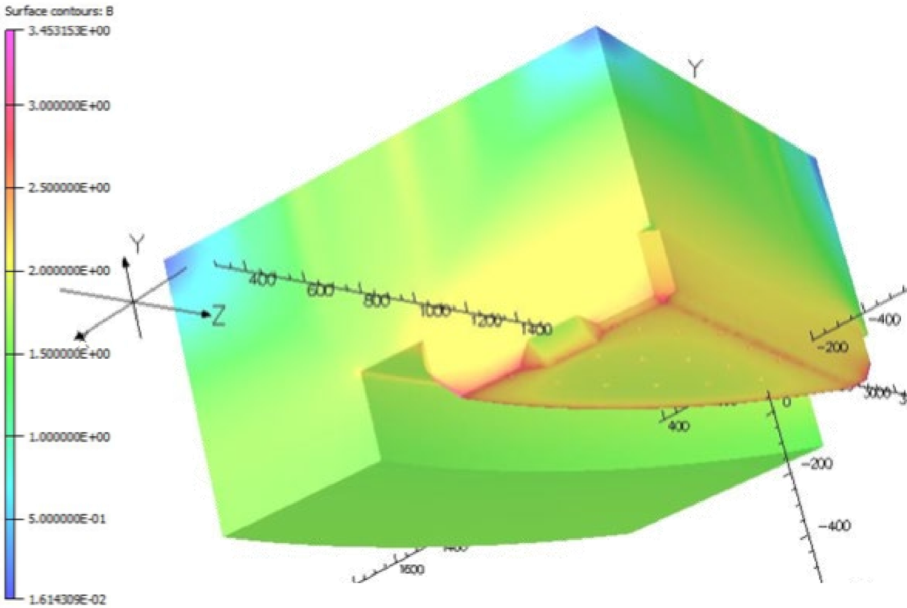
Beam free aperture	**120**	mm
Magnet gap	**132**	mm
Curvature radius	1800	mm
Entrance face angle	-7 (-2)	°
Exit face angle	**-44** (-50)	°
Deviation angle	31.5	°
Effective length	1007	mm
Good Field region	440	mm

Max field	1.8	T
Max current	919	A
# turns (1 coil)	120	
Max current density	7.4	A/mm²
Magnet power	139	kW
Yoke weight	25.7	ton
Copper weight	1.24	ton

D1 design (1)

Large exit angle makes a conventional structure very difficult.
Entrance and exit faces side by side
Change on one generate change on the other -> joint optimization
Complex profile on entrance face

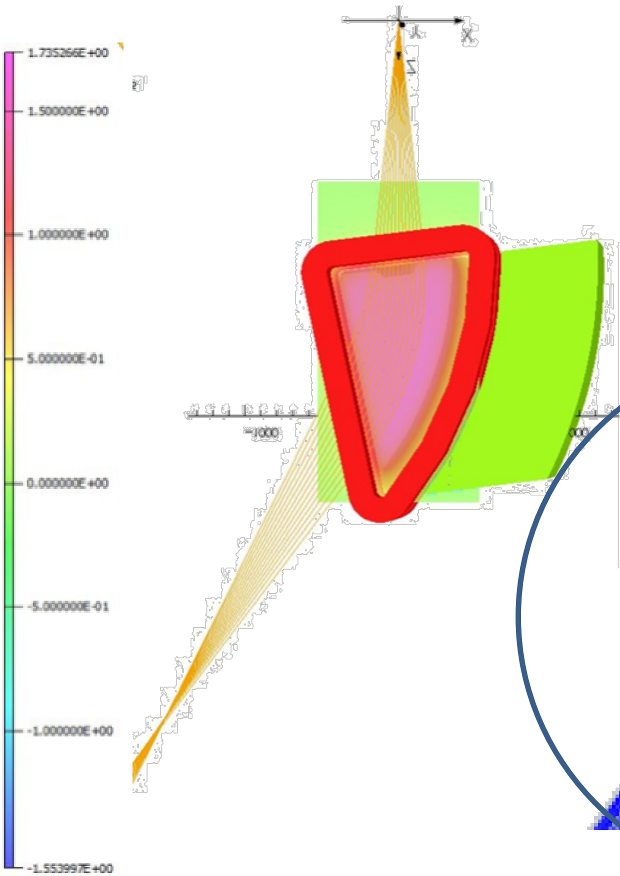


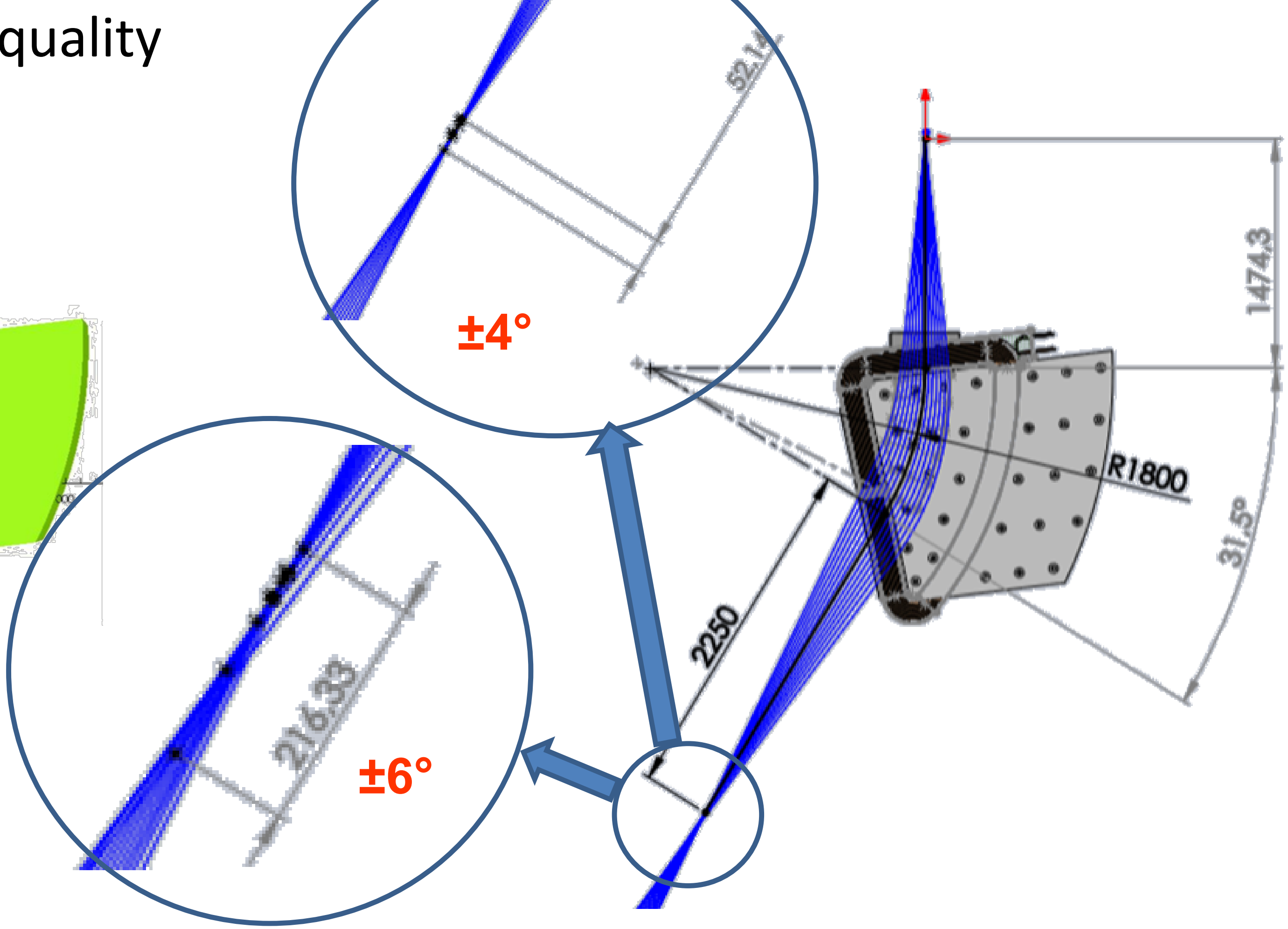


D1 design (2)

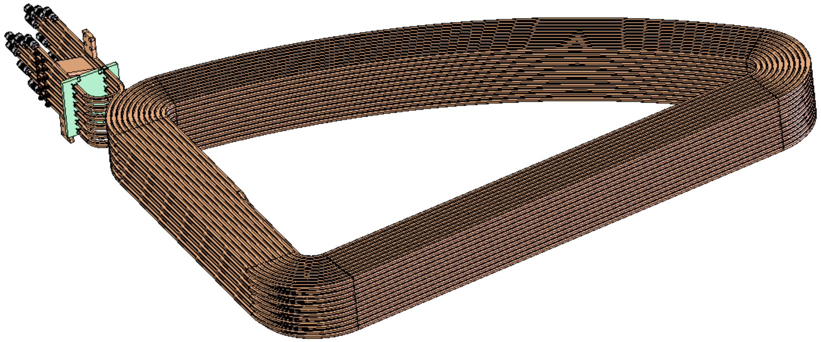
Design driven by particle tracking focusing quality

