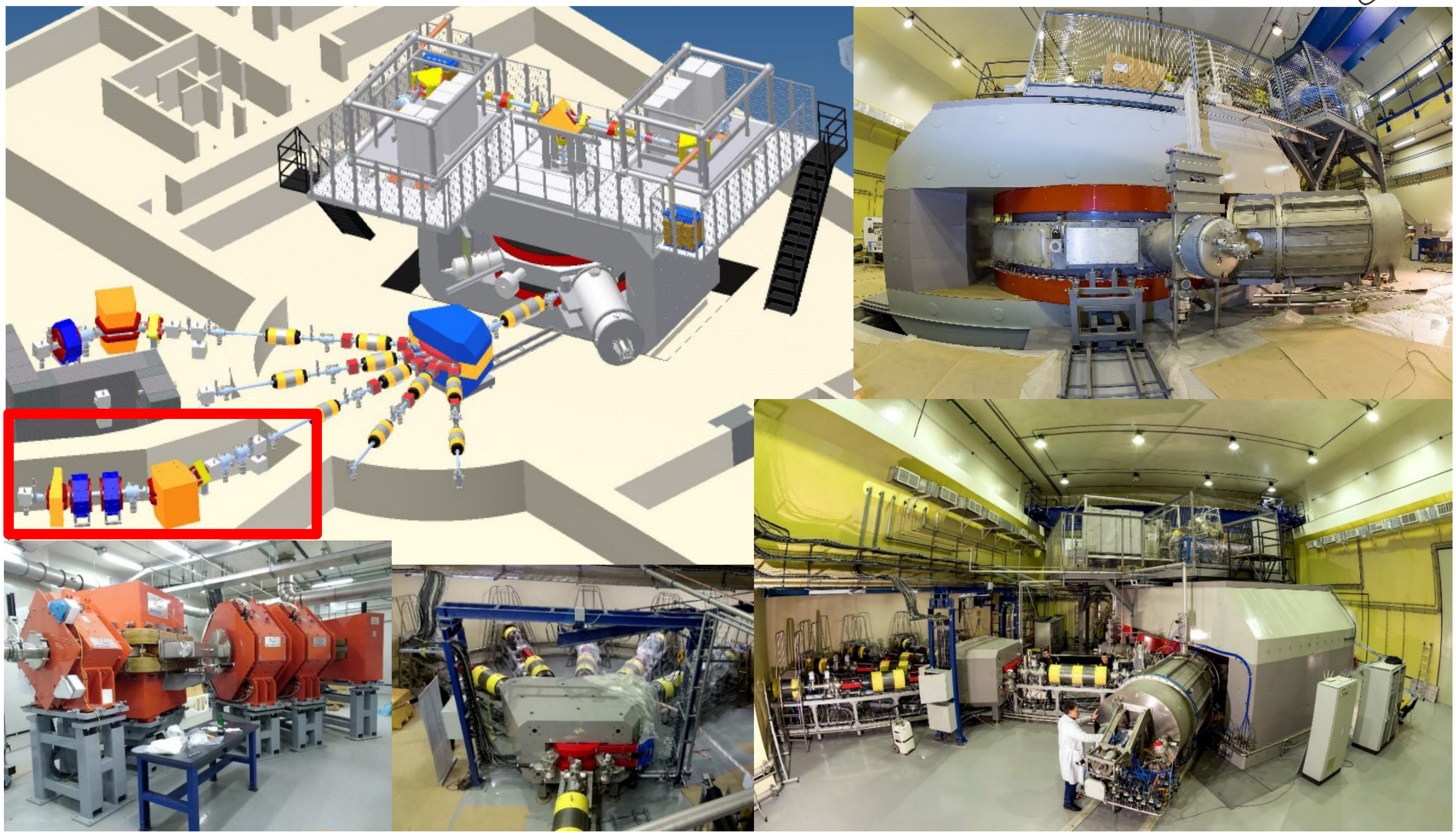
GFS-2 - The New Gas-filled Separator for Super-Heavy Elements in JINR. A Guided Walk through the Genesis of the Project from First Thoughts to Completion

