



# 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



**More on Thursday**

13:40

THC01: Igor Kalagin - Cyclotron Facility for Super Heavy Elements Research



# Super Heavy Elements



## WHY ?



**SIGMA PHI**  
MAGNETS AND BEAM TRANSPORT

# Filling in Mendeleev's



## Tableau périodique des éléments

Université de Paris et des Hauts-de-Seine  
scienceamusante.net  
wiki+forum  
chimie physique biologie

Numéro atomique

Nom de l'élément  
Masse atomique, basée sur  $^{100}$ C  
[ ] : nombre de masse de l'isotope le plus stable

Électronégativité (échelle de Pauling)

Energie de première ionisation (eV)

Configuration électronique (en rouge : exception à la règle de Koekoek)

Principaux nombres d'oxydation (le plus fréquent en gris)

1	H	Hydrogène	1,008	13,99	1s <sup>1</sup>	-1 +1	2						
2	He	Hélium	4,003	24,60	1s <sup>2</sup>	-	1s <sup>0</sup>						
3	Li	Lithium	6,94	6,991	1s <sup>2</sup> 2s <sup>1</sup>	+1	4	Be	Béryllium	9,012	9,322	1s <sup>2</sup> 2s <sup>2</sup>	+2
4	Mg	Magnésium	24,31	7,646	[Ne] 3s <sup>2</sup>	+2	5	B	Bore	10,81	8,798	1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>1</sup>	+3
11	Na	Sodium	22,99	6,139	[Ne] 3s <sup>1</sup>	+1	12	Al	Aluminium	26,98	8,985	1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>1</sup>	+3
19	K	Potassium	38,10	4,340	[Ar] 4s <sup>1</sup>	+1	20	Ca	Calcium	40,08	8,620	[Ar] 4s <sup>2</sup>	-
21	Sc	Scandium	44,95	8,613	[Ar] 3d <sup>1</sup> 4s <sup>2</sup>	+3	22	Ti	Titanium	47,87	8,746	[Ar] 3d <sup>2</sup> 4s <sup>2</sup>	+3
23	V	Vanadium	50,94	8,796	[Ar] 3d <sup>3</sup> 4s <sup>2</sup>	+3	24	Cr	Chrome	52,00	8,796	[Ar] 3d <sup>4</sup> 4s <sup>1</sup>	+5
25	Mn	Manganèse	54,94	7,902	[Ar] 3d <sup>5</sup> 4s <sup>2</sup>	+3	26	Fe	Fer	55,85	7,881	[Ar] 3d <sup>6</sup> 4s <sup>2</sup>	+3
27	Co	Cobalt	58,93	7,839	[Ar] 3d <sup>7</sup> 4s <sup>2</sup>	+3	28	Ni	Nickel	58,69	7,726	[Ar] 3d <sup>8</sup> 4s <sup>2</sup>	+3
29	Cu	Cuivre	63,56	8,394	[Ar] 3d <sup>9</sup> 4s <sup>1</sup>	+1	30	Zn	Zinc	65,38	8,399	[Ar] 3d <sup>10</sup> 4s <sup>2</sup>	+2
31	Ga	Gallium	69,72	8,782	[Ar] 3d <sup>10</sup> 4p <sup>1</sup>	+1	32	Ge	Germanium	72,63	8,782	[Ar] 3d <sup>10</sup> 4p <sup>2</sup>	+2
33	As	Arsenic	74,92	8,782	[Ar] 3d <sup>10</sup> 4p <sup>3</sup>	+3	34	Se	Sélénium	78,96	8,782	[Ar] 3d <sup>10</sup> 4p <sup>4</sup>	+4
35	Br	Brome	78,96	8,782	[Ar] 3d <sup>10</sup> 4p <sup>5</sup>	+5	36	Kr	Krypton	83,80	8,782	[Ar] 3d <sup>10</sup> 4p <sup>6</sup>	+6
37	Rb	Rubidium	86,47	4,177	[Ar] 5s <sup>1</sup>	+1	38	Sr	Strontium	87,62	8,694	[Ar] 5s <sup>2</sup>	+2
39	Y	Yttrium	88,91	8,633	[Ar] 5s <sup>2</sup> 4d <sup>1</sup>	+3	40	Zr	Zirconium	91,22	8,750	[Ar] 5s <sup>2</sup> 4d <sup>2</sup>	+4
41	Nb	Niobium	92,91	8,750	[Ar] 5s <sup>2</sup> 4d <sup>3</sup>	+5	42	Mo	Molybdène	95,96	7,702	[Ar] 5s <sup>2</sup> 4d <sup>4</sup>	+6
43	Tc	Technétium	[98]	8,736	[Ar] 5s <sup>2</sup> 4d <sup>5</sup>	+7	44	Ru	Ruthénium	101,07	2,2	[Ar] 5s <sup>2</sup> 4d <sup>6</sup>	+7
45	Rh	Rhodium	102,81	7,466	[Ar] 5s <sup>2</sup> 4d <sup>7</sup>	+8	46	Pd	Palladium	106,42	8,336	[Ar] 5s <sup>2</sup> 4d <sup>8</sup>	+8
47	Ag	Argent	107,87	7,878	[Ar] 5s <sup>2</sup> 4d <sup>9</sup>	+9	48	Cd	Cadmium	112,41	8,863	[Ar] 5s <sup>2</sup> 4d <sup>10</sup>	+10
49	In	Ininium	114,82	7,878	[Ar] 5s <sup>2</sup> 4d <sup>10</sup> 5p <sup>1</sup>	+1	50	Sn	Etain	118,71	8,736	[Ar] 5s <sup>2</sup> 4d <sup>10</sup> 5p <sup>2</sup>	+2
51	Sb	Antimoine	121,76	8,863	[Ar] 5s <sup>2</sup> 4d <sup>10</sup> 5p <sup>3</sup>	+3	52	Te	Tellure	127,80	8,863	[Ar] 5s <sup>2</sup> 4d <sup>10</sup> 5p <sup>4</sup>	+4
53	I	Iode	131,29	10,45	[Ar] 5s <sup>2</sup> 4d <sup>10</sup> 5p <sup>5</sup>	+5	54	Xe	Xénon	132,90	12,12	[Ar] 5s <sup>2</sup> 4d <sup>10</sup> 5p <sup>6</sup>	+6
55	Cs	Césium	132,91	3,893	[Ar] 6s <sup>1</sup>	+1	56	Ba	Baryum	137,33	8,711	[Ar] 6s <sup>2</sup>	+2
57	La	Lanthane	138,91	8,677	[Ar] 6s <sup>2</sup> 5d <sup>1</sup>	+3	58	Ce	Cérium	140,12	8,630	[Ar] 6s <sup>2</sup> 5d <sup>1</sup>	+3
59	Pr	Praséodyme	140,91	8,646	[Ar] 6s <sup>2</sup> 5d <sup>2</sup>	+4	60	Nd	Néodyme	144,24	8,628	[Ar] 6s <sup>2</sup> 5d <sup>3</sup>	+5
61	Pm	Prométhium	[145]	8,644	[Ar] 6s <sup>2</sup> 5d <sup>4</sup>	+6	62	Sm	Samarium	150,86	8,644	[Ar] 6s <sup>2</sup> 5d <sup>5</sup>	+7
63	Eu	Europium	151,96	8,644	[Ar] 6s <sup>2</sup> 5d <sup>6</sup>	+8	64	Gd	Gadolinium	158,85	8,650	[Ar] 6s <sup>2</sup> 5d <sup>7</sup>	+9
65	Tb	Terbium	161,98	8,650	[Ar] 6s <sup>2</sup> 5d <sup>8</sup>	+10	66	Dy	Dysprosium	167,26	8,656	[Ar] 6s <sup>2</sup> 5d <sup>9</sup>	+11
67	Ho	Holmium	168,93	8,662	[Ar] 6s <sup>2</sup> 5d <sup>10</sup>	+12	68	Er	Erbium	169,93	8,667	[Ar] 6s <sup>2</sup> 5d <sup>11</sup>	+13
69	Tm	Thulium	173,06	8,677	[Ar] 6s <sup>2</sup> 5d <sup>12</sup>	+13	70	Yb	Ytterbium	174,97	8,684	[Ar] 6s <sup>2</sup> 5d <sup>13</sup>	+13
71	Lu	Lutétium	174,97	8,684	[Ar] 6s <sup>2</sup> 5d <sup>14</sup>	+13	72	Fr	Francium	[223]	4,072	[Ar] 7s <sup>1</sup>	+1
73	Rf	Rutherfordium	[287]	—	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>1</sup>	+4	74	Hf	Haftium	178,49	8,625	[Ar] 7s <sup>1</sup> 5f <sup>6</sup>	+3
75	W	Tungstène	183,84	7,664	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>2</sup>	+5	76	Re	Rhénum	188,21	7,633	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>3</sup>	+7
77	Ir	Iridium	192,22	8,967	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>4</sup>	+8	78	Pt	Platine	196,08	8,988	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>5</sup>	+10
79	Au	Or	198,97	8,988	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>6</sup>	+12	80	Hg	Mercurie	200,68	10,42	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>7</sup>	+13
81	Tl	Thallium	204,38	8,718	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>8</sup>	+14	82	Pb	Plomb	207,2	8,718	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>9</sup>	+15
83	Bi	Bismuth	208,98	8,416	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>10</sup>	+16	84	Po	Polonium	[208]	8,416	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>11</sup>	+16
85	At	Astate	[210]	8,697	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>12</sup>	+17	86	Rn	Radon	[222]	10,74	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>13</sup>	+17
87	Ra	Radium	[226]	8,279	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>14</sup>	+18	88	Rf	Rutherfordium	[287]	—	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>15</sup>	+18
89	Ac	Actinium	[227]	8,117	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>15</sup>	+18	90	Th	Thorium	232,04	8,306	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>16</sup>	+18
91	Pa	Protactinium	231,04	8,689	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>17</sup>	+18	92	U	Uranium	238,03	8,194	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>18</sup>	+18
93	Np	Neptunium	[237]	8,285	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>19</sup>	+18	94	Pu	Plutonium	[244]	8,626	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>19</sup>	+18
95	Am	Américium	[243]	8,672	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>20</sup>	+18	96	Cm	Curium	[247]	8,672	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>20</sup>	+18
97	Bk	Berkélium	[247]	8,623	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>21</sup>	+18	98	Cf	Californium	[251]	8,630	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>21</sup>	+18
99	Es	Einsteinium	[258]	8,642	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>22</sup>	+18	100	Fm	Fermium	[257]	8,650	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>22</sup>	+18
101	Md	Mendélévium	[268]	8,680	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>23</sup>	+18	102	No	Nobélium	[268]	8,680	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>23</sup>	+18
103	Lr	Lawrencium	[262]	8,680	[Ar] 7s <sup>1</sup> 5f <sup>6</sup> 6d <sup>24</sup>	+18	119	120					

# Filling in Mendeleev's

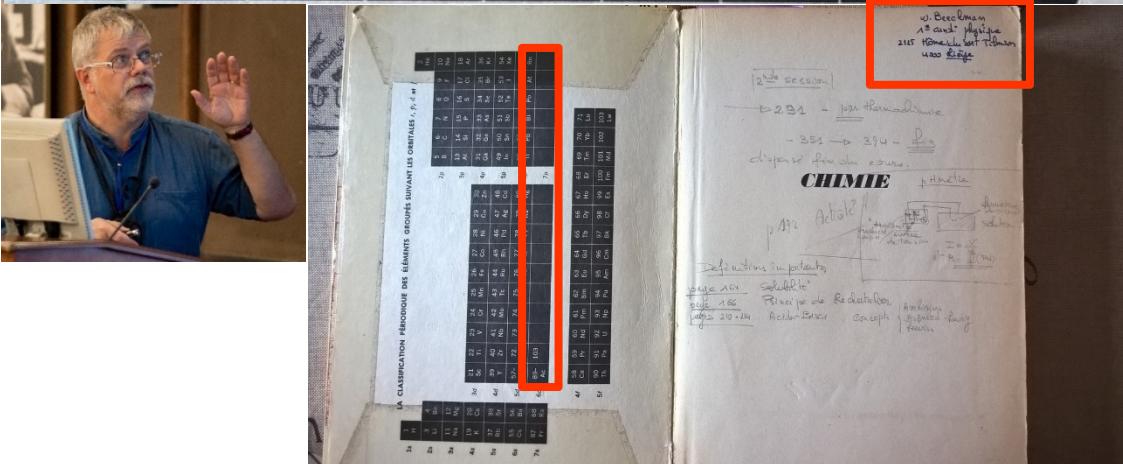
89 à 103	104 <b>Rf</b> Rutherfordium [267]	105 <b>Db</b> Dubnium [268]	106 <b>Sg</b> Seaborgium [271]	107 <b>Bh</b> Bohrium [272]	108 <b>Hs</b> Hassium [277]	109 <b>Mt</b> Meitnerium [278]	110 <b>Ds</b> Darmstadtium [281]	111 <b>Rg</b> Roentgenium [280]	112 <b>Cn</b> Copernicium [285]	113 <b>Nh</b> Nihonium [288]	114 <b>Fl</b> Flerovium [289]	115 <b>Mc</b> Moscovium [288]	116 <b>Lv</b> Livermorium [293]	117 <b>Ts</b> Tennessine [284]	118 <b>Og</b> Oganesson [284]
	[ $Z=89$ ] 7s $\times$ 5f $\times$ 6d $\times$ 4	[ $Z=90$ ] 7s $\times$ 5f $\times$ 6d $\times$ 5	[ $Z=91$ ] 7s $\times$ 5f $\times$ 6d $\times$ 6	[ $Z=92$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	[ $Z=93$ ] 7s $\times$ 5f $\times$ 6d $\times$ 6	[ $Z=94$ ] 7s $\times$ 5f $\times$ 6d $\times$ 6	[ $Z=95$ ] 7s $\times$ 5f $\times$ 6d $\times$ 6	[ $Z=96$ ] 7s $\times$ 5f $\times$ 6d $\times$ 6	[ $Z=97$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	[ $Z=98$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	[ $Z=99$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	[ $Z=100$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	[ $Z=101$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	[ $Z=102$ ] 7s $\times$ 5f $\times$ 6d $\times$ 7	