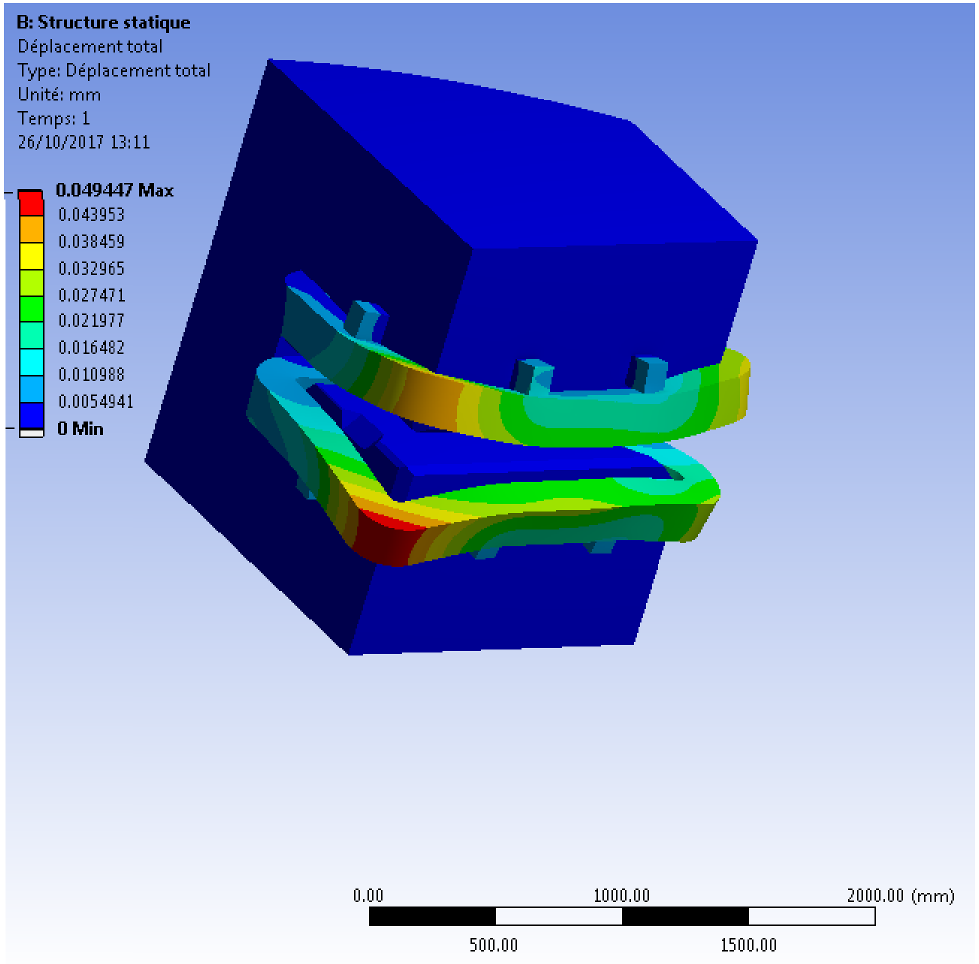
^{288}Rf



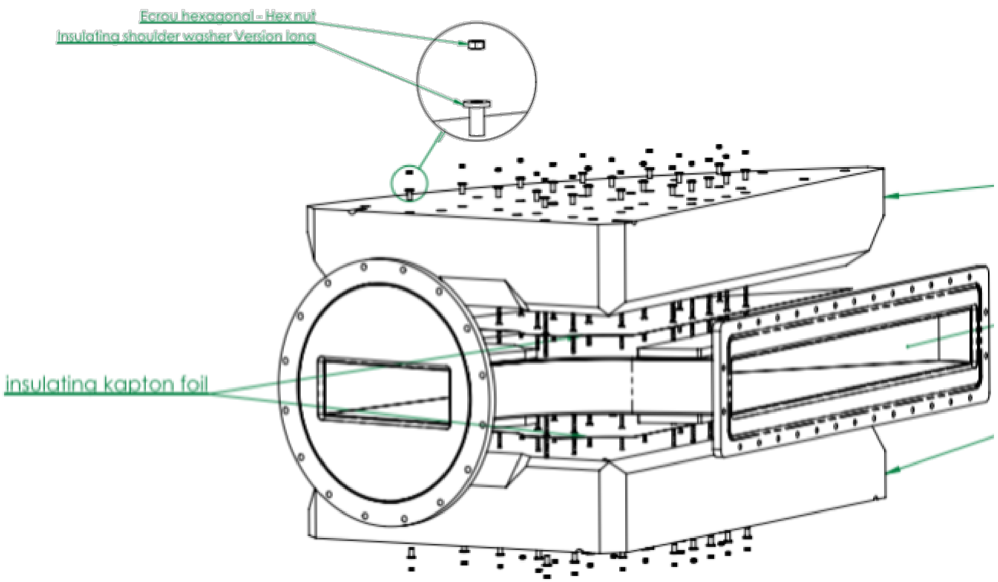


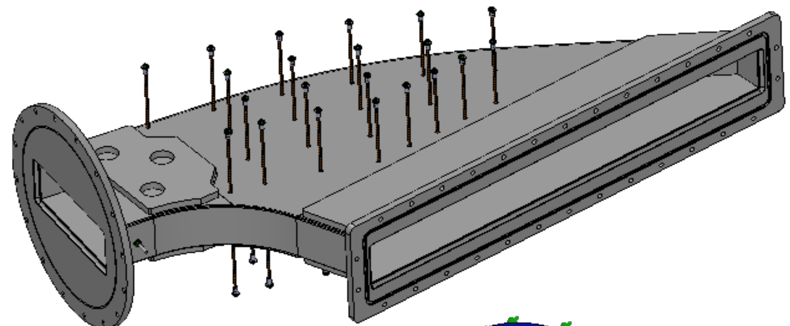
D1 coils

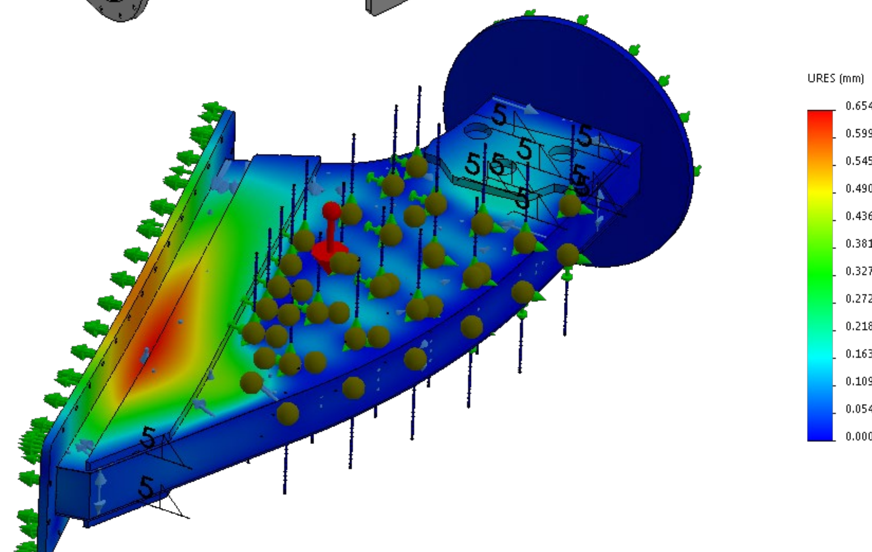



B: Structure statique
Déplacement total
Type: Déplacement total
Unité: mm
Temps: 1
26/10/2017 13:11
0.049447 Max
0.043953
0.038459
0.032965
0.027471
0.021977
0.016482
0.010988
0.0054941
0 Min
0.00
1000.00
2000.00 (mm)
500.00
1500.00

D1 chamber (1)







Very large surface
Wall must be thick to prevent deformation
21 struts + edge reinforcement allow thin walls
0.65 mm max displacement

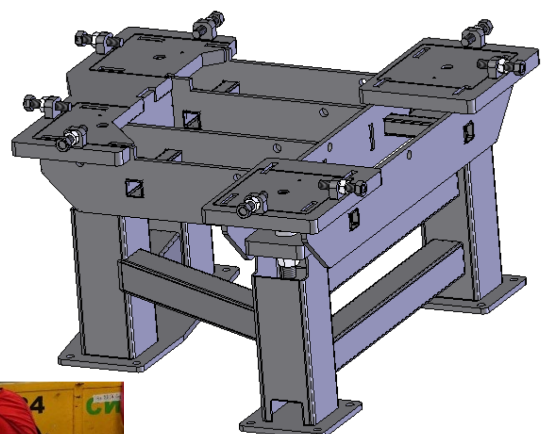
D1 chamber (2)

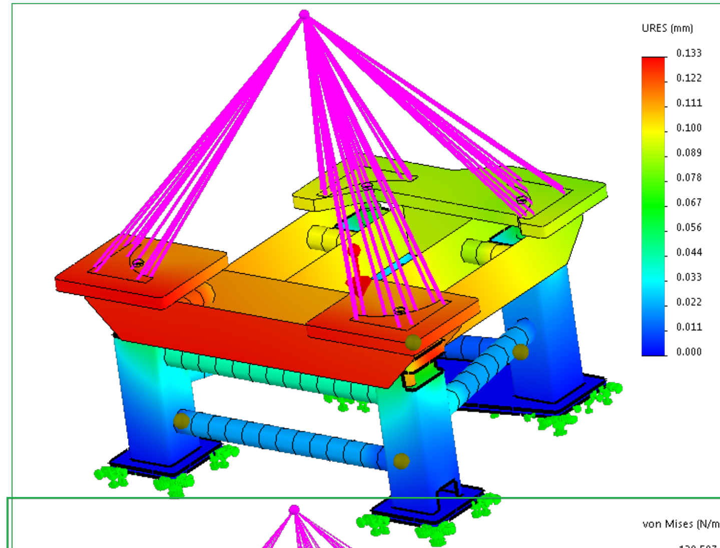
Chamber is electrically insulated

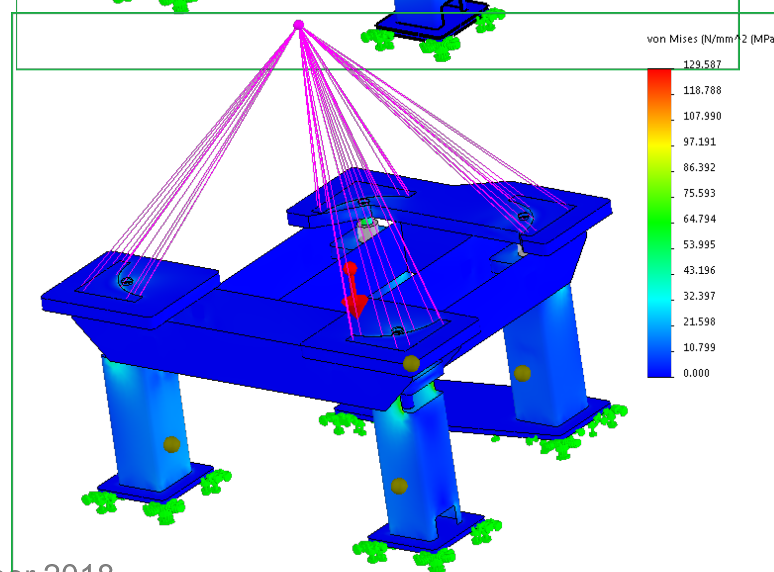
Chamber assembly and testing in factory

D1 Stand

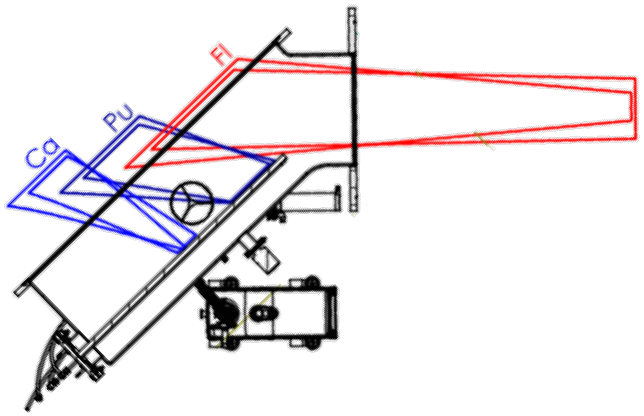
Magnet + chamber : 27.5 tons
Deformation < 0.2 mm
Stress < 130 Mpa (req. <235 Mpa)



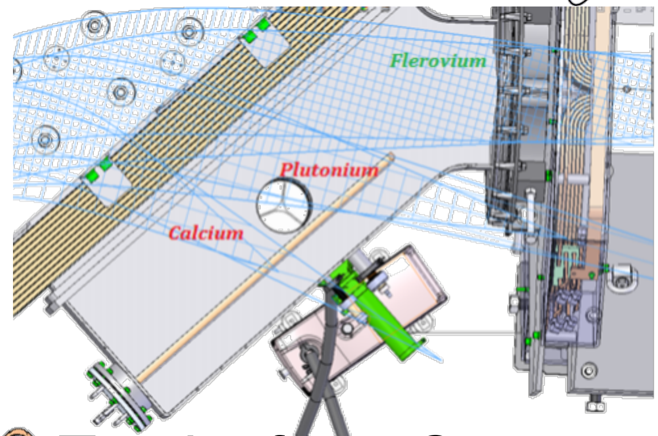




D1 Beam stop



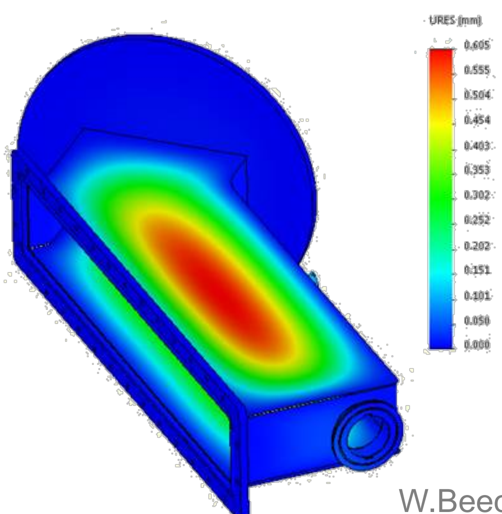
block most background species and let EVR pass