W. Beeckman, S. Antoine, V. Dumilly, F. Forest, P. Jehanno, P. Jivkov,
M.J. Leray, X. Milpied, C. Nignol, O. Tasset
SIGMAPHI, F-56000 Vannes, France

A.G. Popeko, V.K. Utyonkov
Flerov Laboratory of Nuclear Reactions, JINR, RU-141980 Dubna, Russia

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



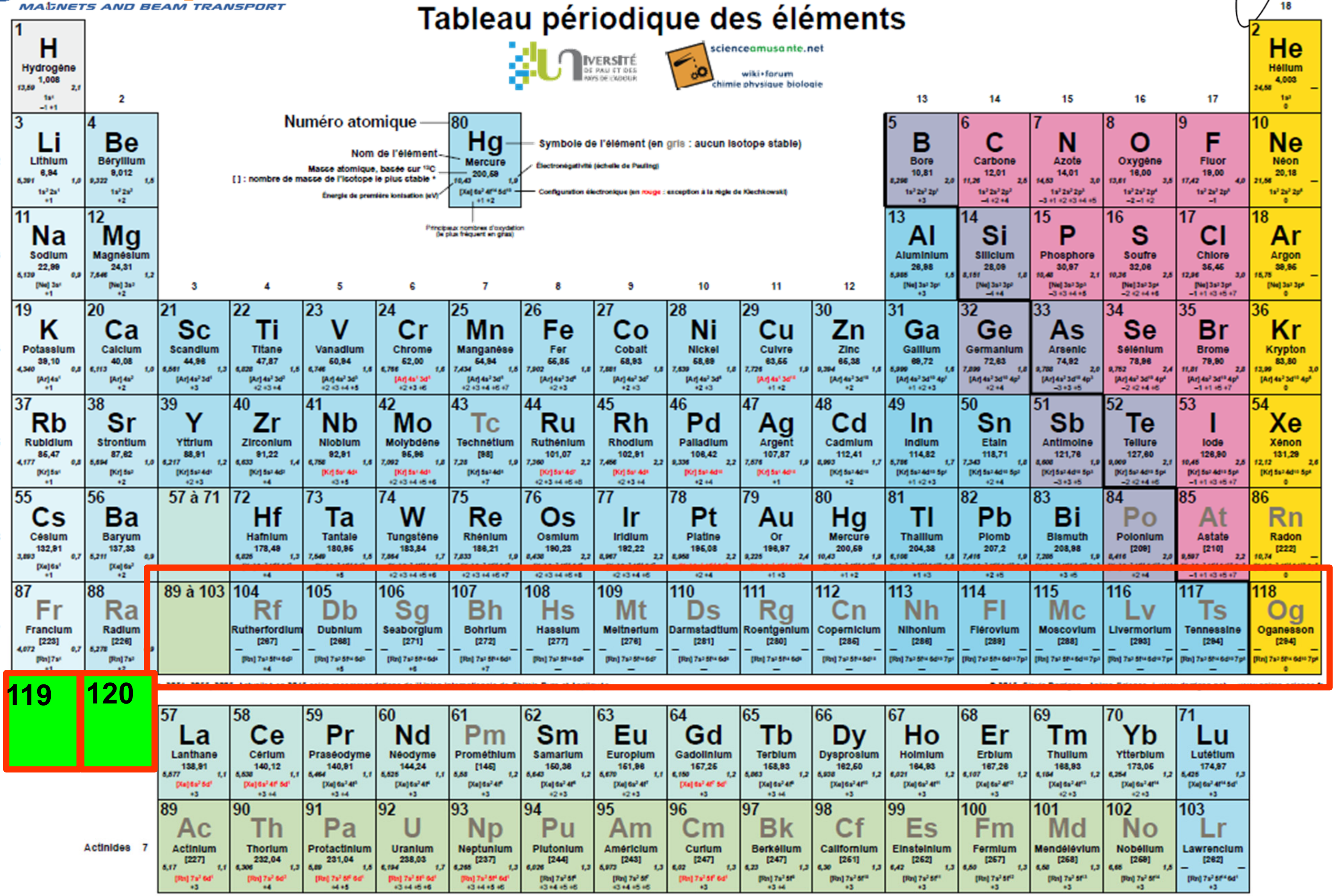
More on Thursday

13:40	THC01: Igor Kalagin - Cyclotron Facility for Super Heavy Elements Research

Super Heavy Elements

WHY ?