The 7th period of the table in 2017: complete with its last element named after one of its most prominent scientist ... during his lifetime.  
Yuri Oganessian during his talk at ECPM conference, Dubna 03-11-2018



The same row in my 1st year (1977) chemistry textbook (Mahan 2<sup>nd</sup> ed 1969)

103														7p
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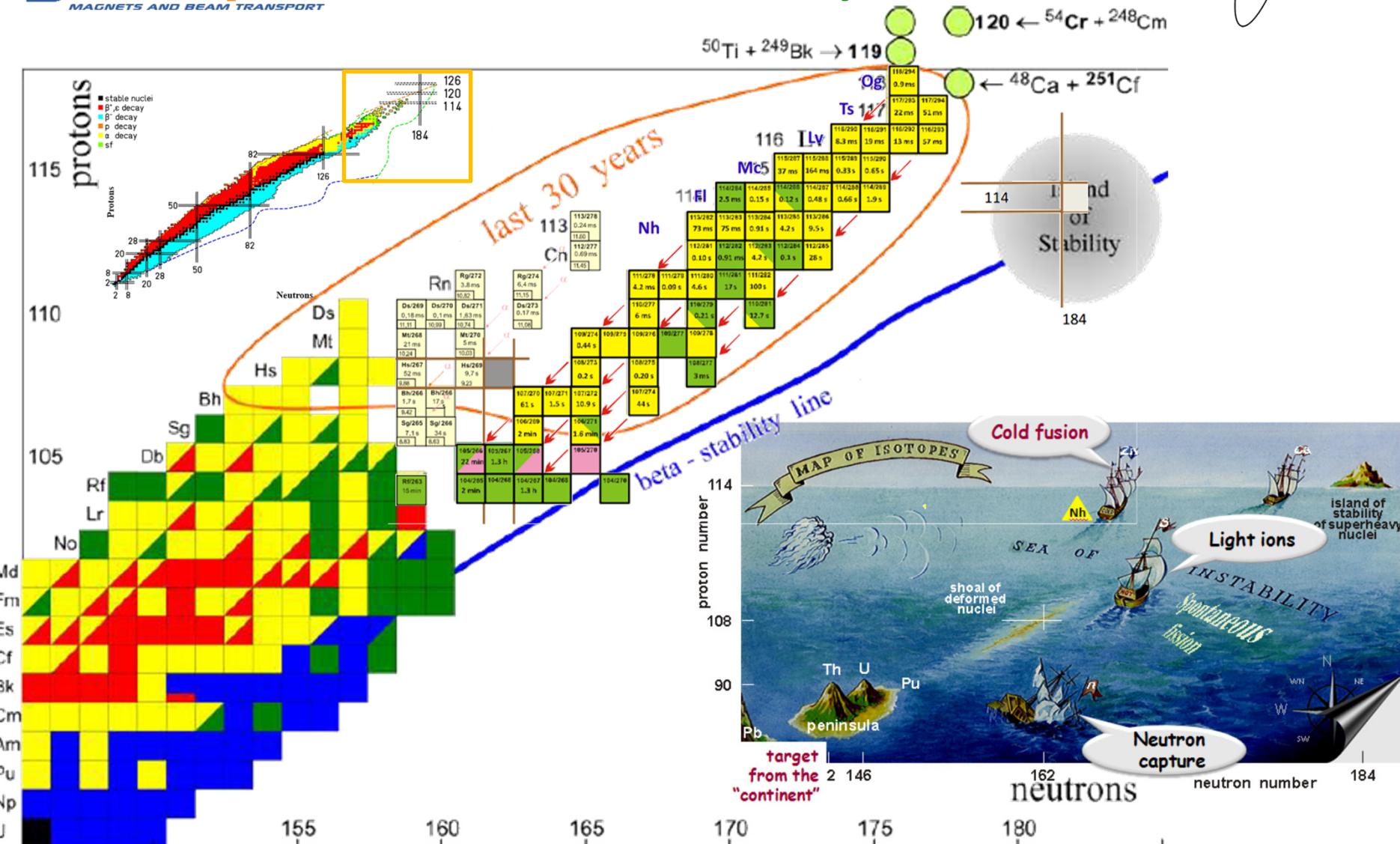


However, there's an upper limit  
~Z=122 for differences in  
chemical properties of adjacent  
nuclei  
~Z=173 for nucleus existence



**SIGMAPHI**  
Magnets and Beam Transport

# Heading towards stability



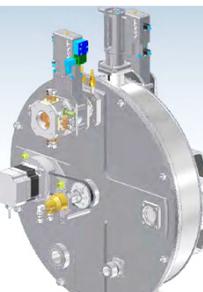
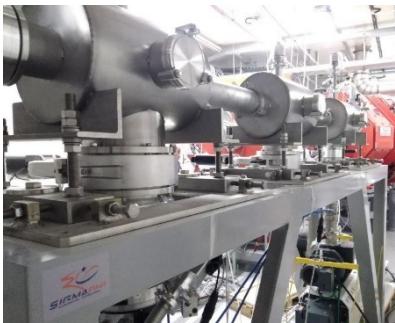


# Super Heavy Elements

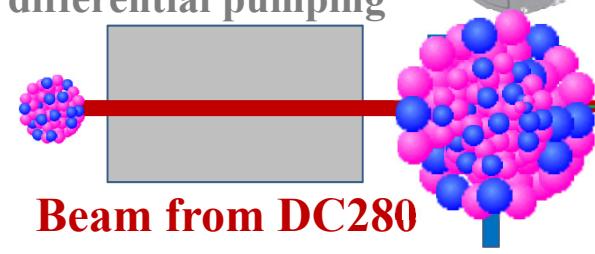


## HOW ?

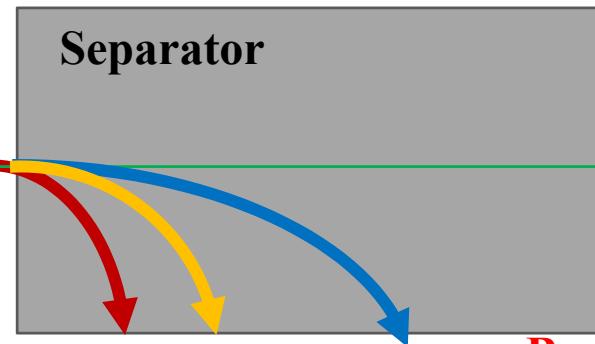
# Schematics of a separator



Window or  
differential pumping



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



48×128 strips    128×128 strips  
6144 pixels    16384 pixels



Focal plane  
detectors

ToF

Detector box



Micron Semiconductors, UK



**SIGMAPHI**  
MAGNETS AND BEAM TRANSPORT

# GFS-2

JINR  
114 Flerovium  
**FLNR**  
Dubna



Reaction products in magnetic separator suffer from

Contamination

Many charge states

Large emission angle

Improve rejection

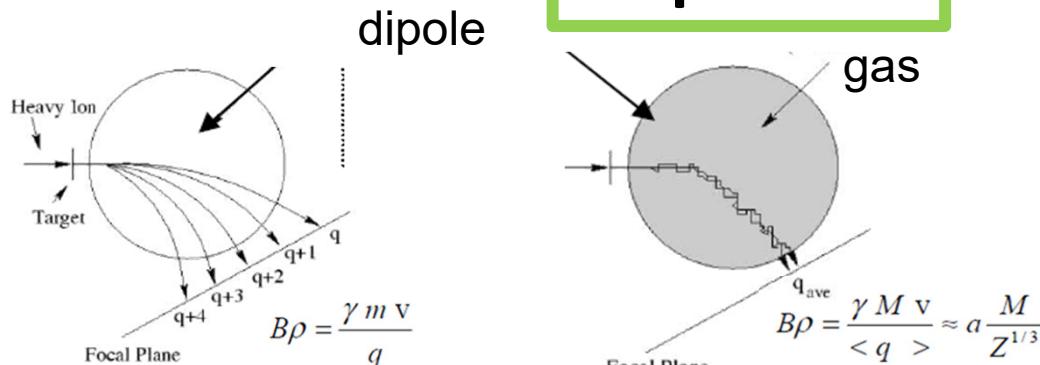
Bending angle  
dispersion

**Separator**

Promote  
mechanisms that  
narrow the charge  
state distribution

**Gas-filled  
Separator**

Increase  
acceptance/transmission  
Optics  
Large apertures  
Focusing  
Optimized chambers



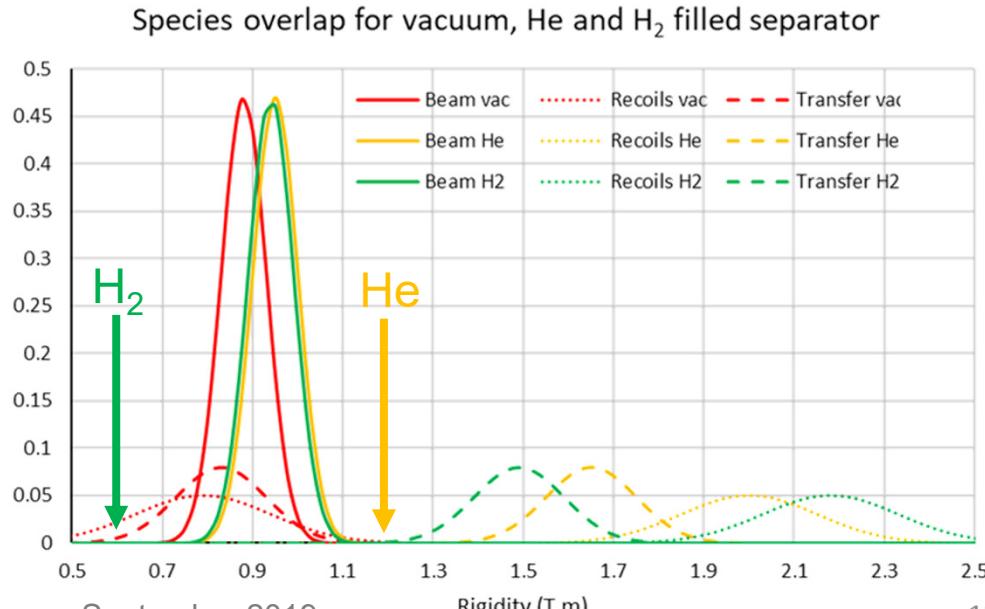
**Large acceptance  
Gas-filled  
Separator**

# Discriminating from background

- Primary beam
- Scattered beam
- Transfer (target-like) products
- High-energy protons or alphas
- Neutrons
- Gammas



Nucl.	E(MeV)	Bp vac (T·m)	Bp He (T·m)	Bp H <sub>2</sub> (T·m)
<sup>48</sup> Ca	236	0.88	0.94	0.94
<sup>292</sup> Fl	38.8	0.79	2	2.18
<sup>244</sup> Pu	129.7	0.83	1.65	1.49
<sup>4</sup> He	67		1.2	
<sup>1</sup> H <sub>2</sub>	18.8			0.62



# What GF separators are not so good at

## Asymmetry: $A_p/(A_p+A_t)$

Completely symmetric reactions

$$\text{Asym} = 0.5$$



Nucl.	E(MeV)	B $\rho$ vac (T·m)	B $\rho$ He (T·m)	B $\rho$ H <sub>2</sub> (T·m)
<sup>136</sup> Xe	600	1.1	1.38	1.38
<sup>272</sup> Hs	300	0.95	1.39	1.21
<sup>136</sup> Xe	600	1.1	1.38	1.38
<sup>4</sup> He	66.6		1.2	
<sup>1</sup> H <sub>2</sub>	17.4			0.6

Very asymmetric reactions  
Asym = 0.085



Nucl.	E(MeV)	B $\rho$ vac (T·m)	B $\rho$ He (T·m)	B $\rho$ H <sub>2</sub> (T·m)
<sup>22</sup> Ne	112.4	0.76	0.76	0.76
<sup>260</sup> No	9.5	0.74	1.82	2.45
<sup>238</sup> U	34.8	0.72	1.89	2.01
<sup>4</sup> He	58.5		1.1	
<sup>1</sup> H <sub>2</sub>	18.7			0.62

Inverse kinematics reactions  
(fusion residues and primary beam have too close rigidities)