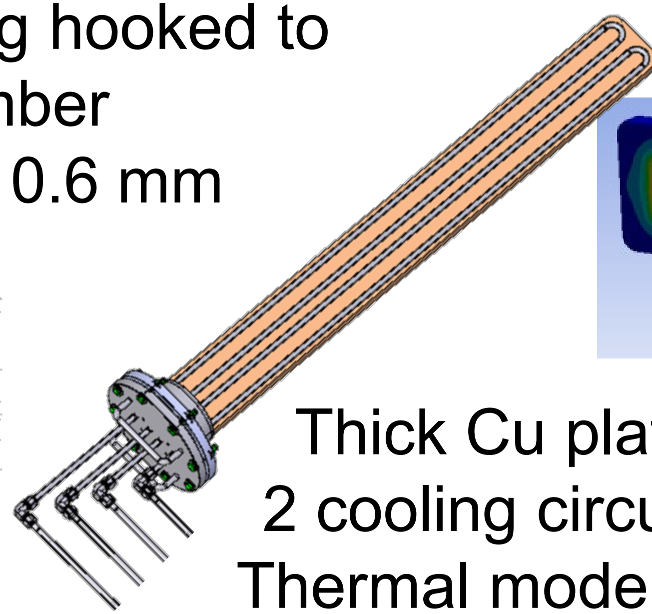


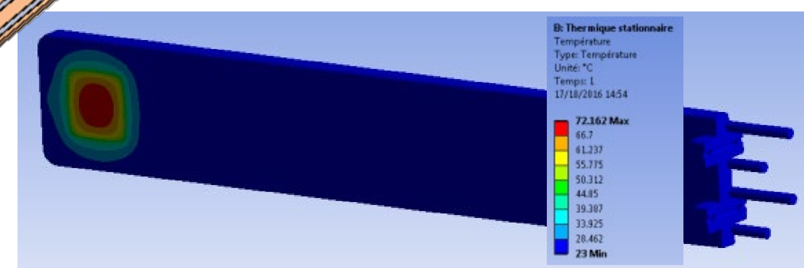
Tracks from Opera model

Beam stop housing hooked to main chamber

Deformation < 0.6 mm







Thick Cu plate

2 cooling circuits

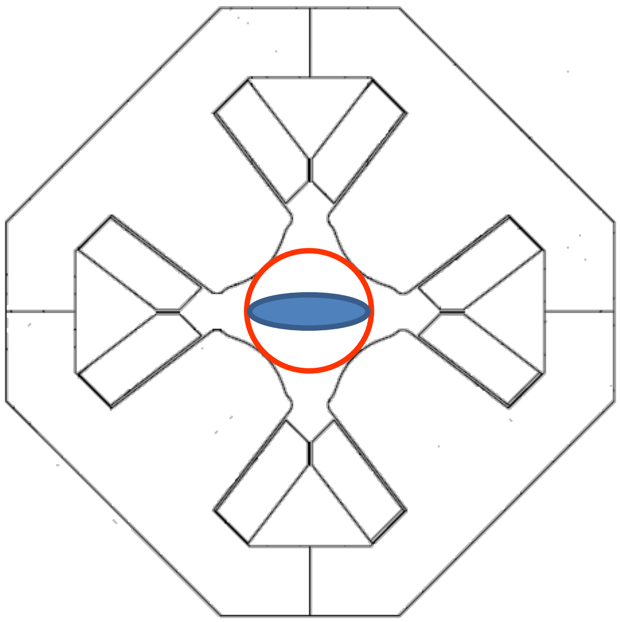
Thermal modelling **crucial**

Quadrupoles

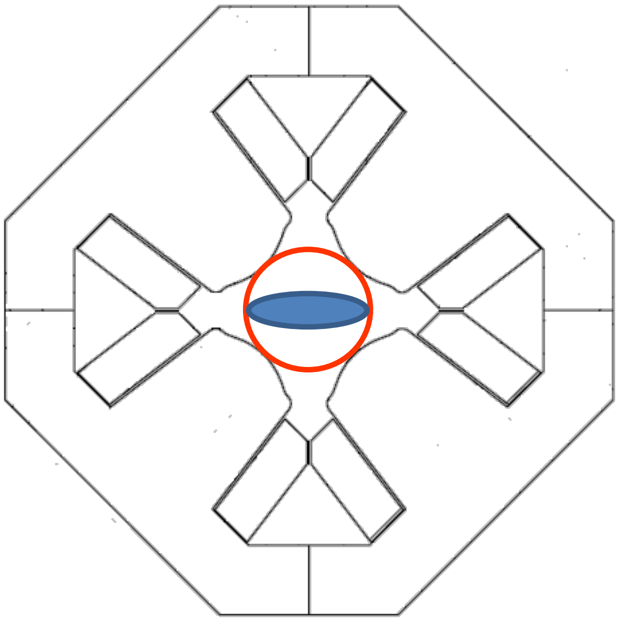
Quadrupoles parameters

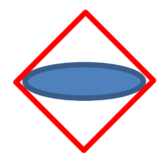
	Q1	Q2/Q3	
Bore diameter	150	300	mm
Iron length	420	520	mm
Effective length	456.6	600	mm
Max gradient	13.2	5.34	T/m
Max current	450	362	A
# turns (1 coil)	88	138	
Max current density	6.35	6.6	A/mm²
Magnet power	28.2	61.6	kW
Yoke weight	2.07	6.65	ton
Copper weight	0.39	0.68	ton