Filling in Mendeleev's

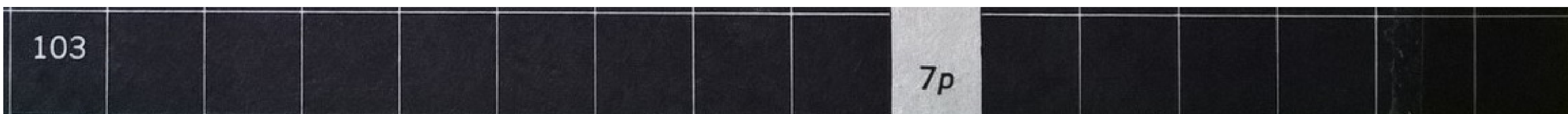


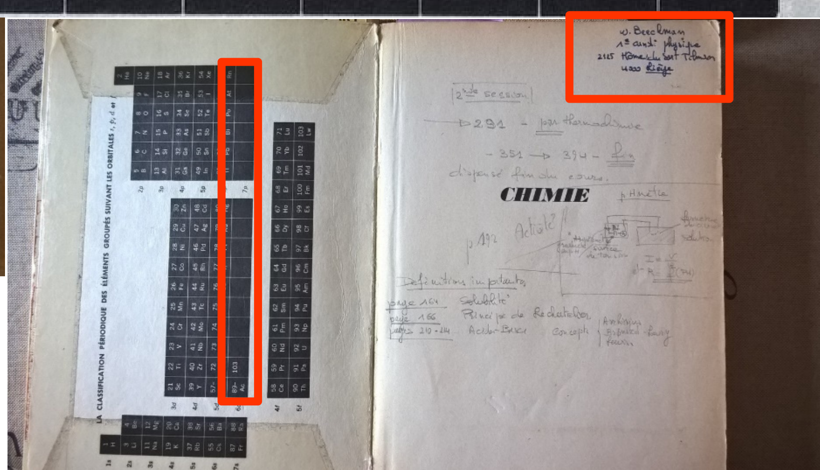
Filling in Mendeleev's

89 à 103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
	Rutherfordium	Dubnium	Seaborgium	Bohrium	Hassium	Meitnerium	Darmstadtium	Roentgenium	Copernicium	Nihonium	Flérovium	Moscovium	Livermorium	Tennessine	Oganesson
	[267]	[268]	[271]	[272]	[277]	[276]	[281]	[280]	[285]	[286]	[289]	[288]	[293]	[294]	[294]
	+4	+5	+6	+7	—	—	—	—	—	—	—	—	—	—	0