... and last but not least  
BE PATIENT



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

At 1p $\mu$ A of  $^{48}\text{Ca}$

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

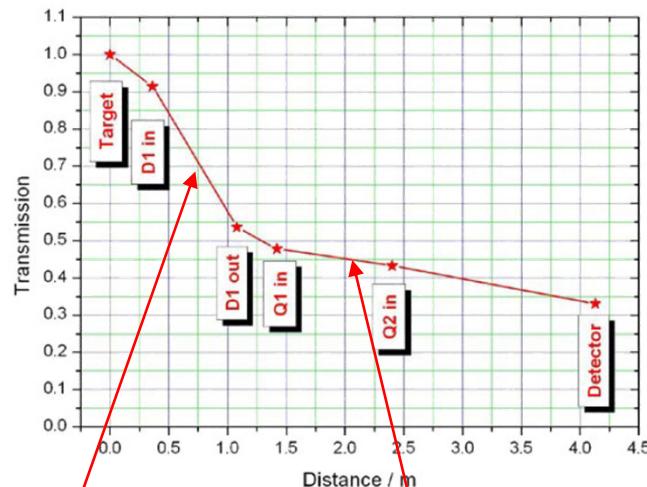


# Rationale for new layout

**SIGMA PHI**  
MAGNETS AND BEAM TRANSPORT

JINR  
<sup>114</sup>Flerovium  
**FLNR**  
Dubna

Losses for  $^{243}\text{Am}(^{48}\text{Ca},4\text{n})^{286}\text{Mc}$  in existing DGFRS  
DQ<sub>h</sub>Q<sub>v</sub> layout : dipole gap 58mm, quad diameter 100mm



Increase  
dipole gap

Q<sub>1</sub> V to  
enter dipole

Large aperture  
quads

40% loss  
in dipole

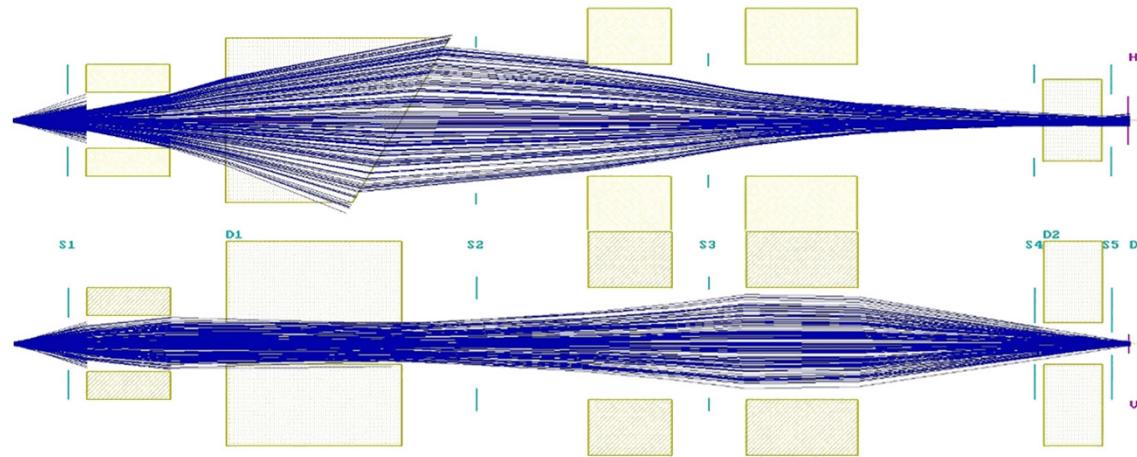
MUST IMPROVE  
TRANSMISSION

15% loss  
in quads

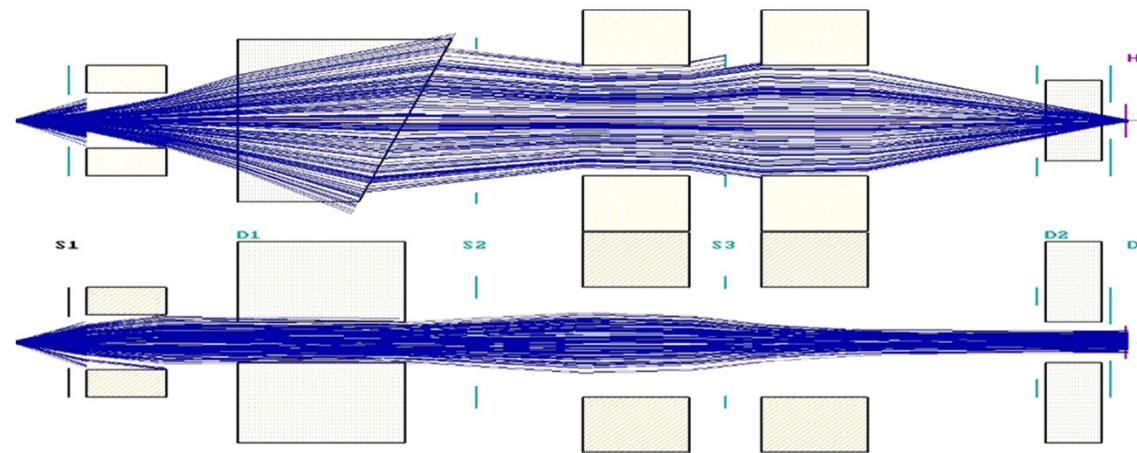
Refocus H  
asap

Large exit  
pole edge  
angle

# Transmission or Resolution ?



VHHV  
Transmission +  
Resolution -  
Separator



VHVH  
Transmission –  
Resolution +  
Spectrometer

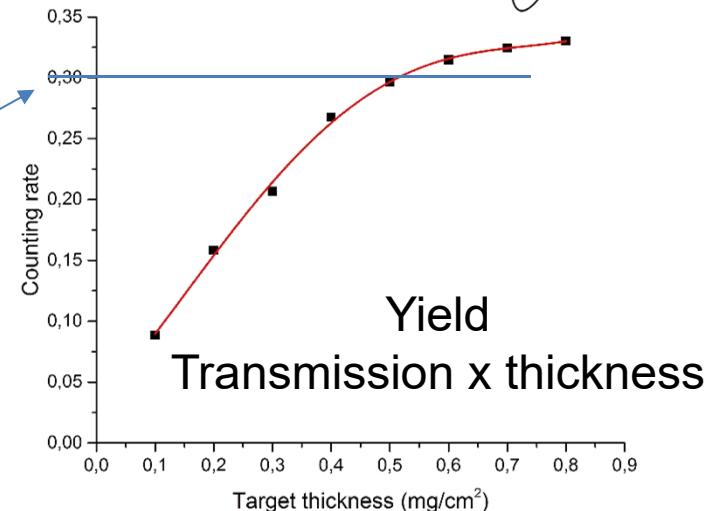
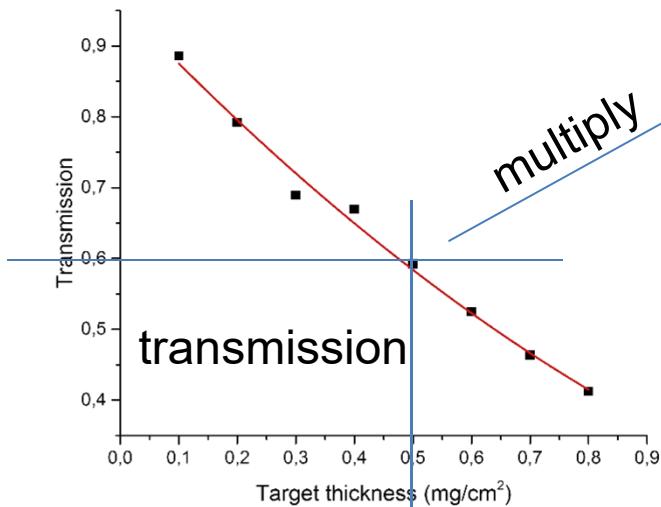


# Some other role players



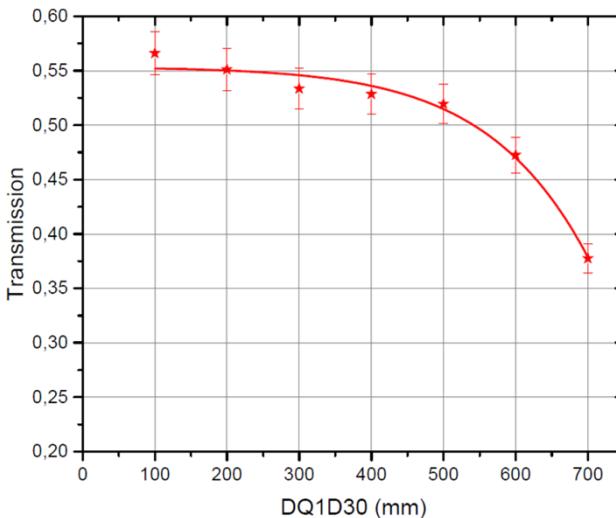
## The target

Caution  
Transmission « in itself » is not THE parameter, yield is important



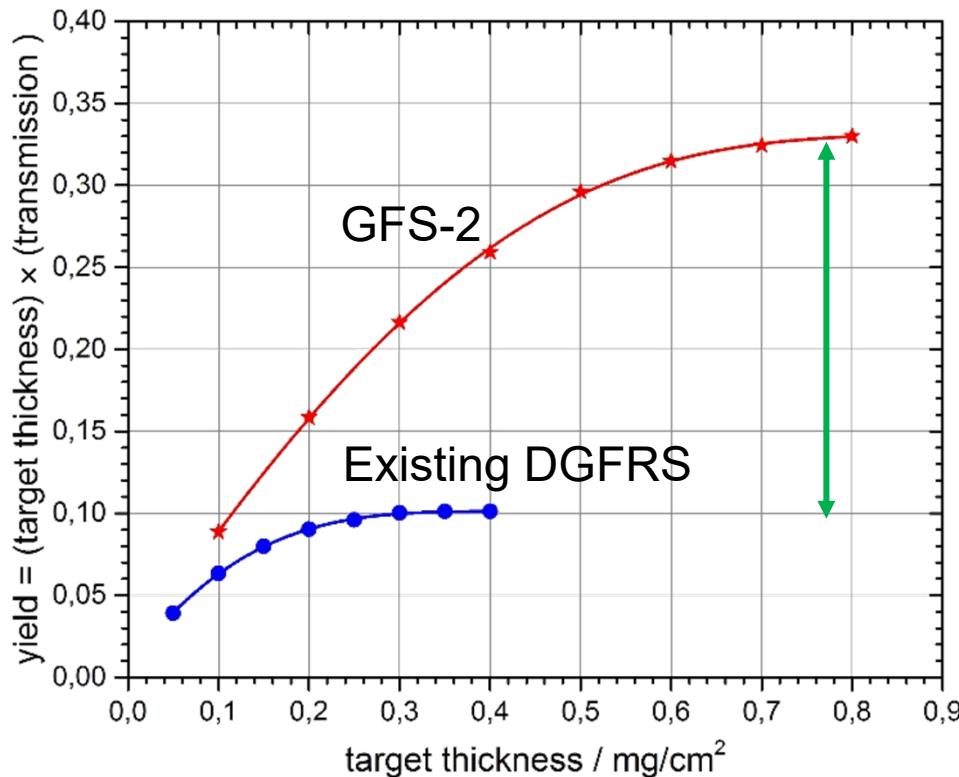
## Distances

Length of elements  
Drifts between elements



# Expected gain

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



$^{244}\text{Pu}(^{48}\text{Ca},4\text{n})^{288}\text{Fl}$   
Over 3 times more !!

From initial spec to final layout  
through various iterations

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 ?

...