Shaping chambers to reduce bore

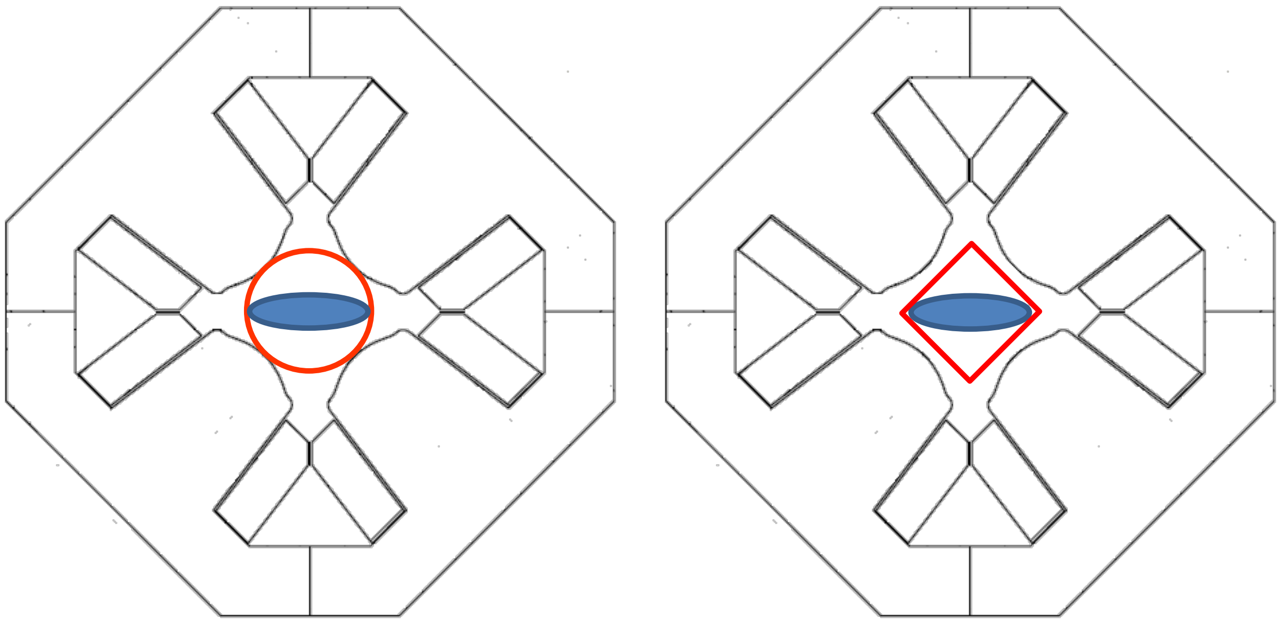


Shaping chambers to reduce bore

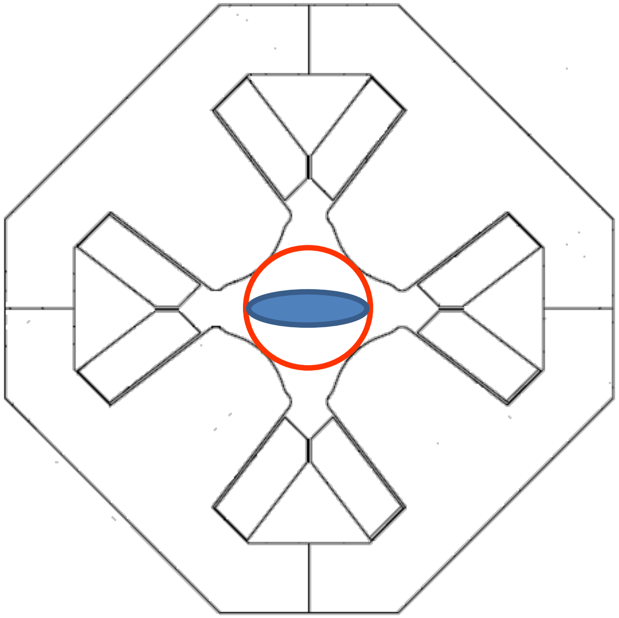


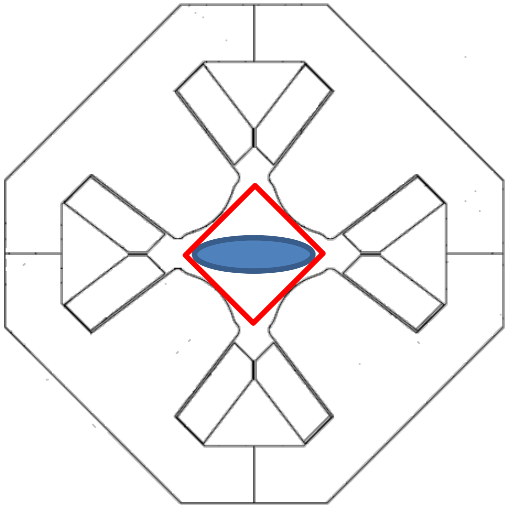


Shaping chambers to reduce bore

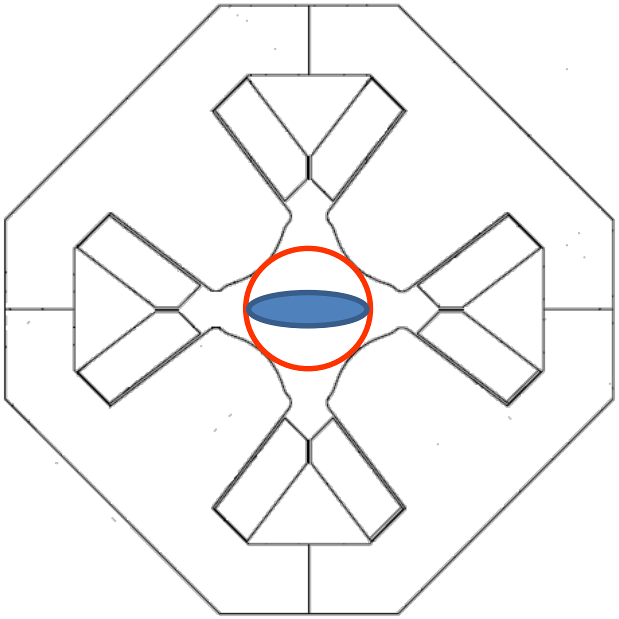


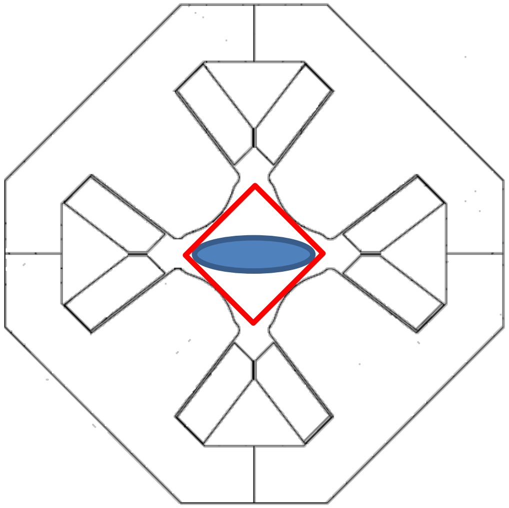
Shaping chambers to reduce bore

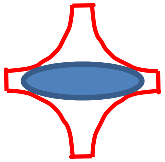




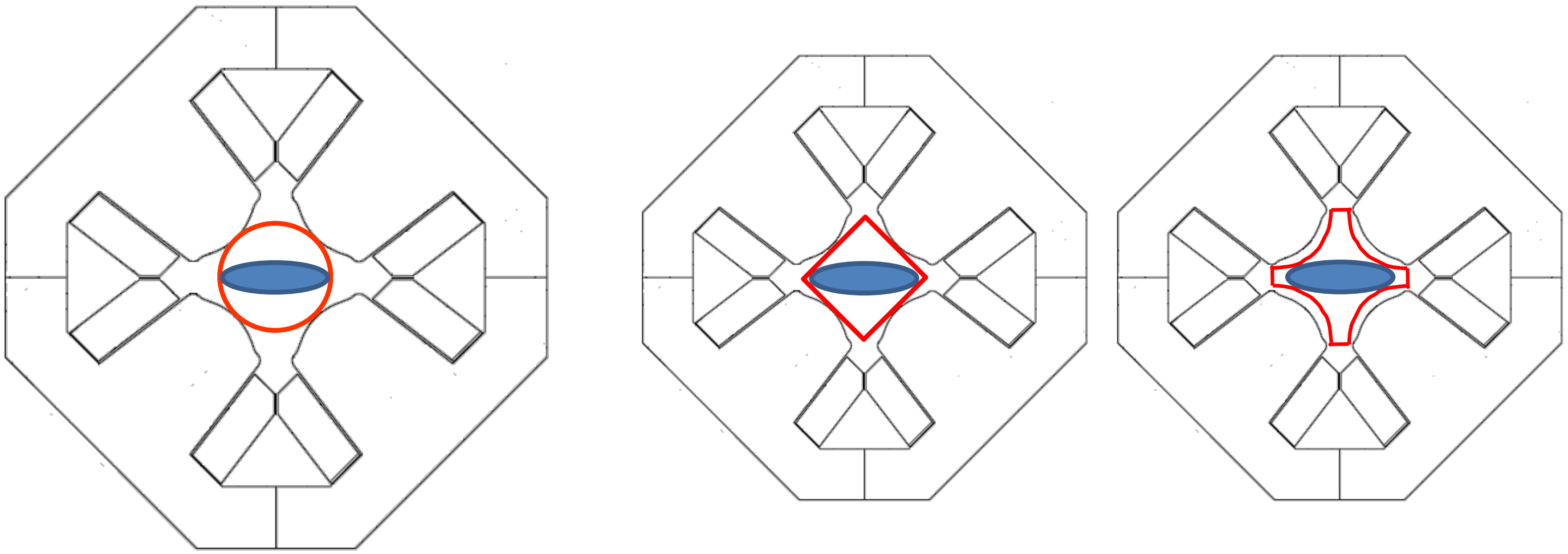
Shaping chambers to reduce bore



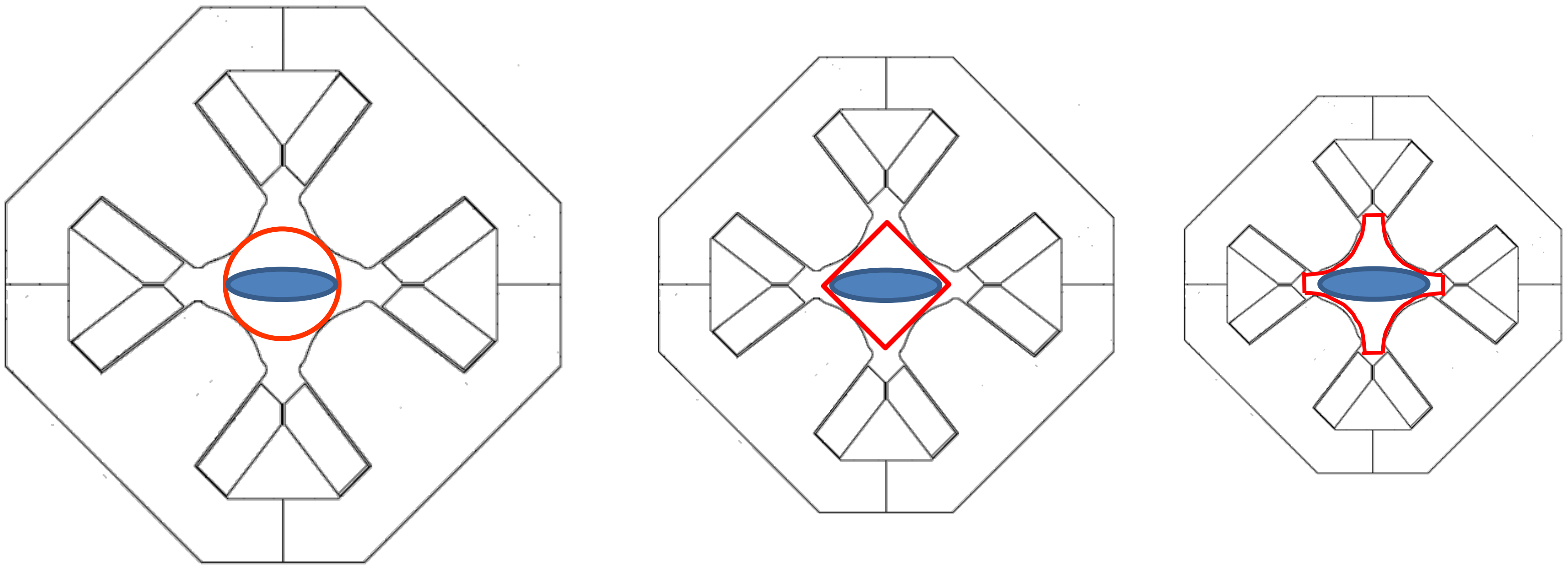




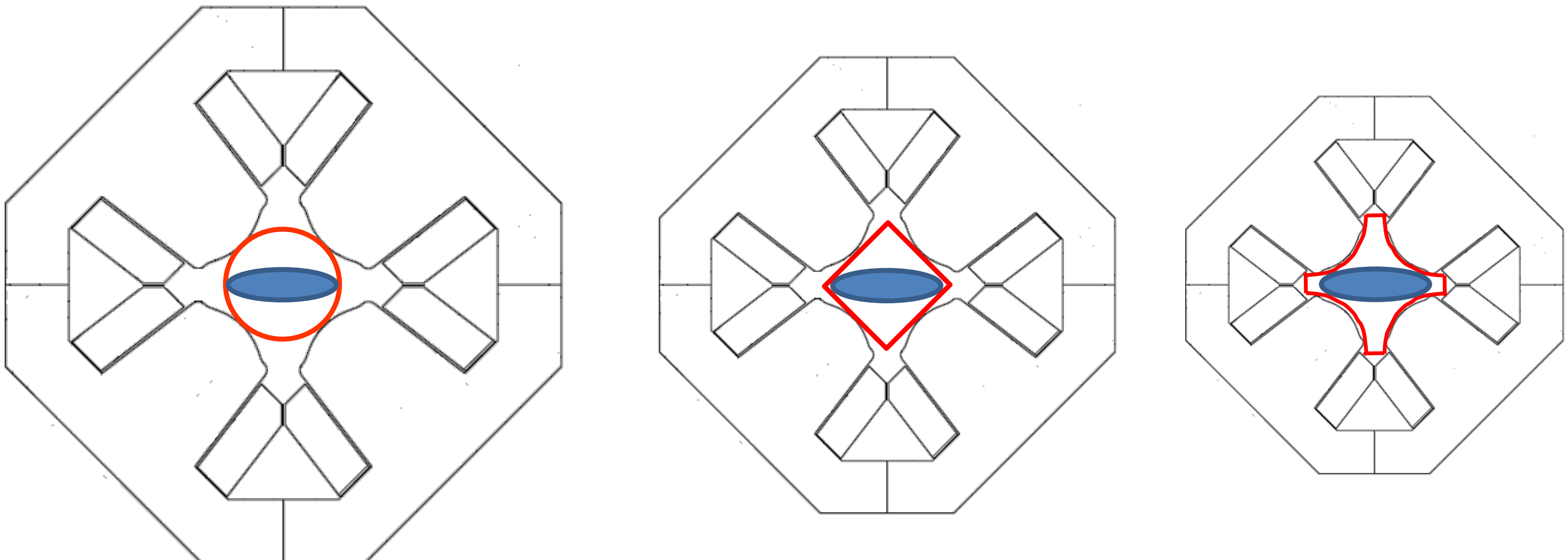
Shaping chambers to reduce bore

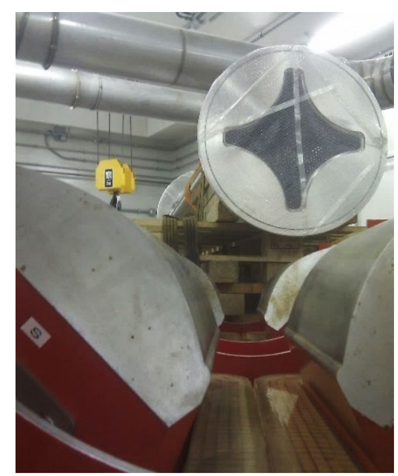


Shaping chambers to reduce bore

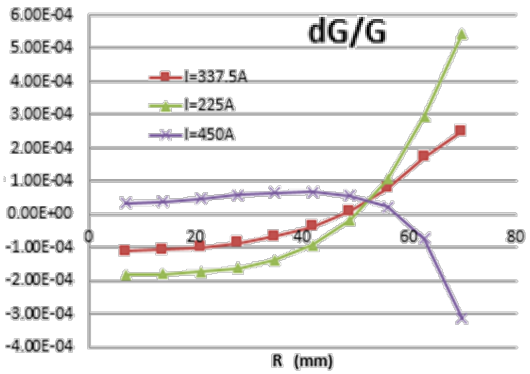


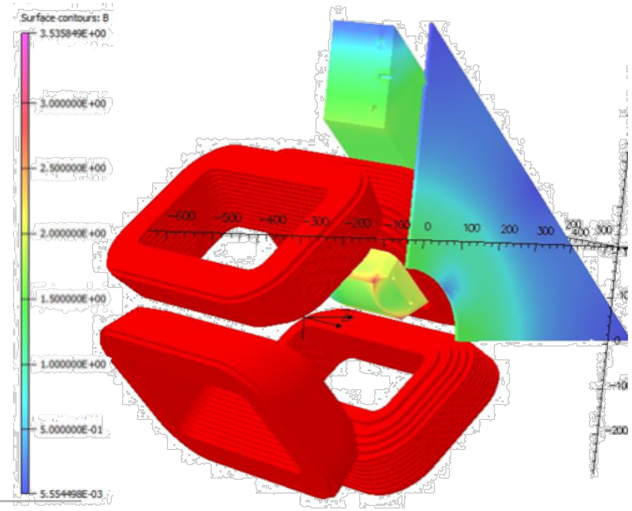
Shaping chambers to reduce bore

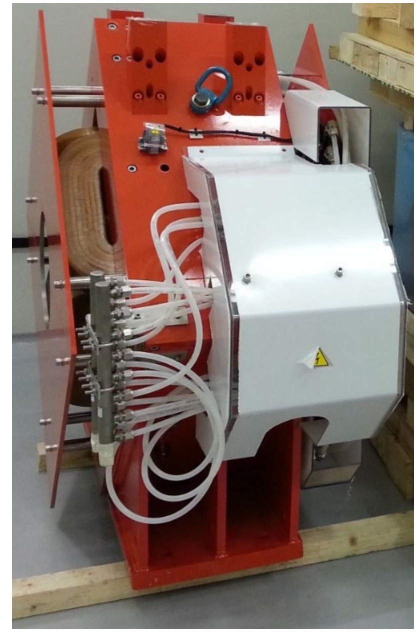


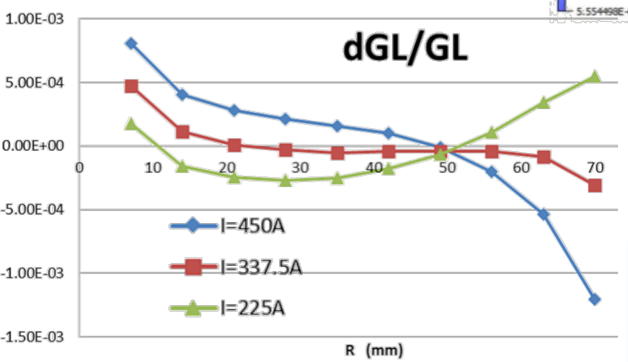


Q1