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

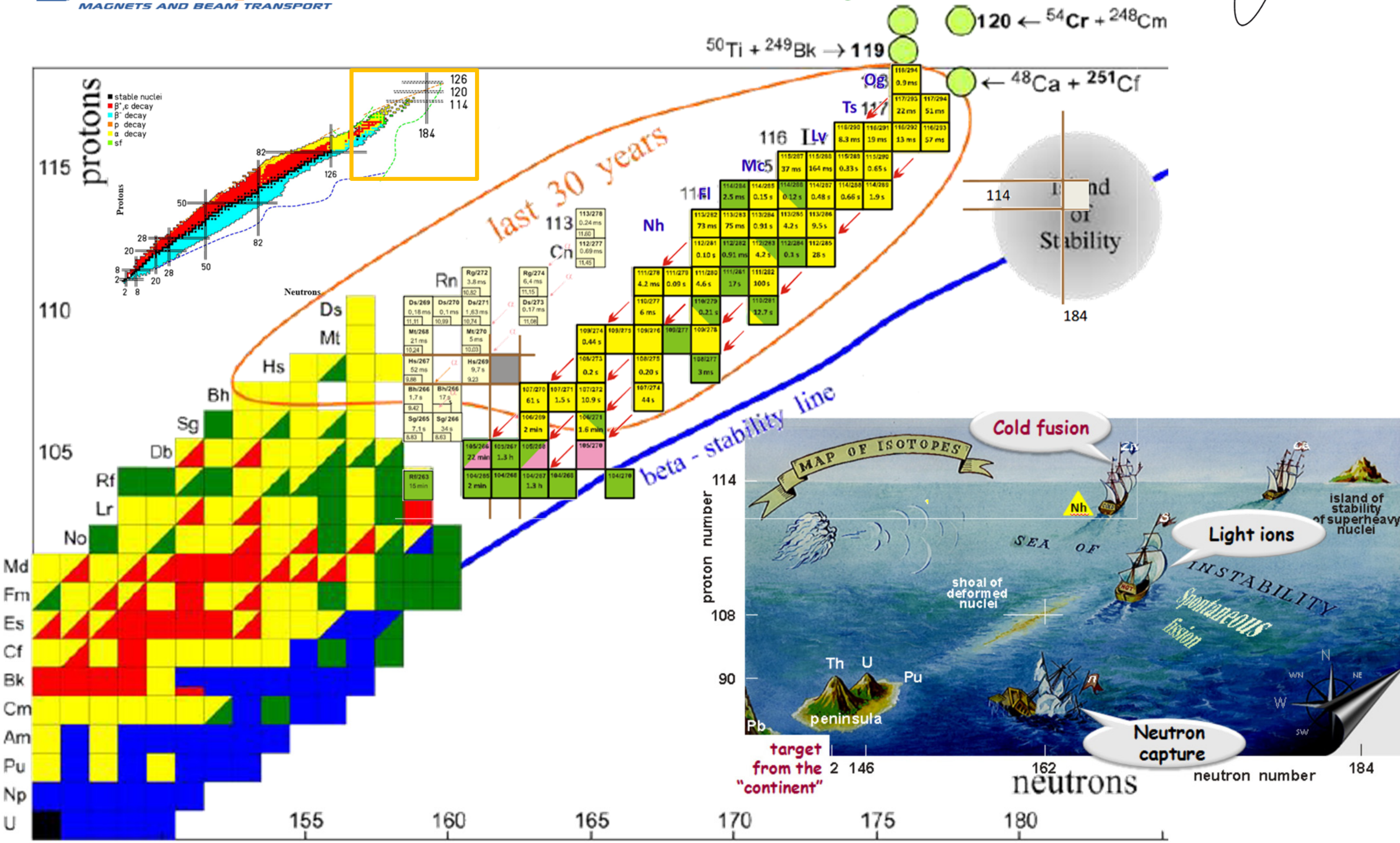
The same row in my 1st year (1977) chemistry textbook (Mahan 2nd ed 1969)





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

Heading towards stability

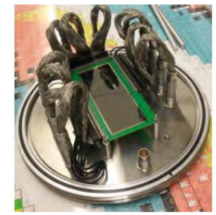


Super Heavy Elements

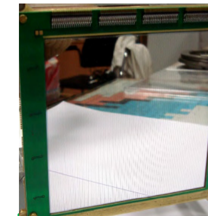
HOW ?