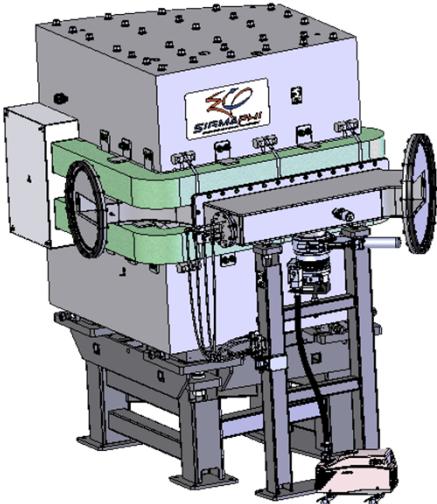


# The big guy – 30° D1

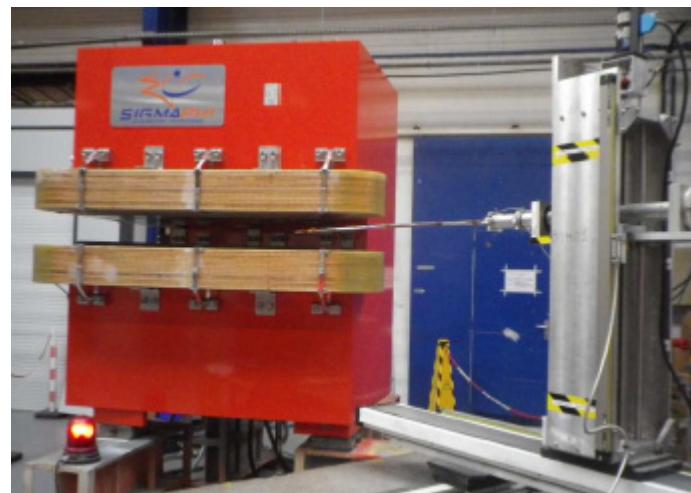


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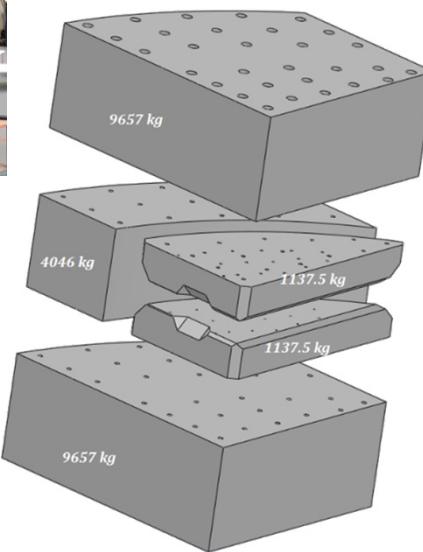
# D1 General



Factory  
assembly



Each part must  
be less than  
10 tons



Assembly on site



Hall probe measurement

# D1 parameters

<b>Beam</b> free aperture	<b>120</b>	mm
<b>Magnet</b> gap	<b>132</b>	mm
Curvature radius	1800	mm
Entrance face angle	-7 (-2)	°
Exit face angle	<b>-44</b> (-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/mm <sup>2</sup>
Magnet power	139	kW
Yoke weight	25.7	ton
Copper weight	1.24	ton

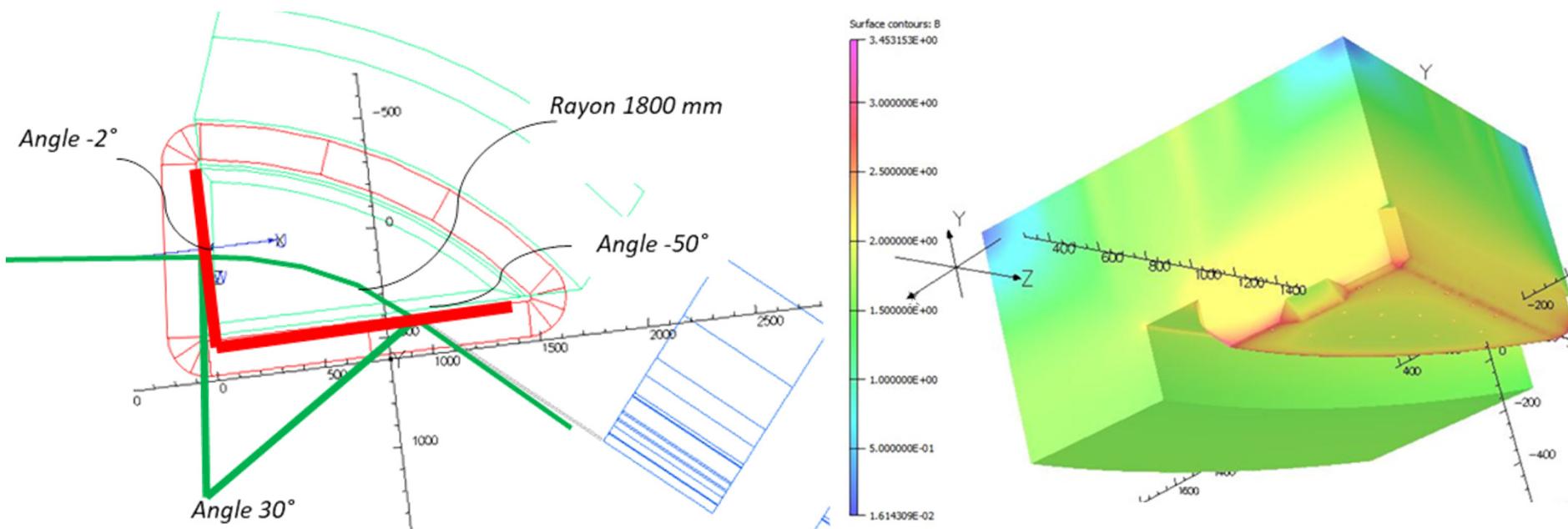
# D1 design (1)

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



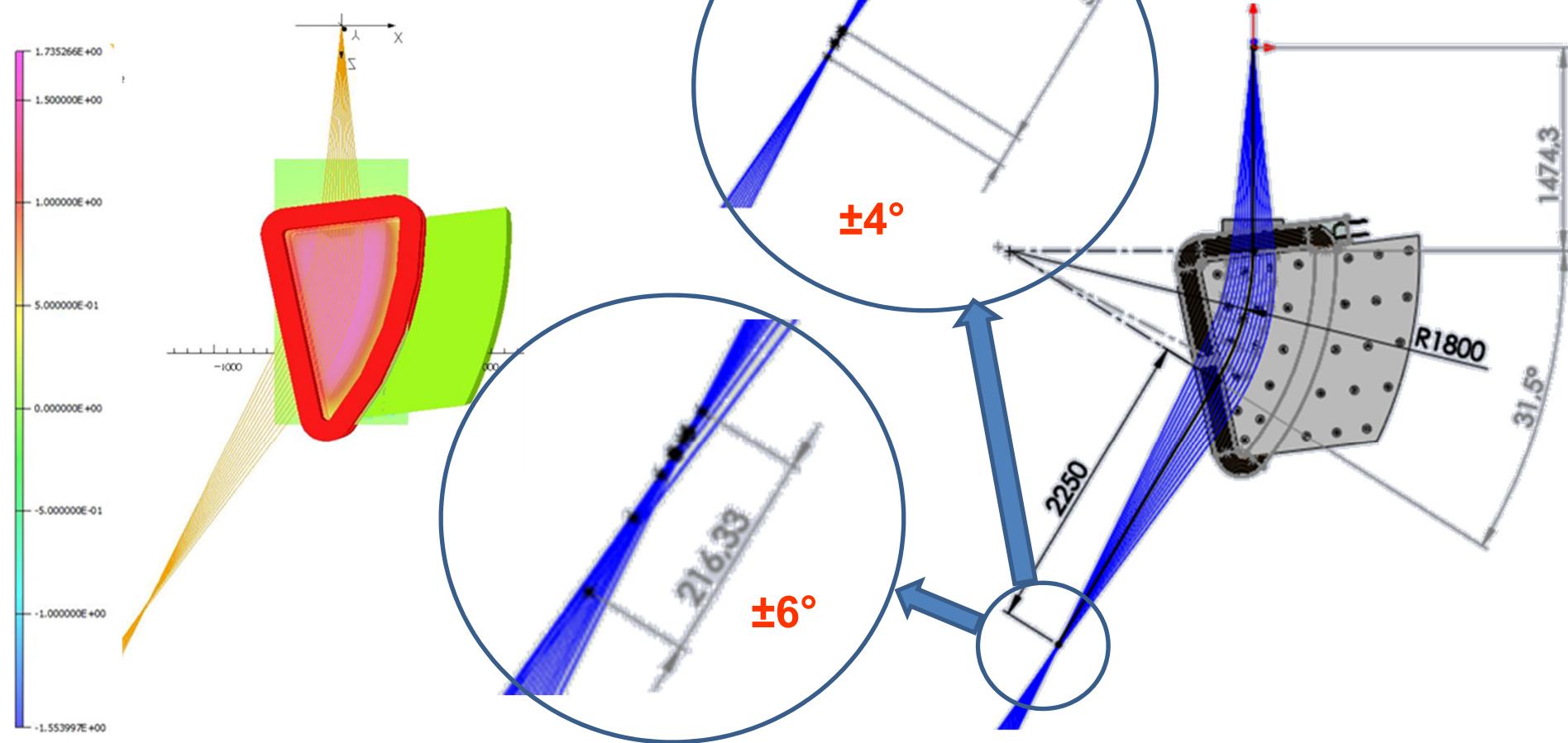


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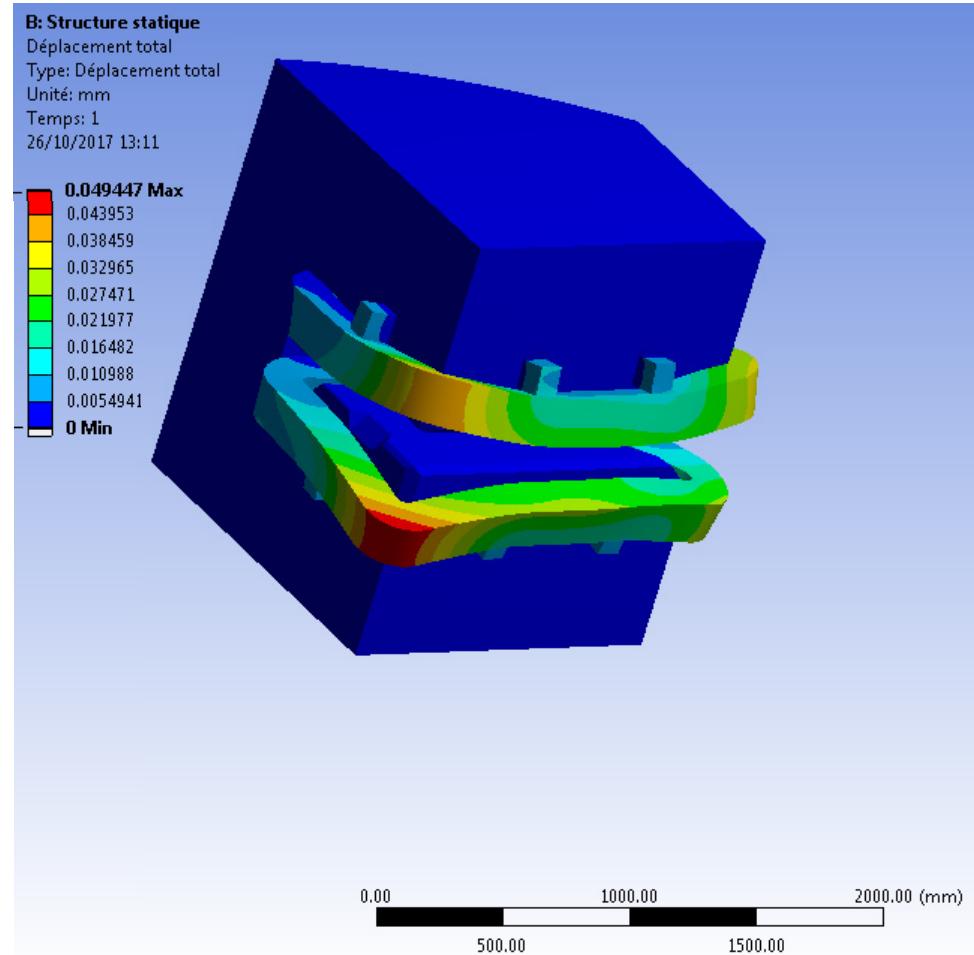
## D1 design (2)



Design driven by particle tracking focusing quality

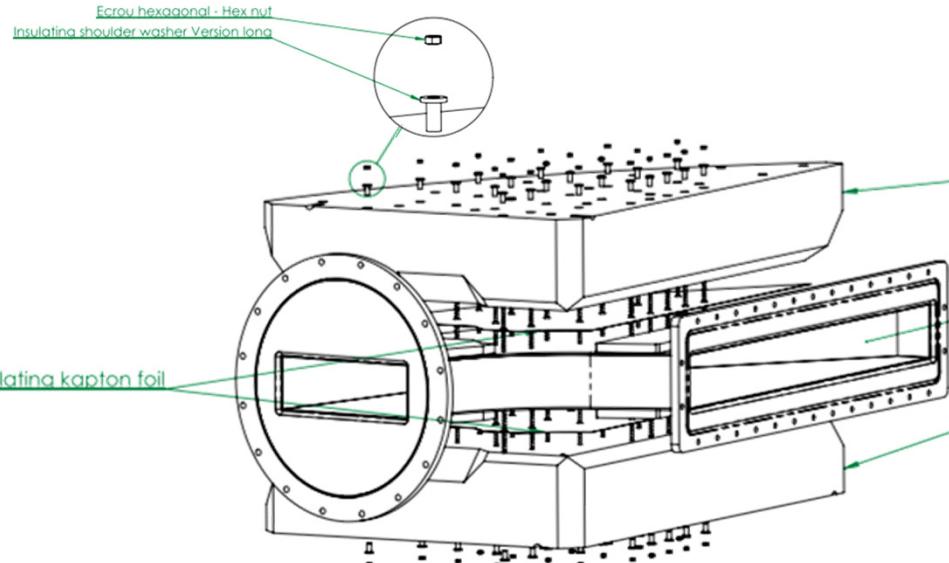


# D1 coils





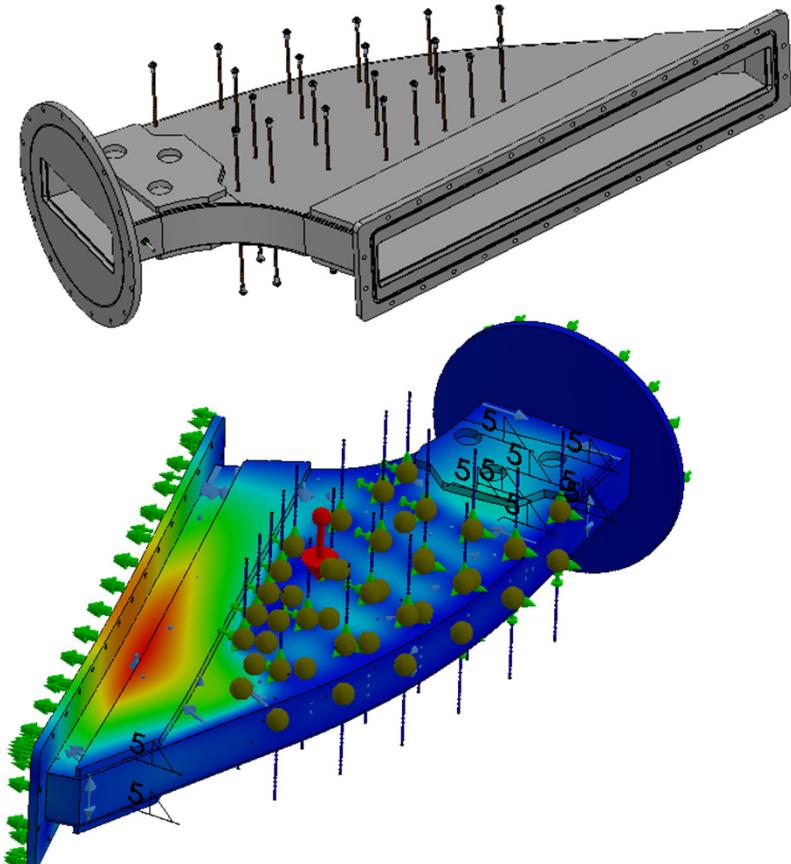
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# D1 chamber (1)