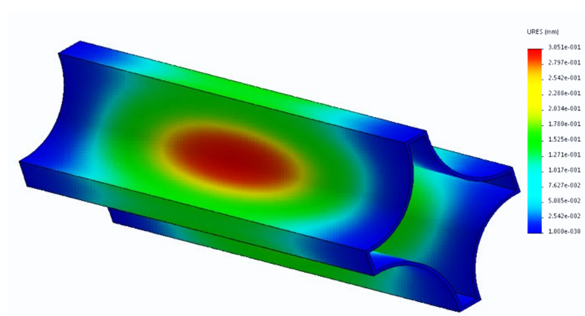


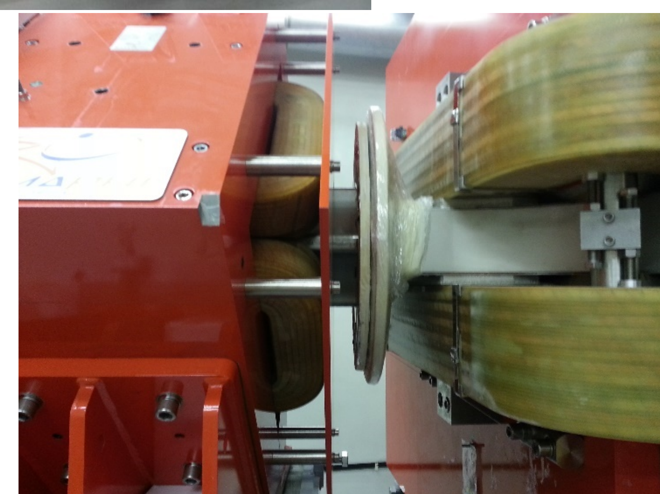






ϕ=150mm
G=13.2 T/m

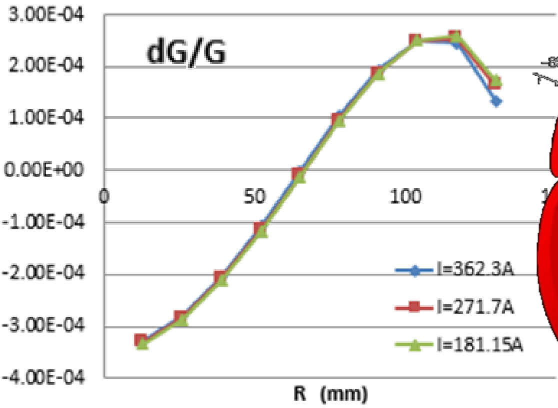


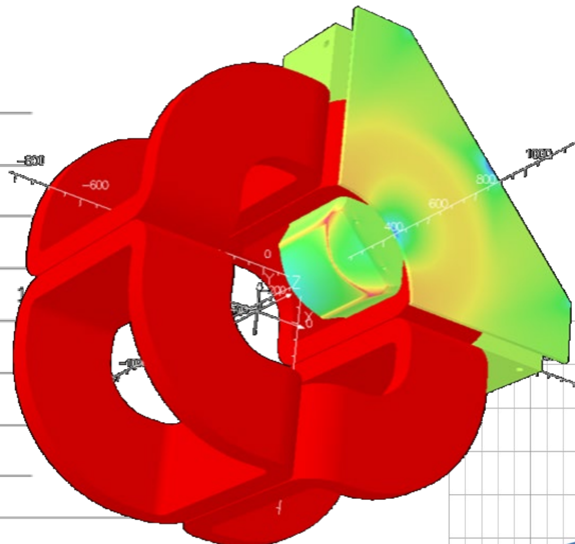


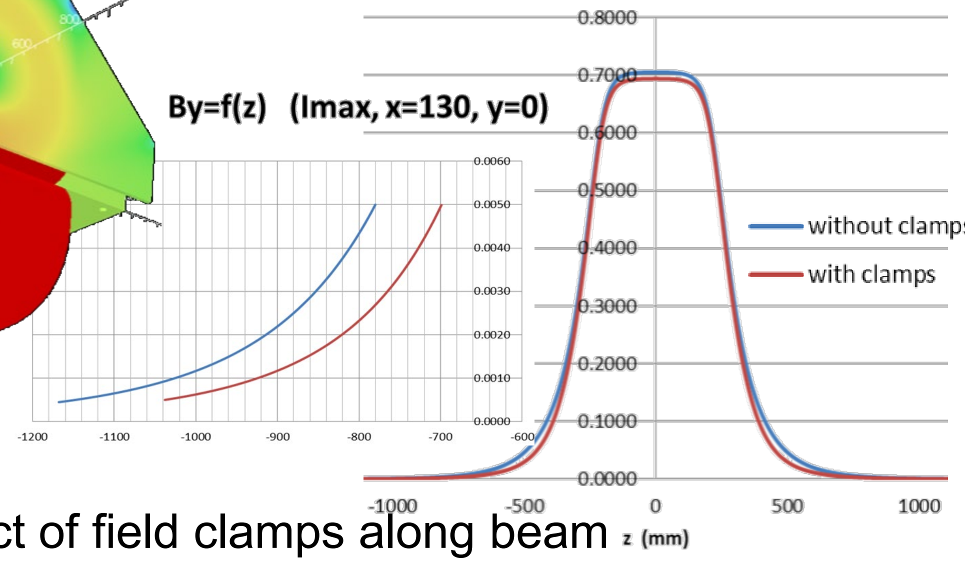
Local & integrated gradient homogeneity along radius

Q2/Q3

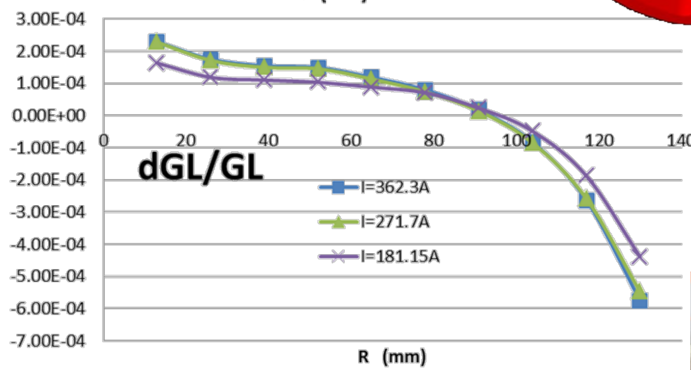
ϕ=300mm
G=5.34 T/m



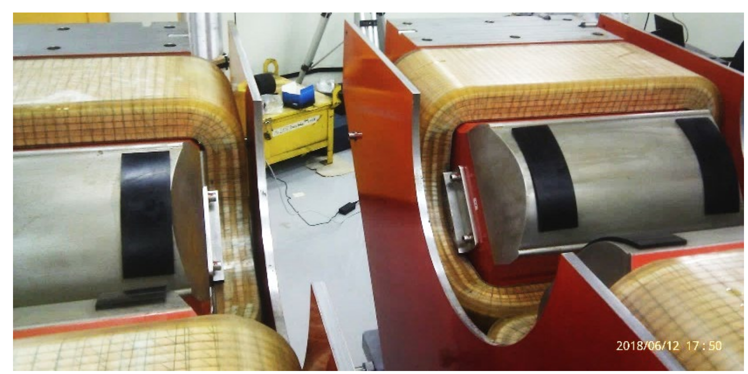




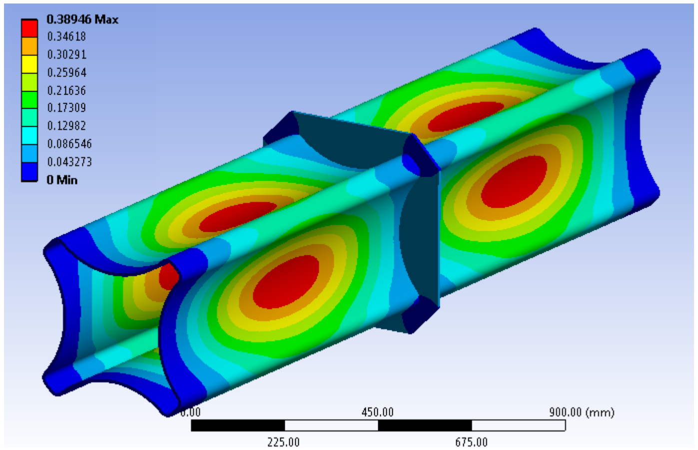
Effect of field clamps along beam

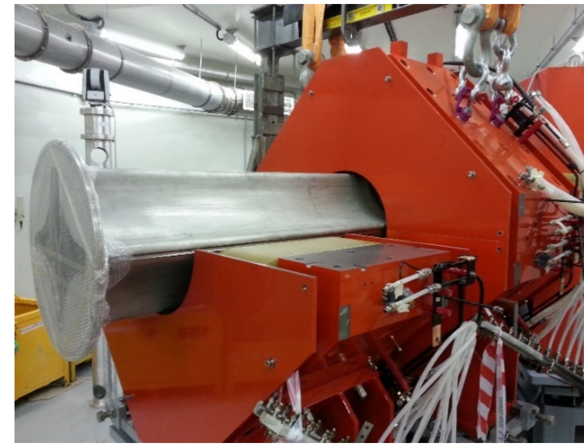


Local & integrated gradient homogeneity along radius



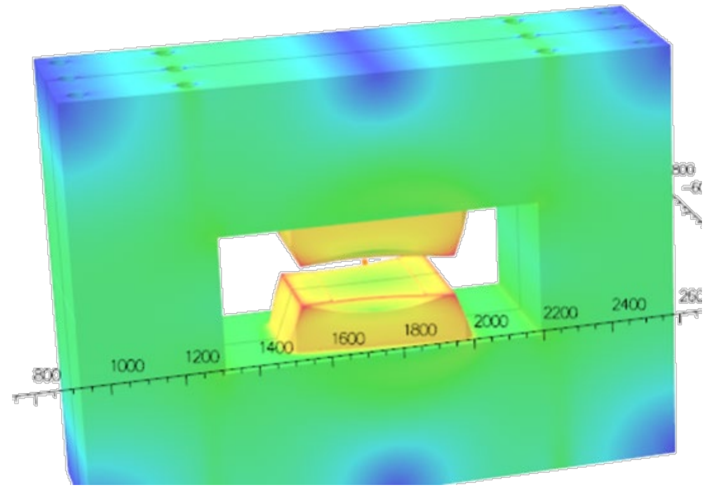
Q2/Q3 Vacuum chamber

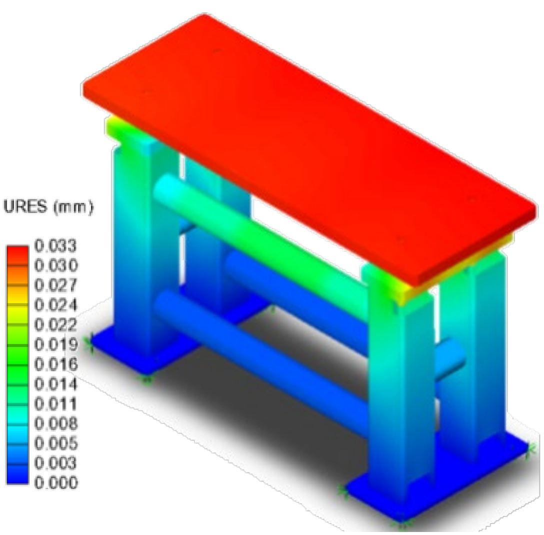


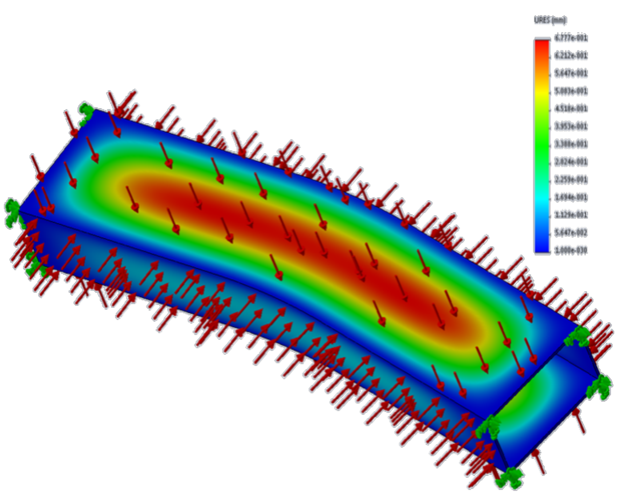


D2

Gap	132 mm
Deflection angle	10^0
Radius of curvature	1.8 m
Maximum field	1.8 T
Face pole rotation angle	0^0
Rear pole rotation angle	10^0