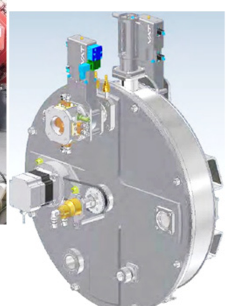
Schematics of a separator

48×128 strips
6144 pixels

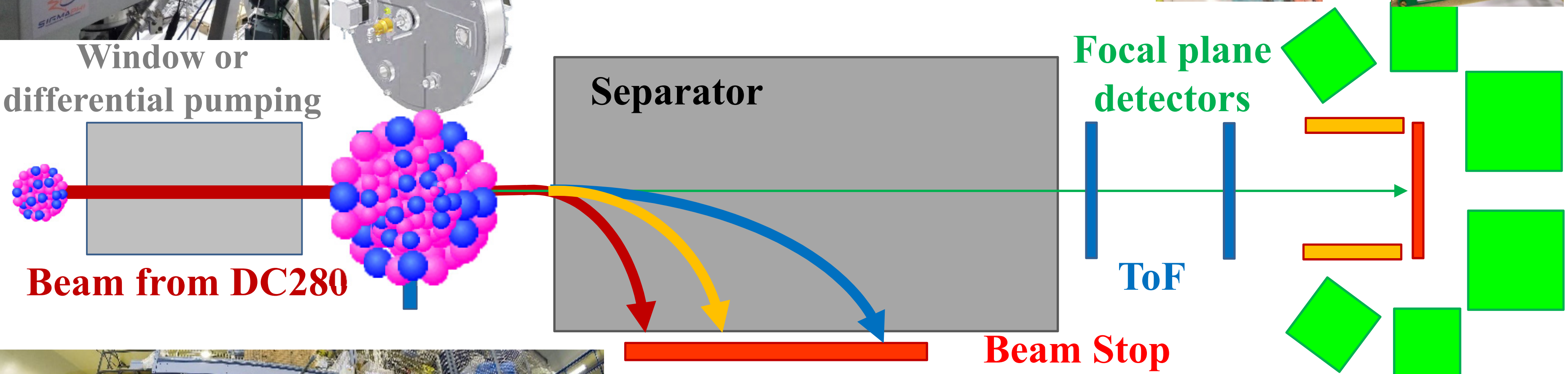


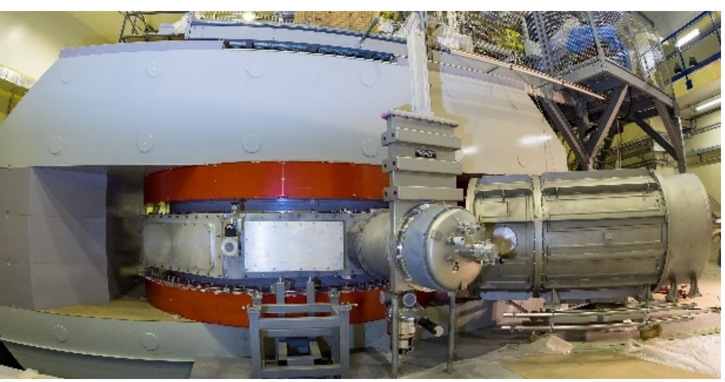
128×128 strips
16384 pixels



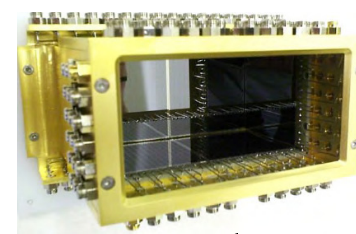


- Ø 480, 1500 rpm synchronous,
- e-beam & optical diagnostics
- Water & gas cooled