Very large surface ~4000 cm<sup>2</sup>  
Wall must be thick to prevent deformation  
21 struts + edge reinforcement allow thin walls  
0.65 mm max displacement





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## D1 chamber (2)



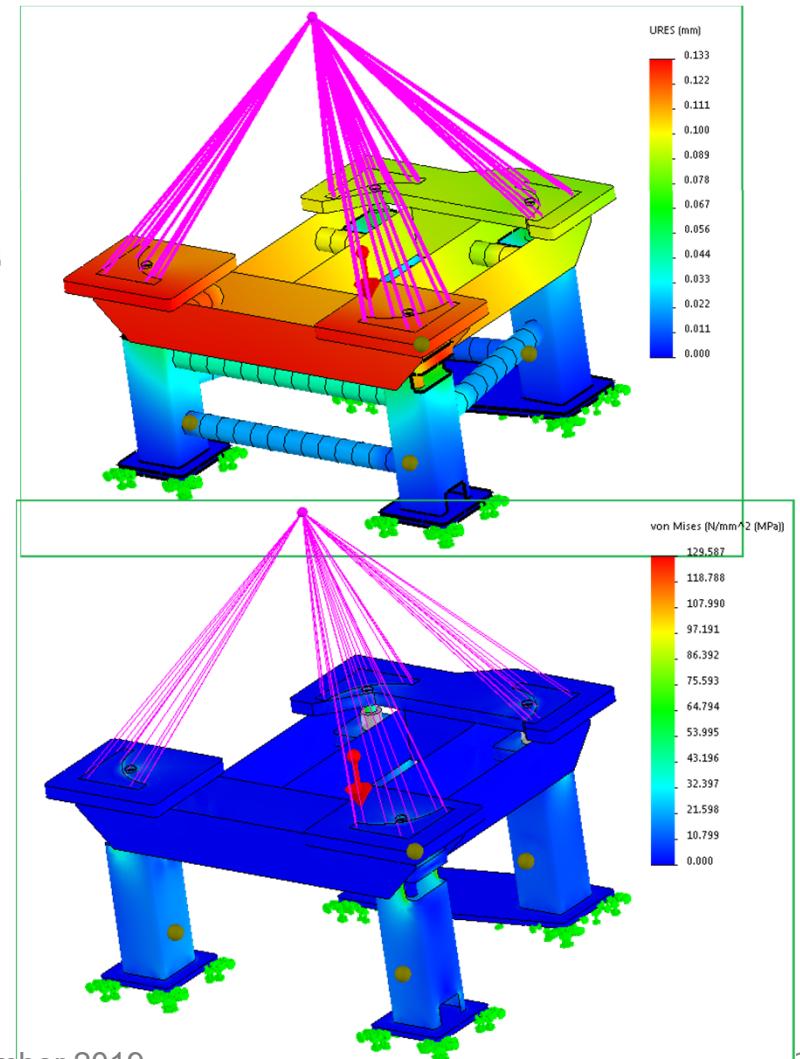
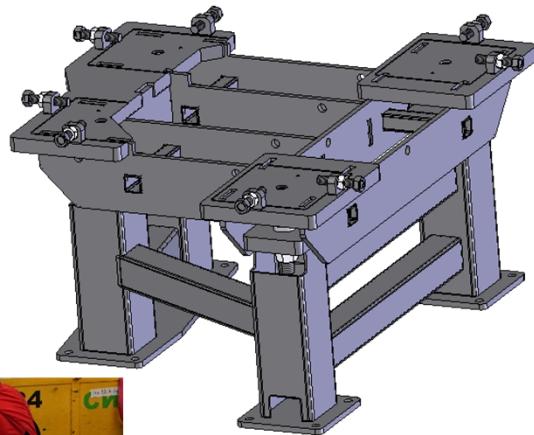
Chamber is  
electrically  
insulated



Chamber assembly and  
testing in factory

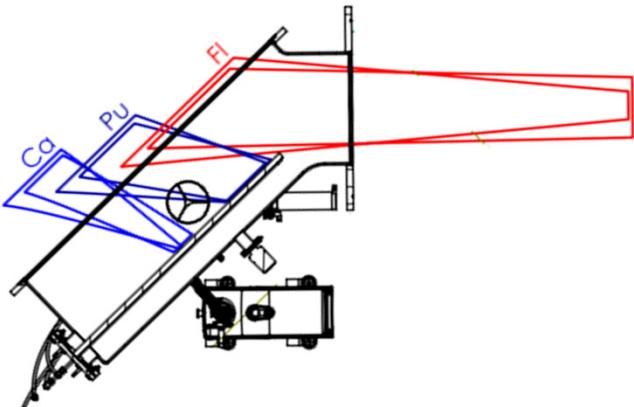
# D1 Stand

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





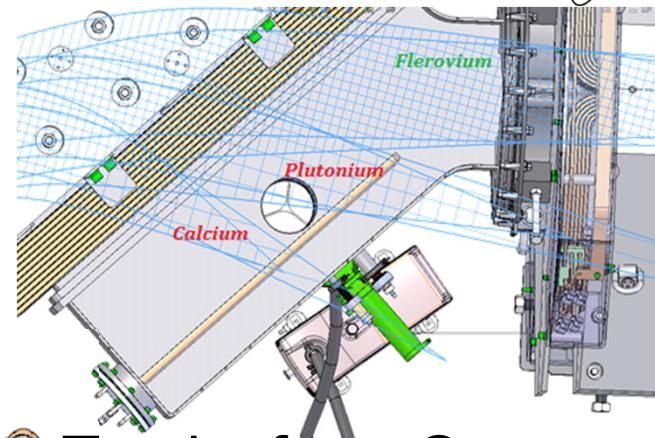
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# D1 Beam stop

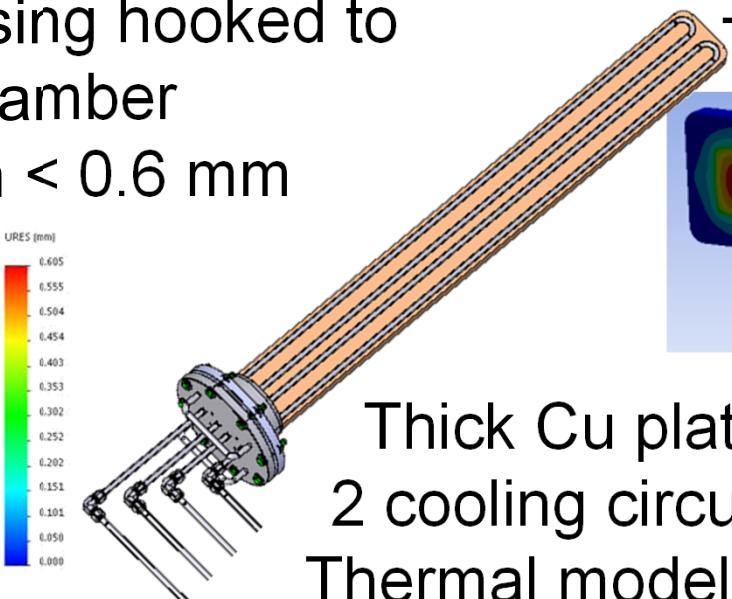
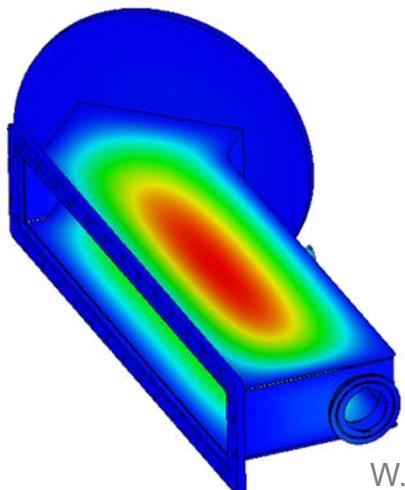
JINR  
114 Flerovium  
**FLNR**  
Dubna

block most  
background  
species  
and let EVR  
pass

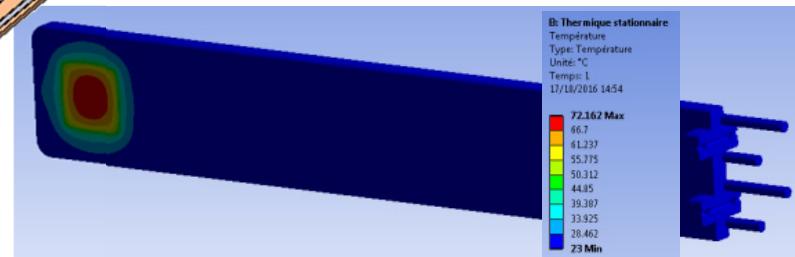


Beam stop housing hooked to  
main chamber

Deformation < 0.6 mm



Thick Cu plate  
2 cooling circuits  
Thermal modelling  
crucial





# Quadrupoles

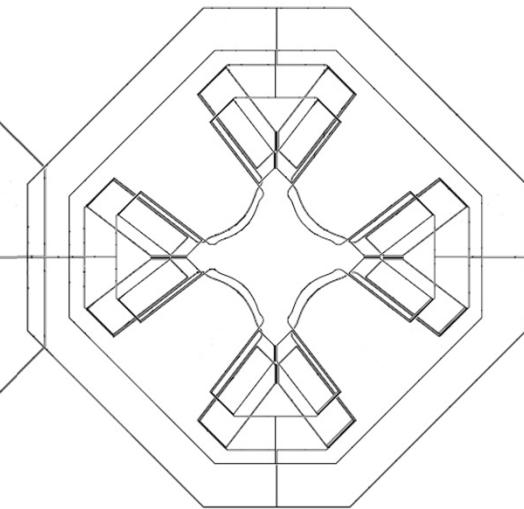
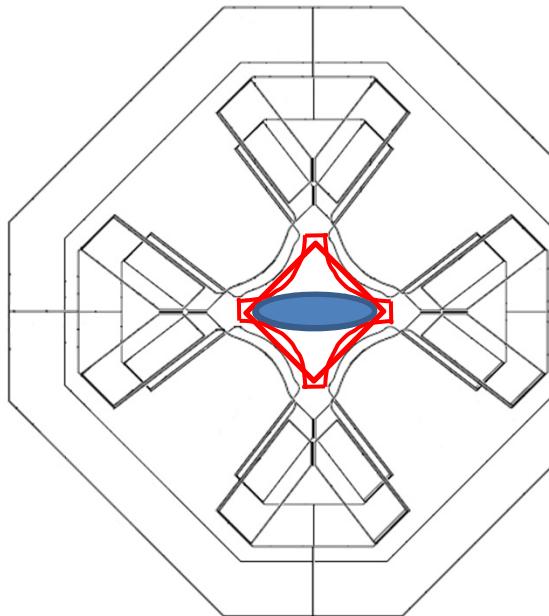
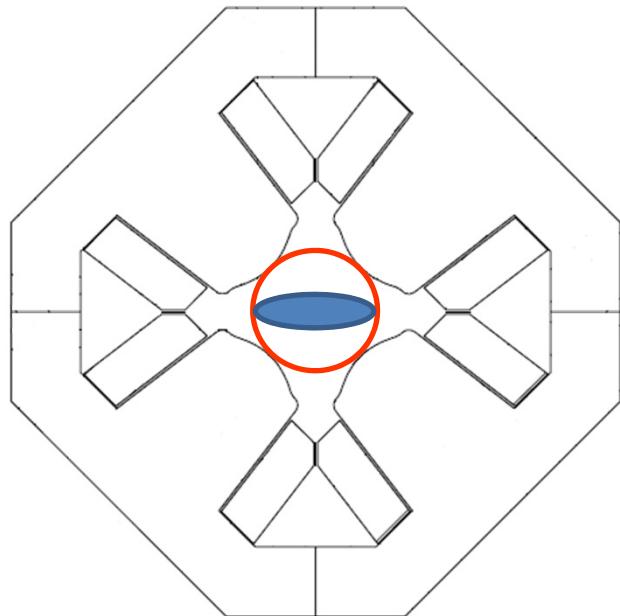