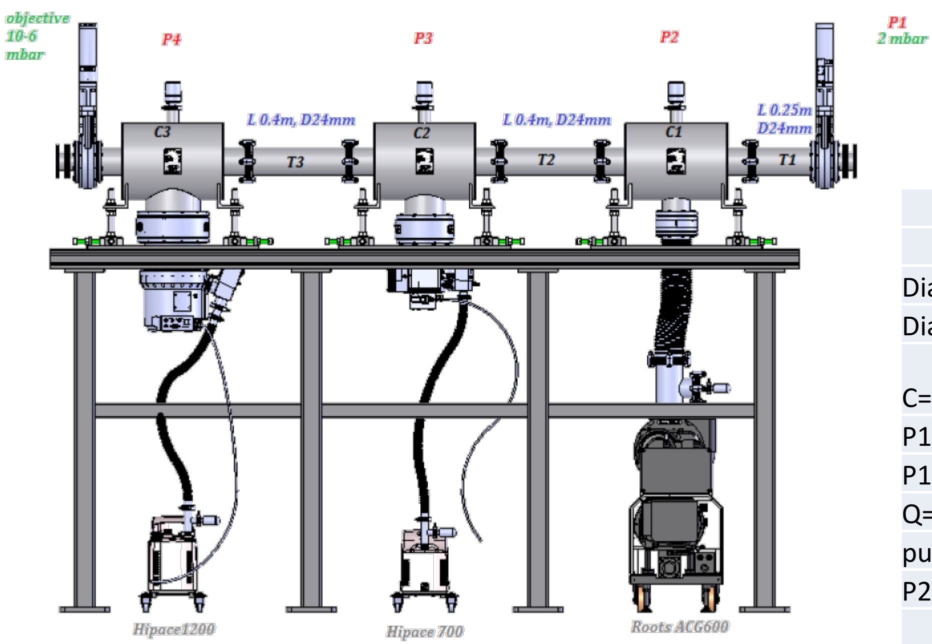


Differential pumping system

Differential pumping (1)

2 configurations

- Allows window-less operation
- Tolerate intense heavy ion beams
- Gas contributes to target cooling
- As all recent gas-filled separators TASCA, GARIS-II, SHANS



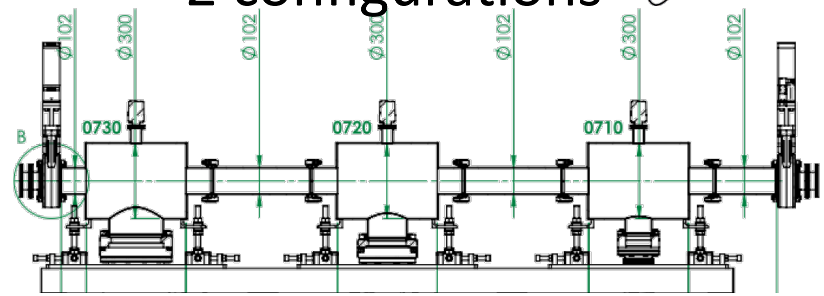
Pressure profile (case of He)

	P1	2.00E+00	P2	1.04E-01	P3	6.47E-04	mbar
	P2 goal	1.00E-03	P3 goal	1.00E-03	P4 goal	1.00E-06	mbar
Diaphragm diameter		24		24		24	mm
Diaphragm length		0.25		0.4		0.4	m
$C=1.22\ 10^{-4}*(D^3/L)$		6.75E+00		4.22E+00		4.22E+00	l/s
P1-P2		2.00E+00		1.03E-01		6.46E-04	mbar
P1-P2		1.97E-03		1.01E-04		6.37E-07	atm
Q=C*(P1-P2)		1.33E-02		4.27E-04		2.69E-06	l/s
pumping speed He		130		670		1200	l/s
P2=Q/pumping speed		1.02E-04		6.38E-07		2.24E-09	atm
	P2	1.04E-01	P3	6.47E-04	P4	2.27E-06	mbar

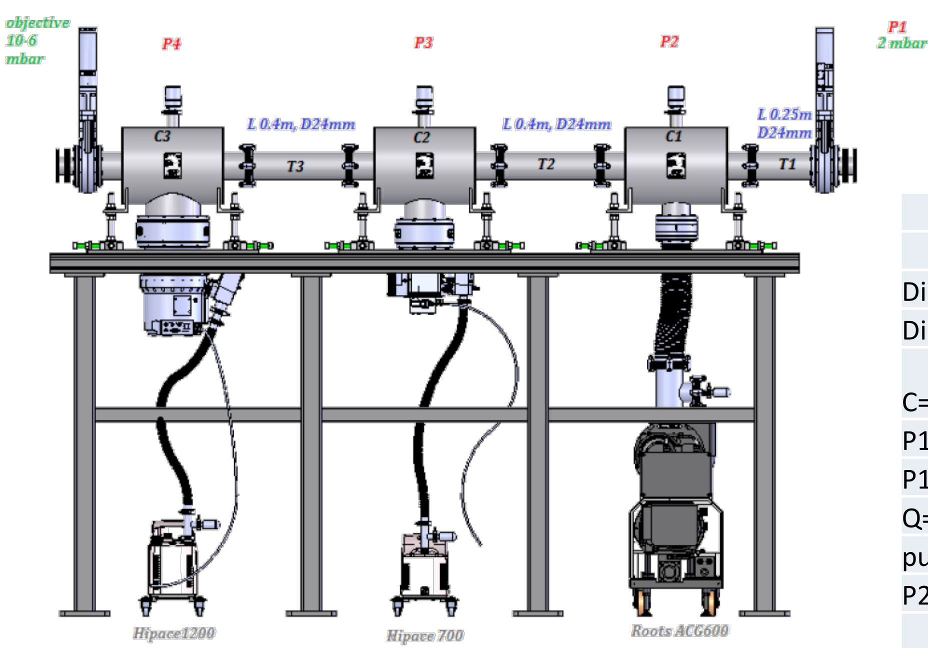
Differential pumping (1)

- Allows window-less operation
- Tolerate intense heavy ion beams
- Gas contributes to target cooling
- As all recent gas-filled separators TASCA, GARIS-II, SHANS

2 configurations



Large tubes (ϕ102): standard pumping



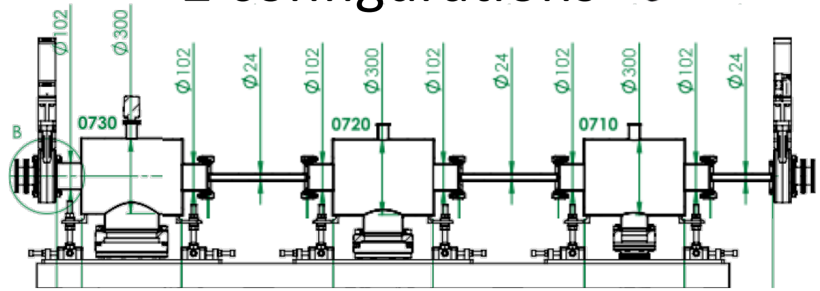
Pressure profile (case of He)

	P1	2.00E+00	P2	1.04E-01	P3	6.47E-04	mbar
	P2 goal	1.00E-03	P3 goal	1.00E-03	P4 goal	1.00E-06	mbar
Diaphragm diameter		24		24		24	mm
Diaphragm length		0.25		0.4		0.4	m
C=1.22 10^{-4}*(D^3/L)		6.75E+00		4.22E+00		4.22E+00	l/s
P1-P2		2.00E+00		1.03E-01		6.46E-04	mbar
P1-P2		1.97E-03		1.01E-04		6.37E-07	atm
Q=C*(P1-P2)		1.33E-02		4.27E-04		2.69E-06	l/s
pumping speed He		130		670		1200	l/s
P2=Q/pumping speed		1.02E-04		6.38E-07		2.24E-09	atm
	P2	1.04E-01	P3	6.47E-04	P4	2.27E-06	mbar

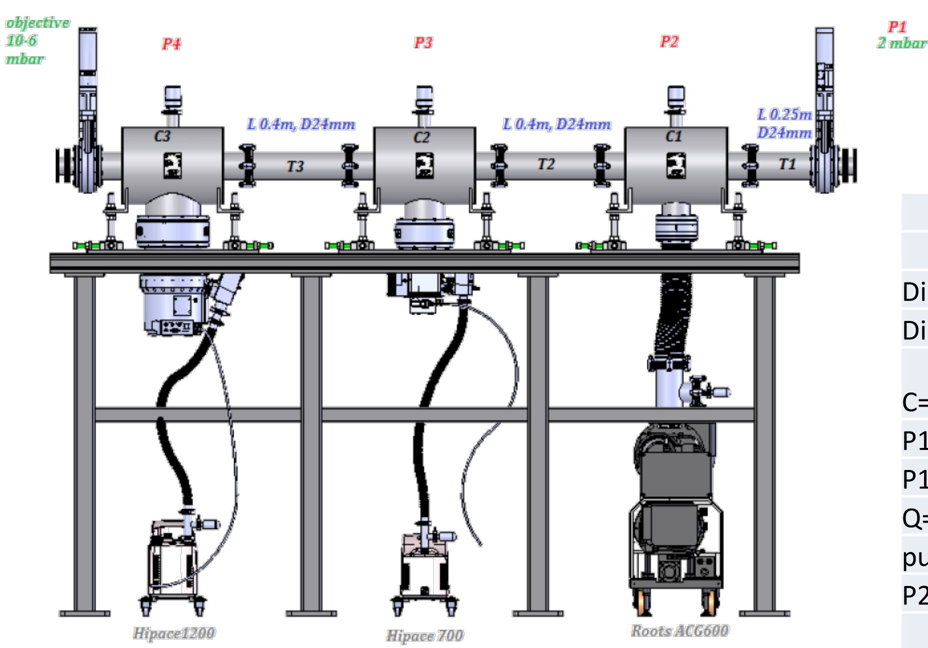
Differential pumping (1)

- Allows window-less operation
- Tolerate intense heavy ion beams
- Gas contributes to target cooling
- As all recent gas-filled separators TASCA, GARIS-II, SHANS

2 configurations



Diaphragms (ϕ24) : differential pumping

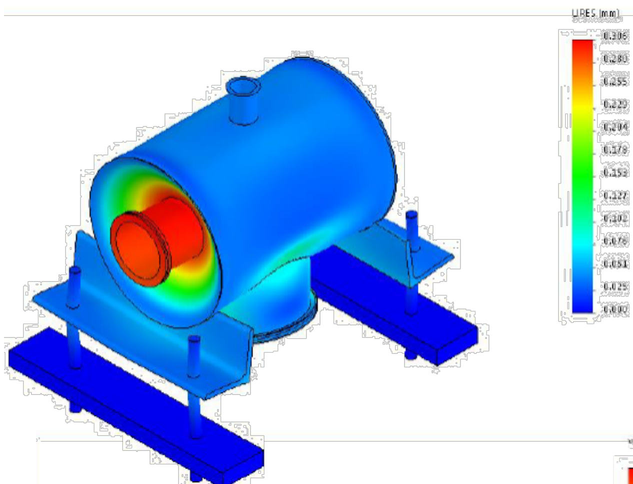


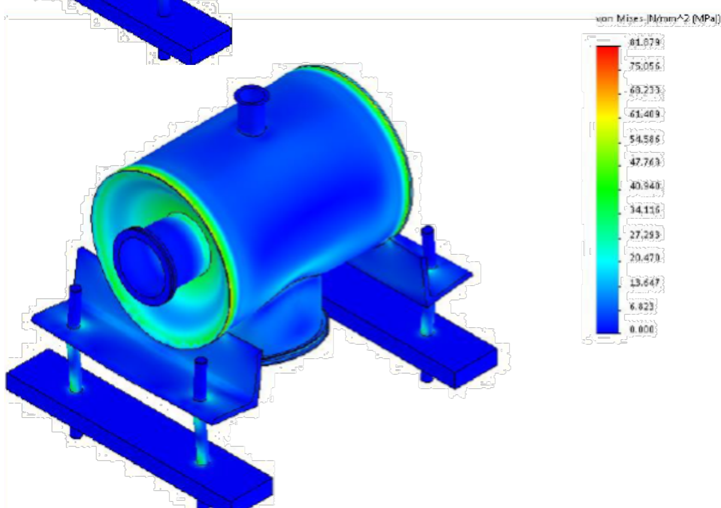
Pressure profile (case of He)

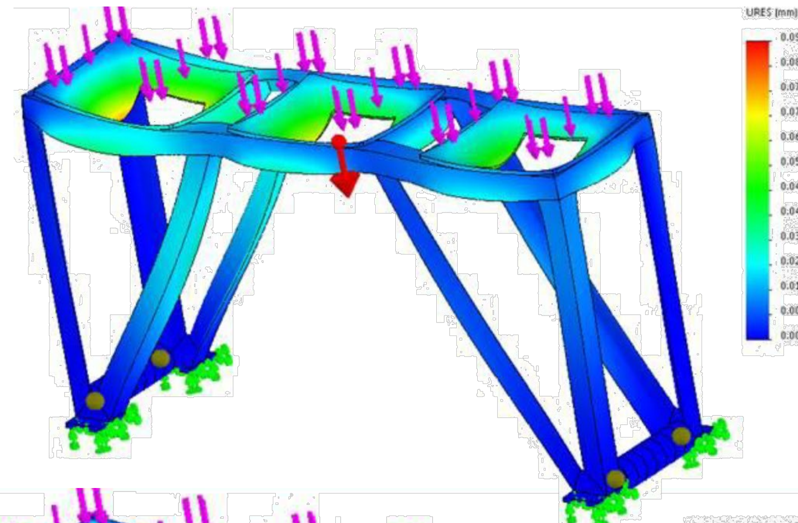
	P1	2.00E+00	P2	1.04E-01	P3	6.47E-04	mbar
	P2 goal	1.00E-03	P3 goal	1.00E-03	P4 goal	1.00E-06	mbar
Diaphragm diameter		24		24		24	mm
Diaphragm length		0.25		0.4		0.4	m
C=1.22 10^{-4}*(D^3/L)		6.75E+00		4.22E+00		4.22E+00	l/s
P1-P2		2.00E+00		1.03E-01		6.46E-04	mbar
P1-P2		1.97E-03		1.01E-04		6.37E-07	atm
Q=C*(P1-P2)		1.33E-02		4.27E-04		2.69E-06	l/s
pumping speed He		130		670		1200	l/s
P2=Q/pumping speed		1.02E-04		6.38E-07		2.24E-09	atm
	P2	1.04E-01	P3	6.47E-04	P4	2.27E-06	mbar

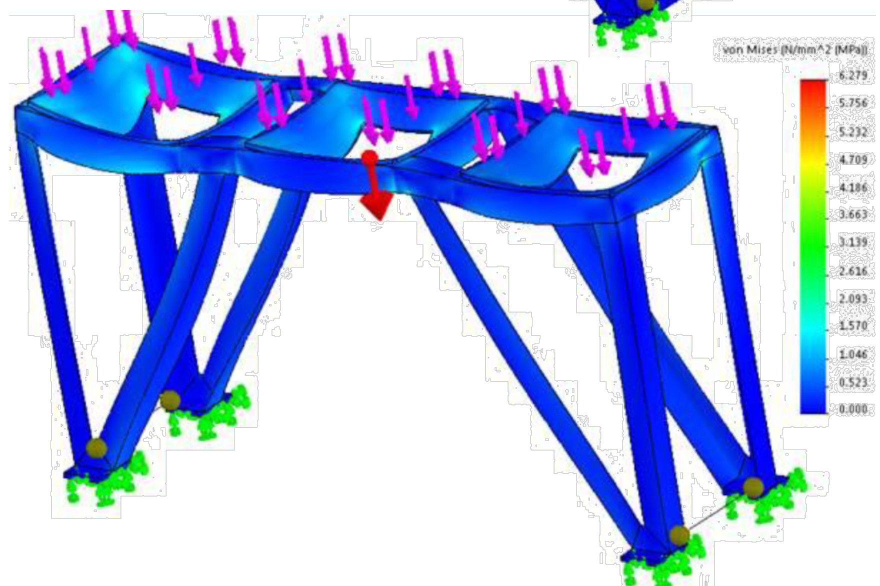
Differential pumping (2)

Mechanically sound









Differential pumping (3)