# Quadrupoles parameters



	<b>Q1</b>	<b>Q2/Q3</b>	
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/mm <sup>2</sup>
Magnet power	28.2	61.6	kW
Yoke weight	2.07	6.65	ton
Copper weight	0.39	0.68	ton

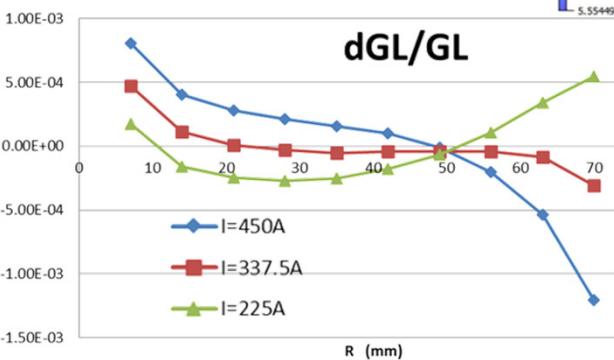
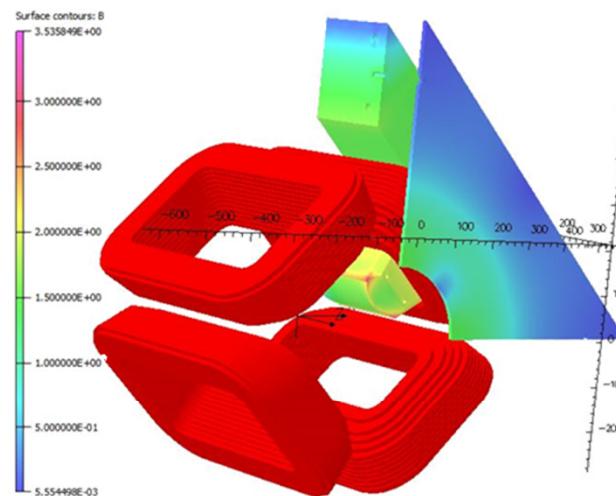
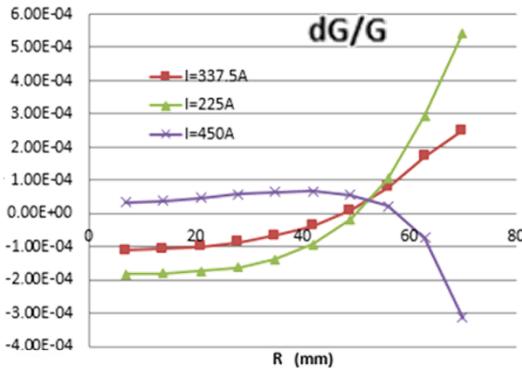
# Shaping chambers to reduce bore



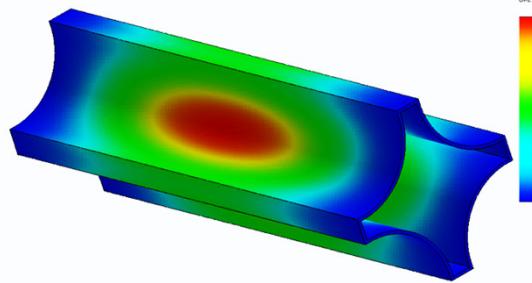


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Q1



$\phi=150\text{mm}$   
 $G=13.2 \text{ T/m}$



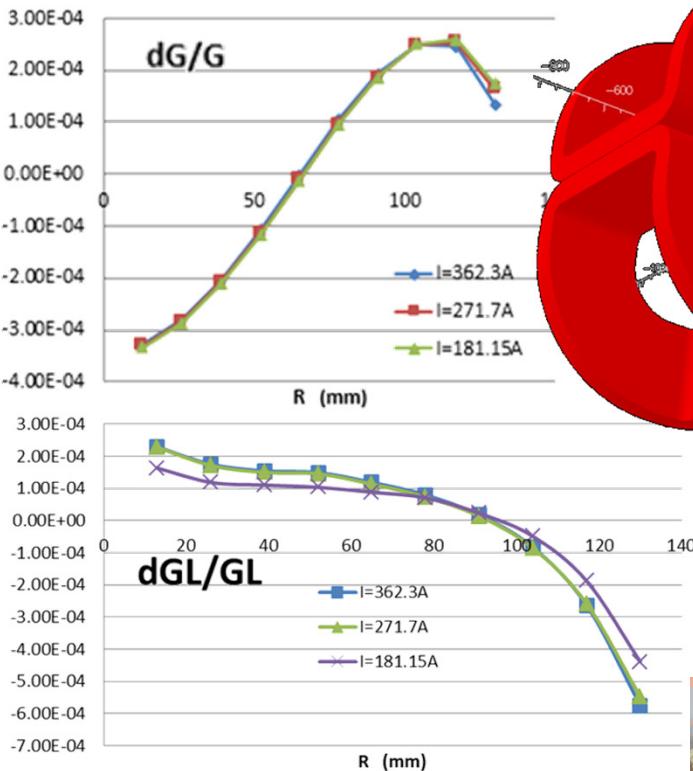
URES (nm)  
3.051e-001  
2.737e-001  
2.542e-001  
2.326e-001  
2.034e-001  
1.780e-001  
1.525e-001  
1.271e-001  
1.021e-001  
7.627e-002  
5.085e-002  
2.542e-002  
1.000e-002



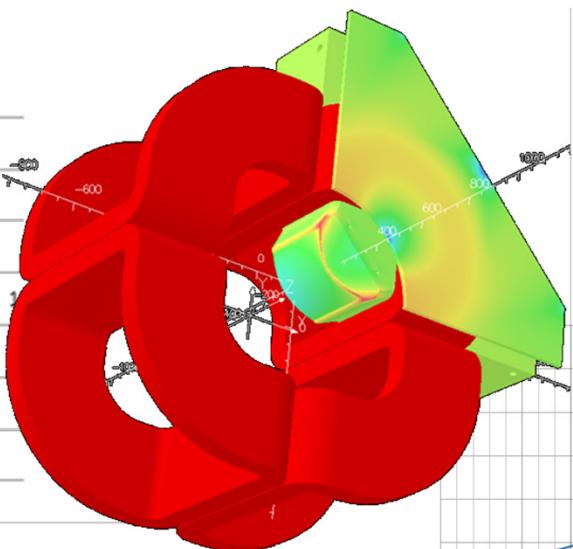
Local & integrated  
gradient  
homogeneity  
along radius



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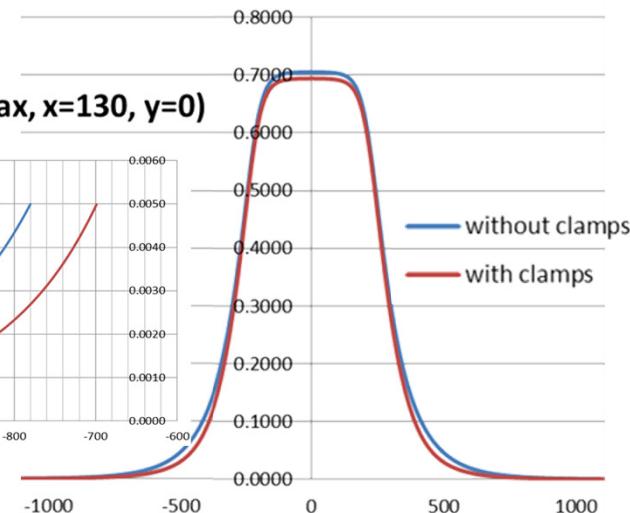
Local & integrated  
gradient  
homogeneity  
along radius



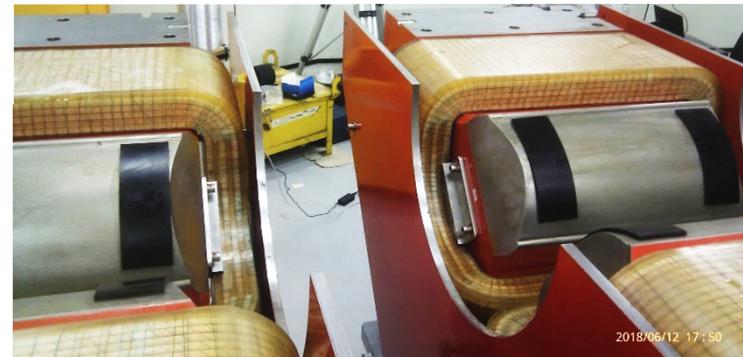
Q2/Q3

$\phi=300\text{mm}$   
 $G=5.34\text{ T/m}$

$By=f(z)$  ( $I_{\text{max}}, x=130, y=0$ )

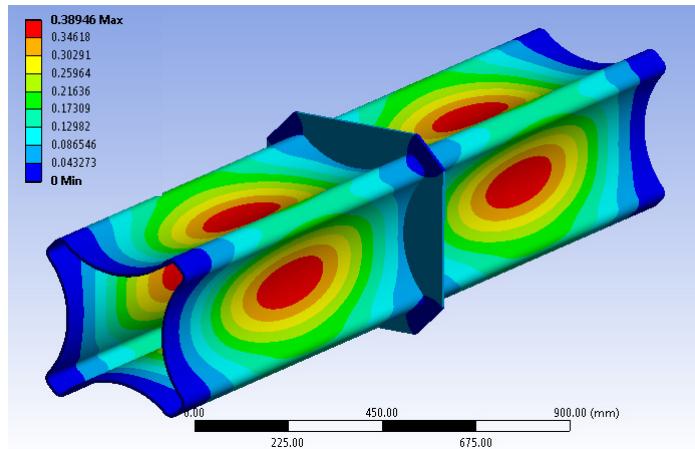


Effect of field clamps along beam  $z$  (mm)



2018/06/12 17:50

# Q2/Q3 Vacuum chamber



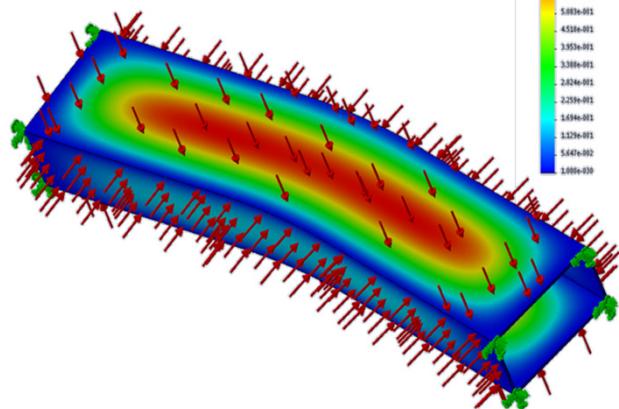
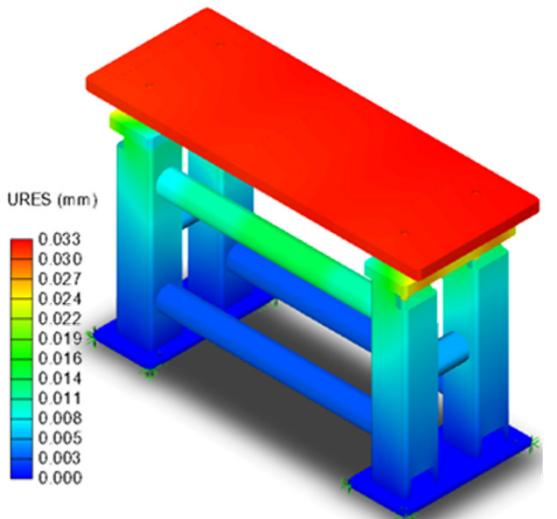
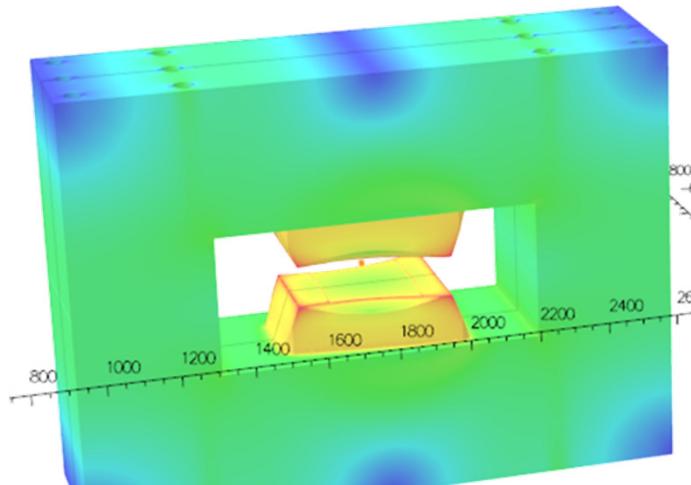


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D2



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

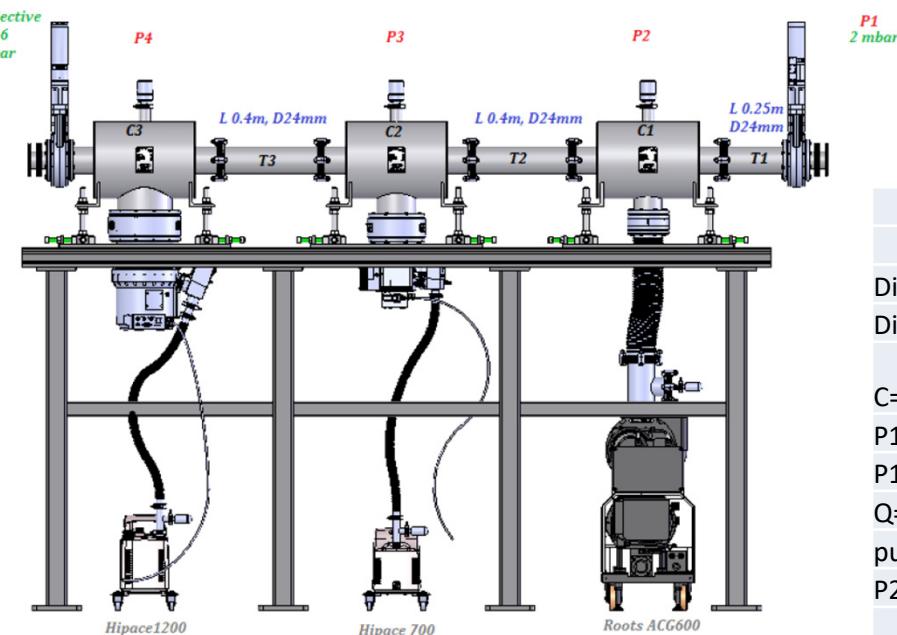


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# Differential pumping (1)

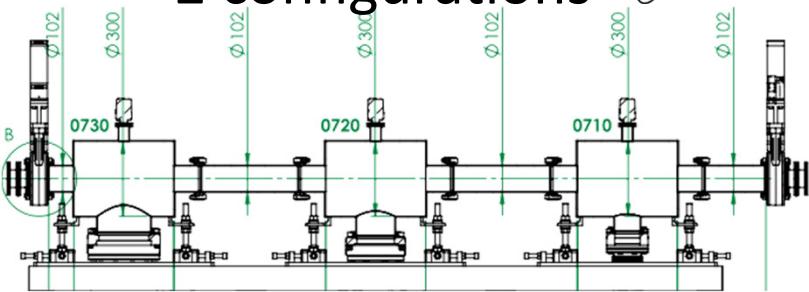


- Allows window-less operation
- Tolerate intense heavy ion beams
- Gas contributes to target cooling
- As all recent gas-filled separators  
TASCA, GARIS-II, SHANS



Large tubes ( $\phi 102$ ): standard pumping

2 configurations



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
$C = 1.22 \cdot 10^{-4} \cdot (D^3/L)$		6.75E+00	0	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
$Q = C \cdot (P1 - P2)$		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

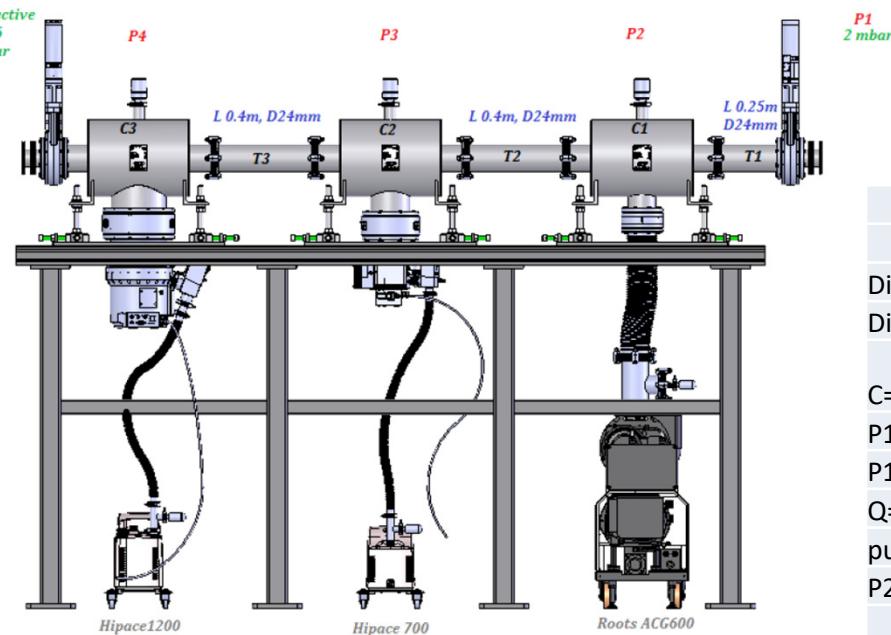


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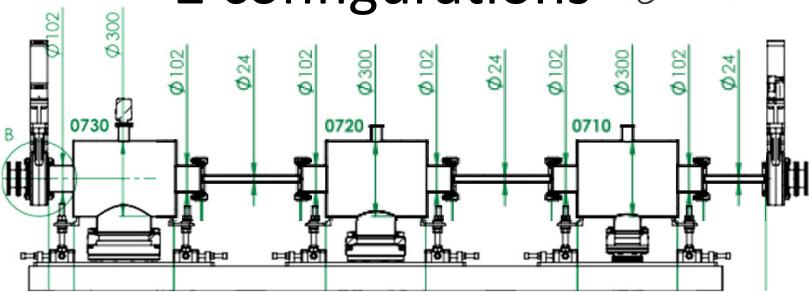
# Differential pumping (1)



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



Diaphragms ( $\phi 24$ ) : differential pumping



2 configurations

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
$C = 1.22 \cdot 10^{-4} \cdot (D^3 / L)$		6.75E+00	0	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
$Q = C \cdot (P1 - P2)$		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

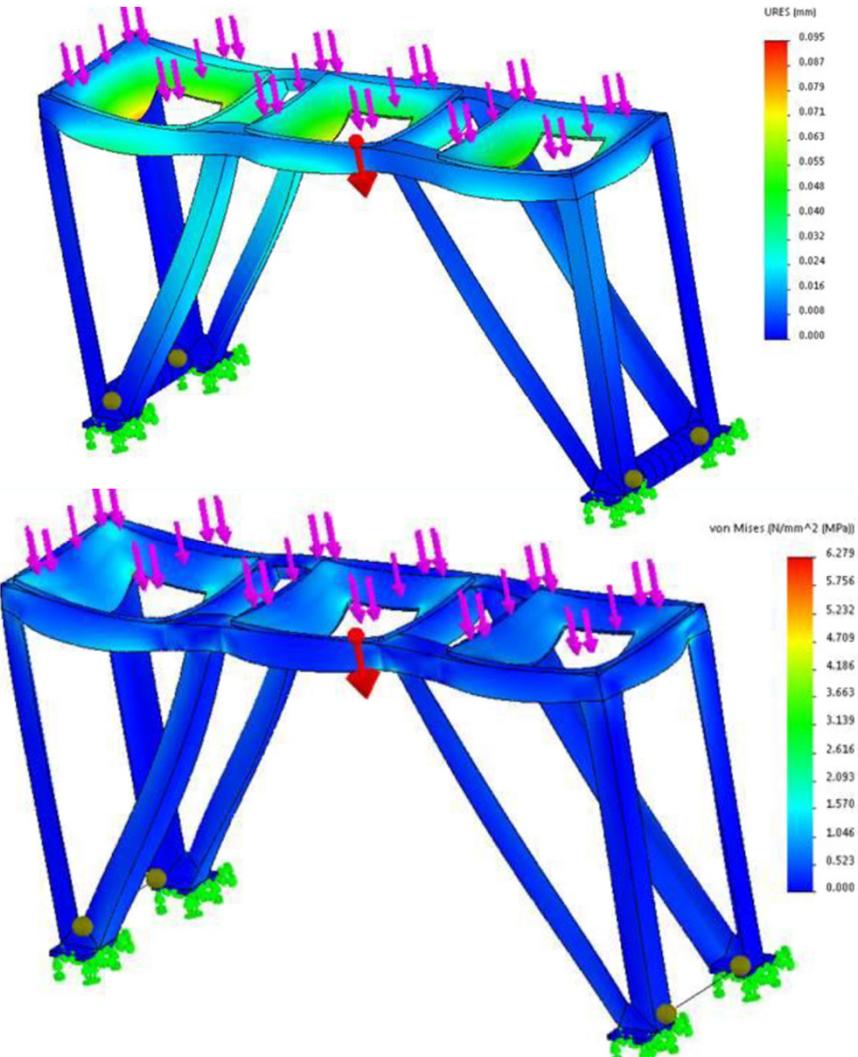
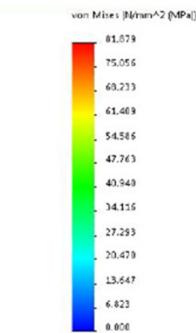
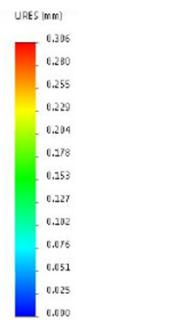
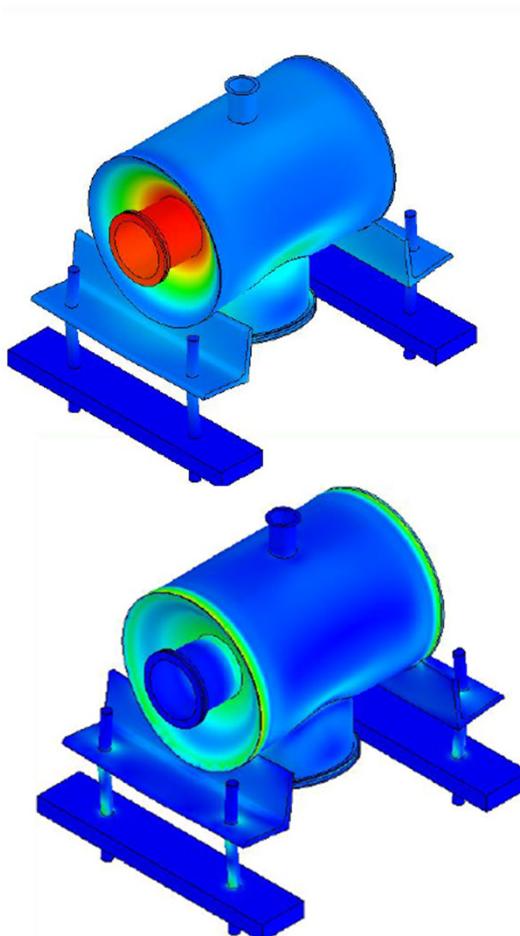


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# Differential pumping (2)



Mechanically sound



# Differential pumping (3)



Factory testing





# Power supplies



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# Power supplies





# Installation

## June 05<sup>th</sup>-14<sup>th</sup> 2018



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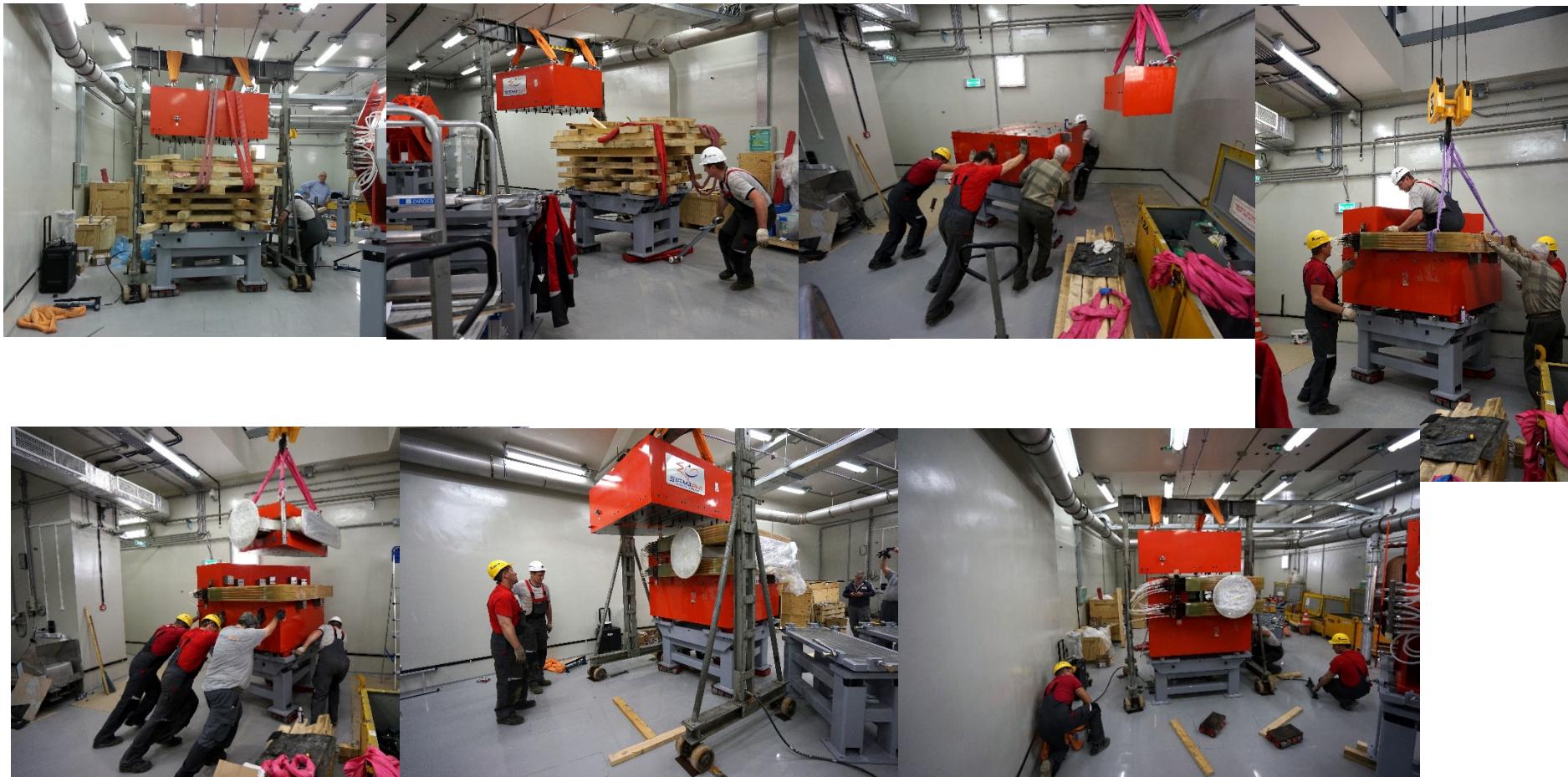
# No crane! So what? (1)