Factory testing

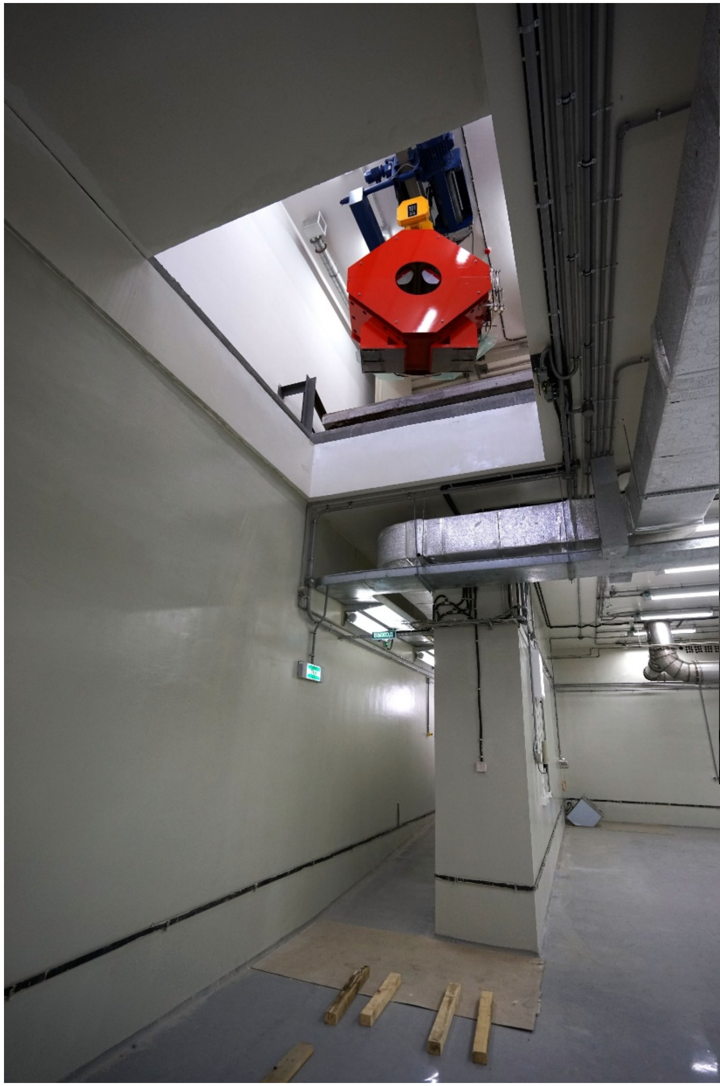
Power supplies

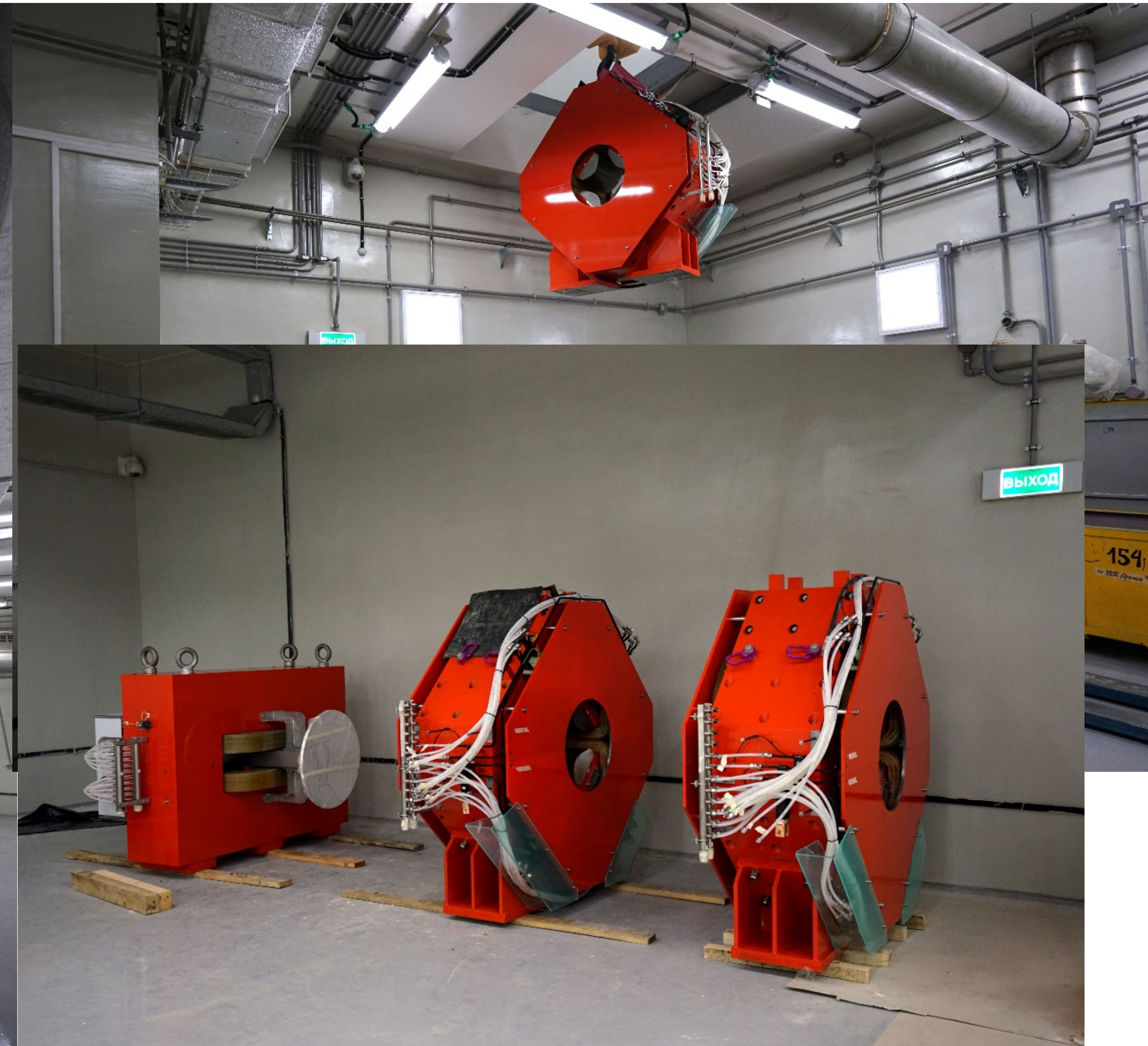
Power supplies

Installation

June 05th-14th 2018

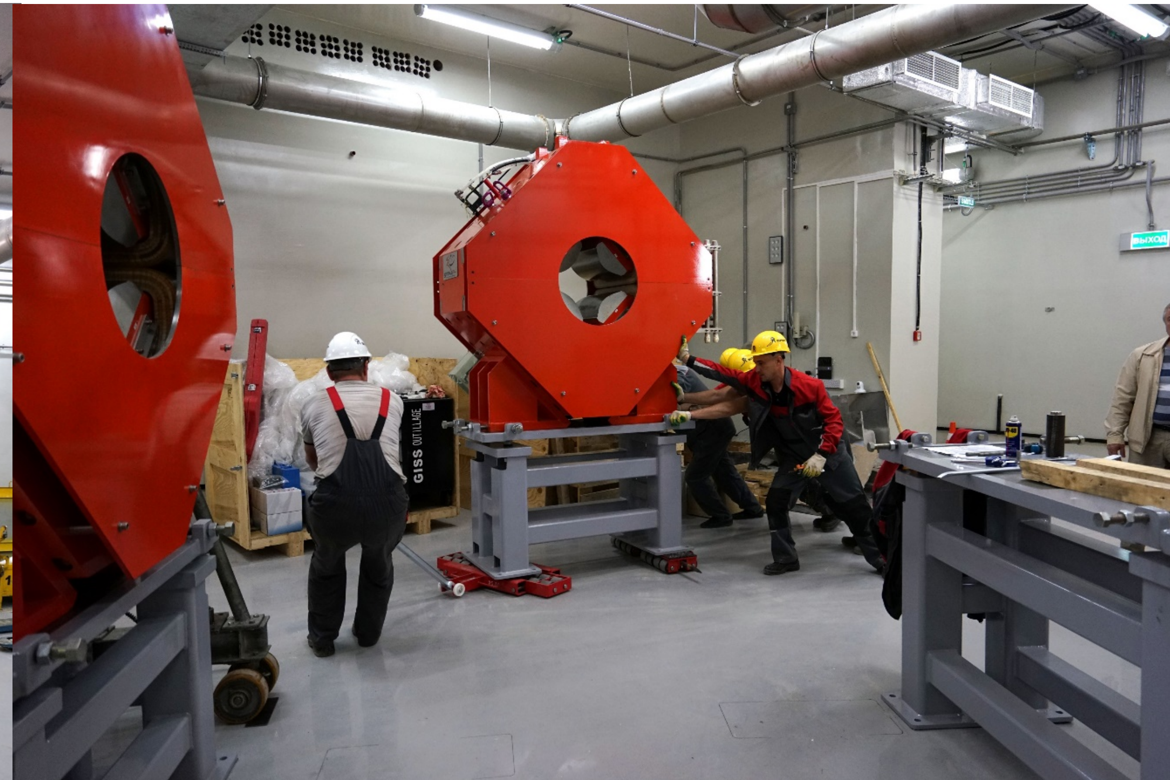
No crane! So what? (1)





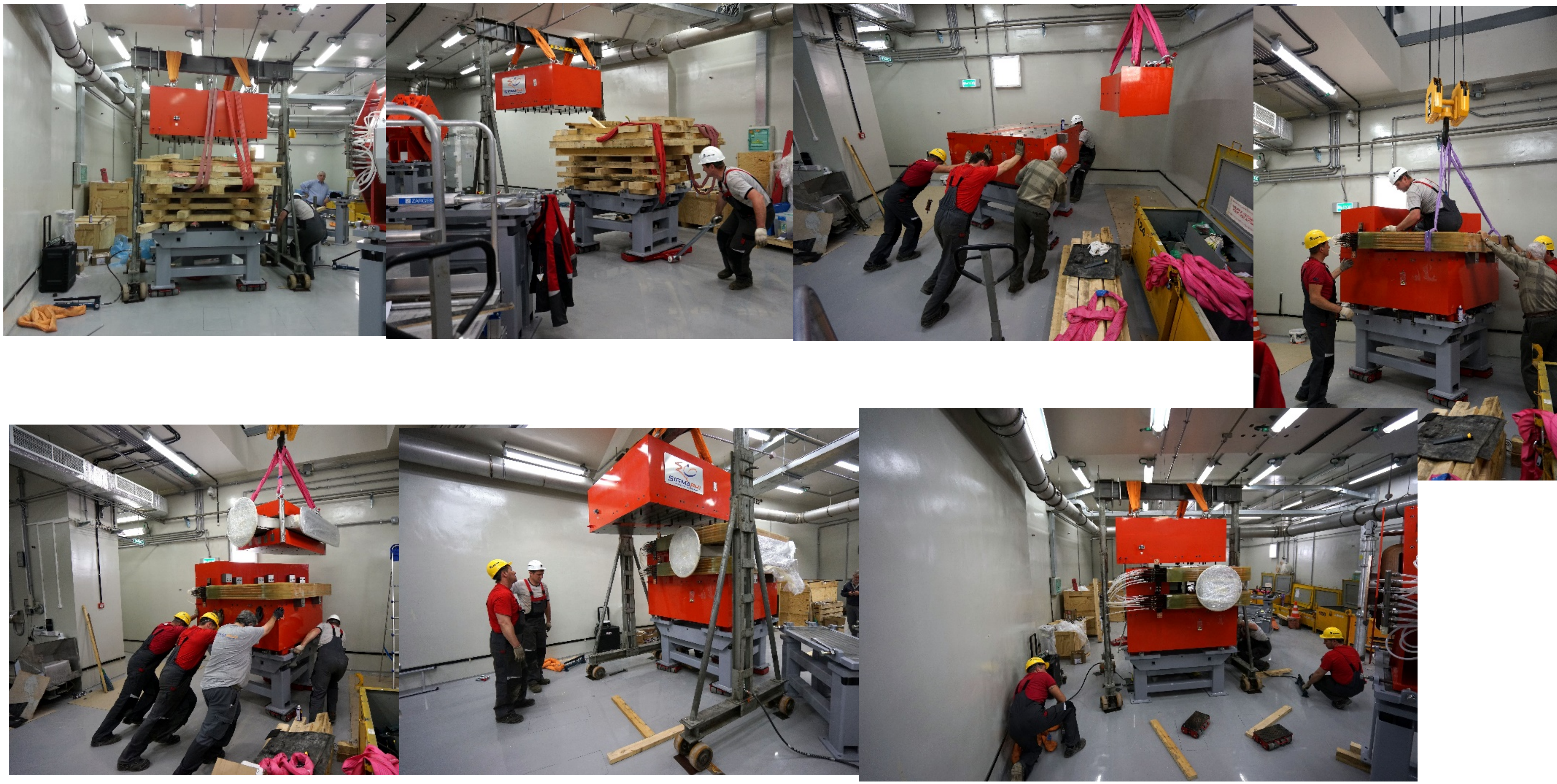
No crane! So what? (1)

No crane! So what? (2)



No crane! So what? (3)

No crane! So what? (4)



Alignment

Alignment

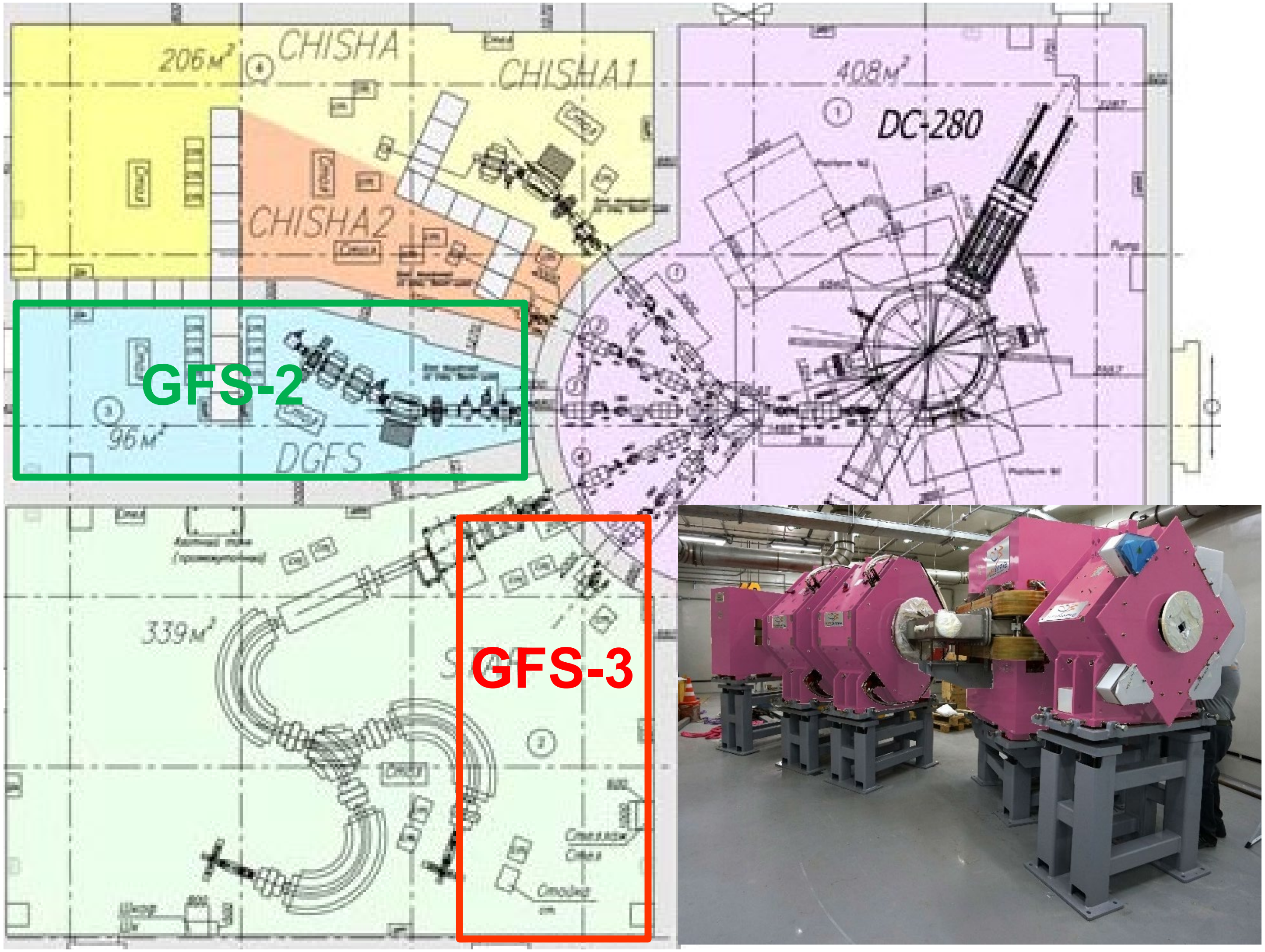
- Leica laser tracker AT401
- Red ring 2.5” targets
- Polyworks software
- Global Alignment accuracy within ± 0.1 mm

The near future

2018 GFS-2 acceptance tests
2018 GFS-2 first beam tests

2018 GFS-3 start fabrication
2019 GFS-3 installation

Future plans



We also built friendship

SIGMAPHI
MAGNETS AND BEAM TRANSPORT

Human interaction

JINR
114 Flerovium
FLNR
Dubna

Team spirit

Conclusions

- GFS-2 is installed and under commissioning. First runs should start by end 2018
- A global contract has opened the possibility for thorough optimization.
- A similar (chiral symmetry) system is produced and will be installed in 2019
- A wonderful human experience!

Thank you for your attention

The essence of the beautiful is unity in variety

W. Somerset Maugham

Questions ?