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# No crane! So what? (2)





# Alignment

# Alignment

- Leica laser tracker AT401
- Red ring 2.5" targets
- Polyworks software
- Global Alignment accuracy within  $\pm 0.1$  mm



## Present status and near future

2018 GFS-2 acceptance tests

2019 GFS-2 first beam tests

2019 GFS-3 manufacturing

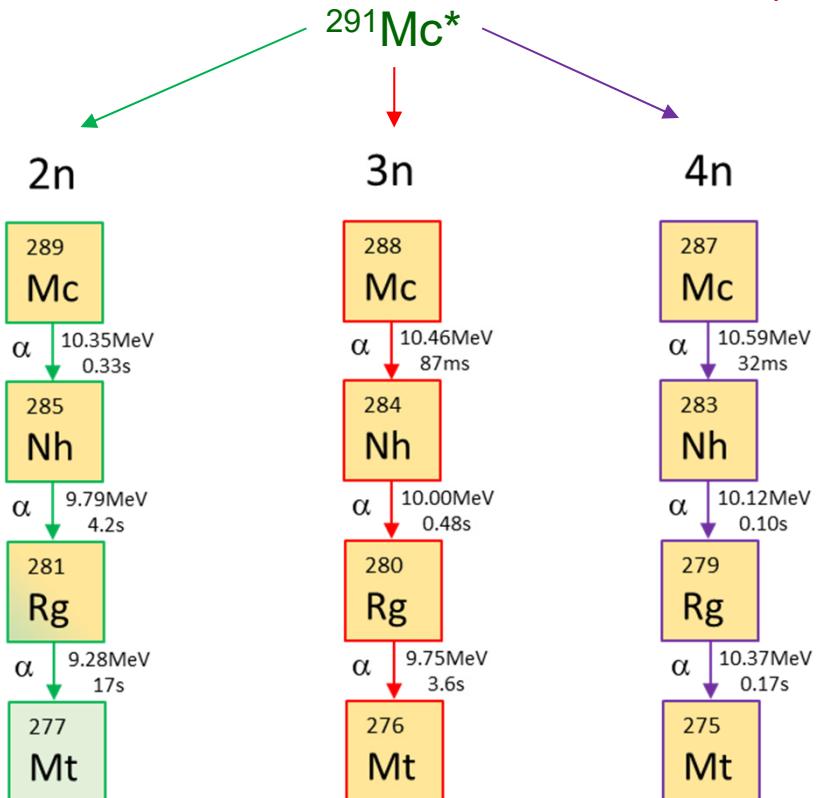
2020 GFS-3 installation



# SHE Factory test reaction



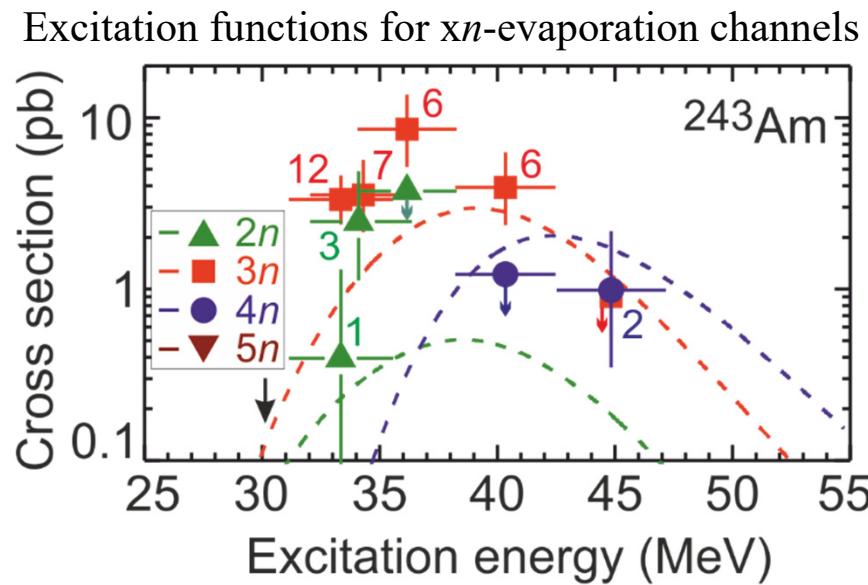
$\sigma=8.5 \text{ pb}$ ,  $h_t=0.5 \text{ mg/cm}^2$ ,  $\varepsilon_{\text{coll}}=0.6$ ,  $I_{\text{beam}} = 1 \text{ p}\mu\text{A} \rightarrow \approx 3/\text{day}$



# Observation of a decay of $^{281}\text{Rg}$

## Two decay times of $^{276}\text{Mt}$

## For all 3, correct level of cross section for the $xn$ channel (log scale)



Figures close to points give the number of  
Mc atoms produced

**Ar(+6) 5 MeV/A beam transmission  
from accelerator to beam stop is 95%.**

$^{nat}\text{Yb} + ^{40}\text{Ar} \rightarrow \text{Ra}$ ,  
 $^{nat}\text{Yb} + ^{48}\text{Ca} \rightarrow \text{Th}$ ,  
 $^{170}\text{Er} + ^{50}\text{Ti} \rightarrow \text{Th}$ ,  
 $^{206,208}\text{Pb} + ^{48}\text{Ca} \rightarrow \text{No}$

## Adjustment of optical elements $Q_v, D_h, Q_h, Q_v, D$

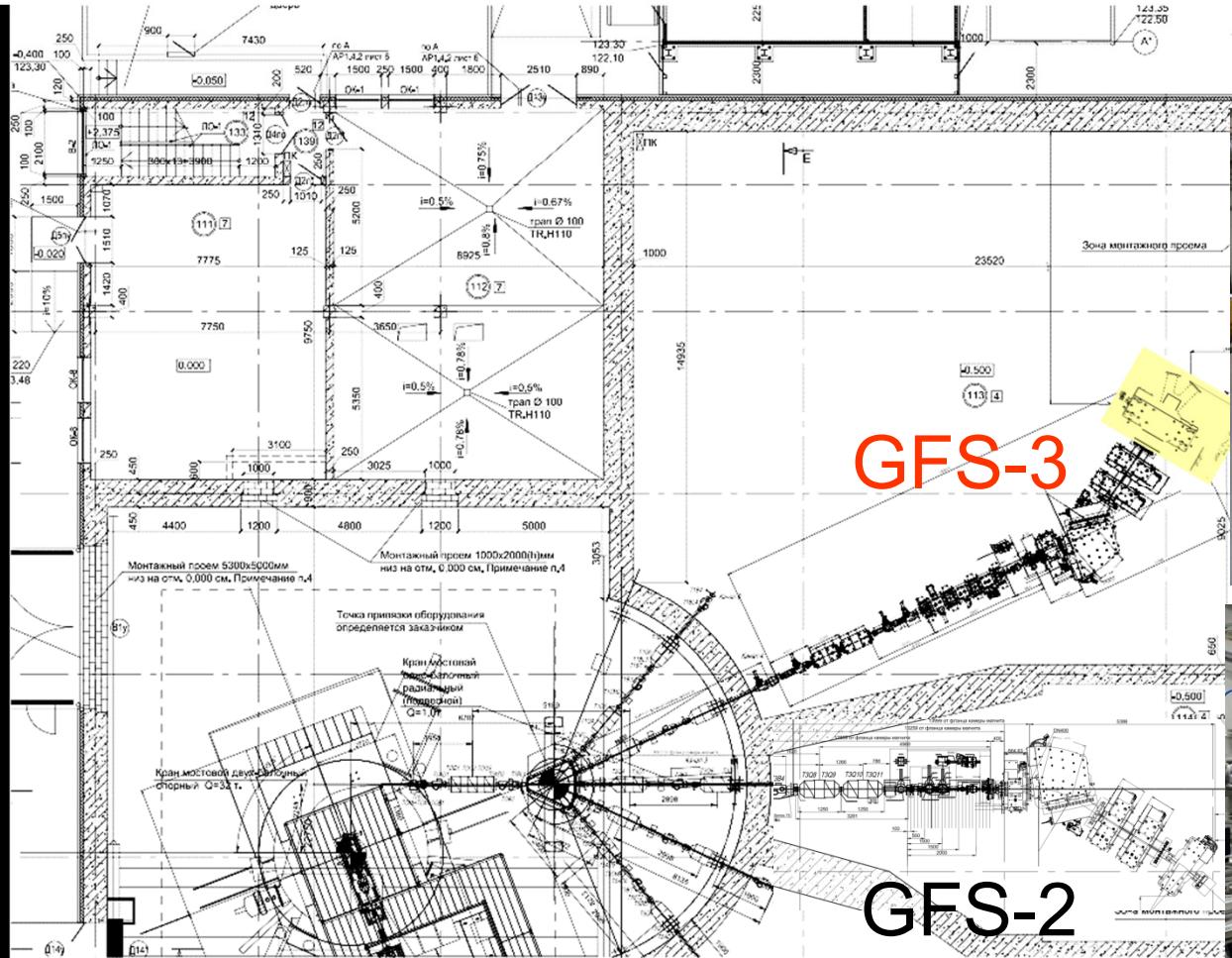
- Transmission
- Image size on detector
- Dispersion
- Background
- Optimal gas pressure
- Yield vs. target thickness
- Systematics of charge states
- Test of data taking systems



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# Future plans

JINR  
114 Flerovium  
**FLNR**  
Dubna



GFS-2

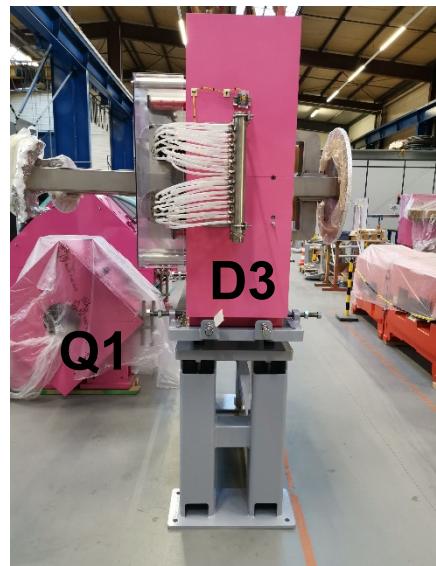
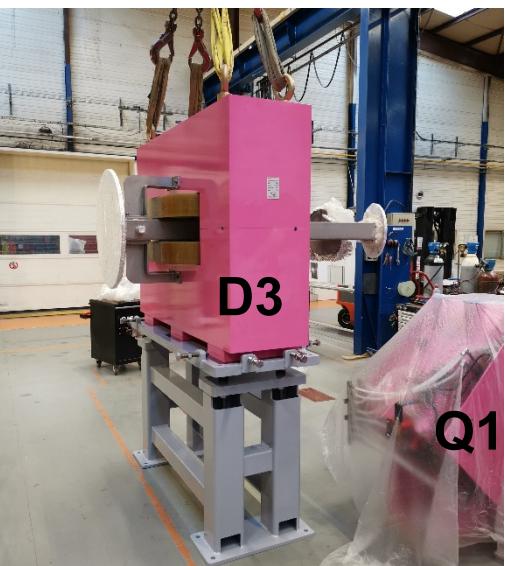




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# GFS-3 in the factory

JINR  
<sup>114</sup>Flerovium  
**FLNR**  
Dubna



# Present status and plans

## SuperHeavy Element Factory

- **GFRS-2**

**status:** commissioned;

tests and tuning are in progress

**purpose:** synthesis of new SHE,

new isotopes of SHE, decay modes, excitation functions, etc.



- **GFRS-3**

**status:** manufactured,

delivery to Dubna is expected by the end of 2019;

assembly and commissioning - 2020

**purpose:** decay spectroscopy; chemistry of SHE



## Long-term plans:

- Specialized radiochemical complex of the 1st class
- ECR ion source on 28 GHz
- Development of experimental set-ups



# We also built friendship

# Human interaction



# Team spirit



# Conclusions

- GFS-2 is installed and under commissioning. First tests are ongoing and look promising
- A global contract has opened the possibility for thorough optimization.
- A similar (chiral symmetry) system is produced and will be delivered in 2019 and installed in 2020
- A wonderful human experience!

# Thank you for your attention

The essence of the beautiful is unity in variety

W. Somerset Maugham