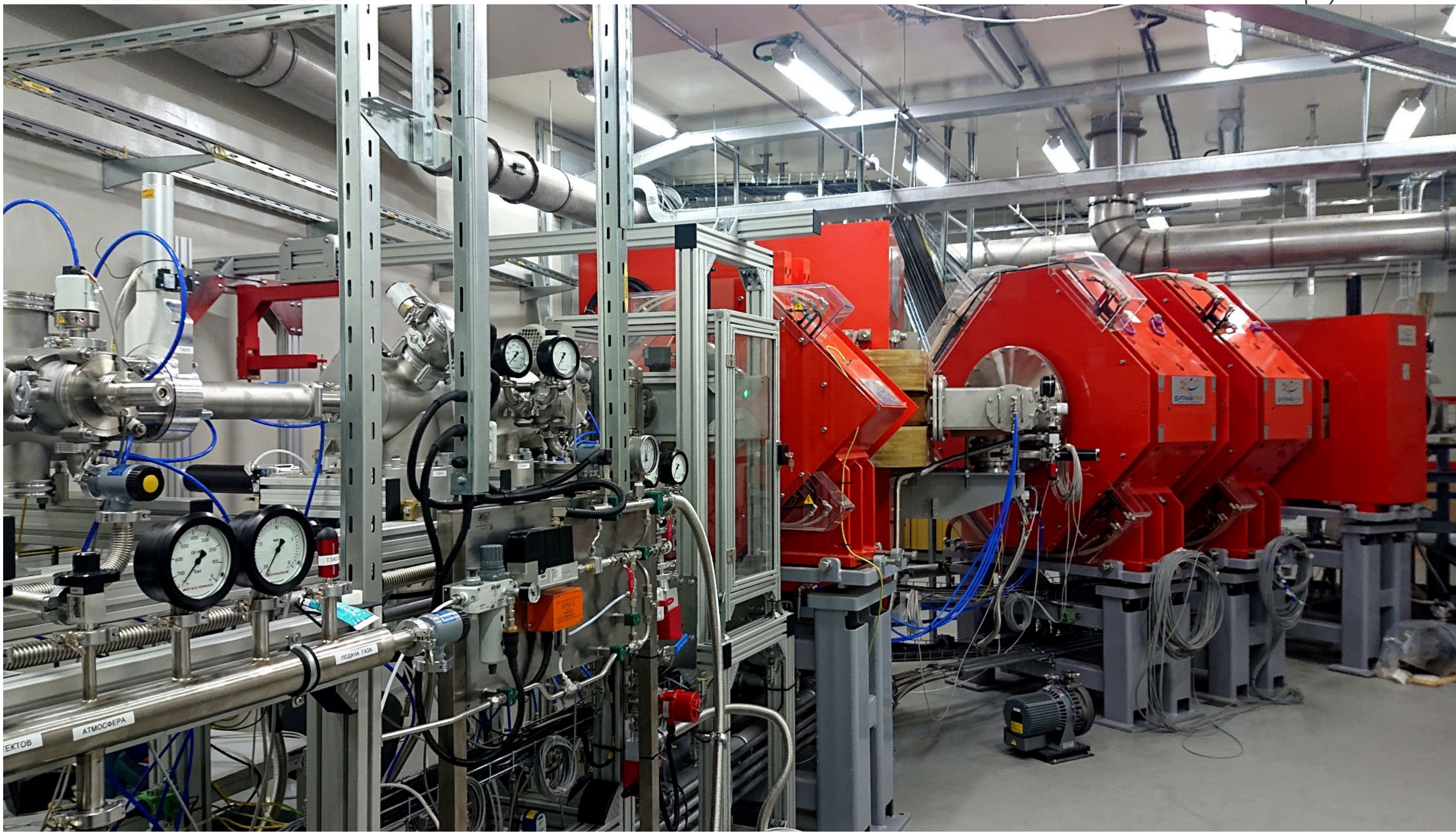


Detector box



Micron Semiconductors, UK

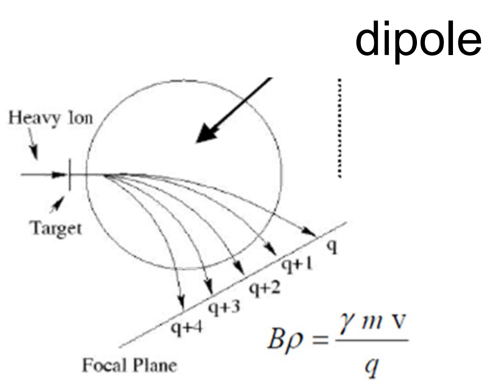
GFS-2

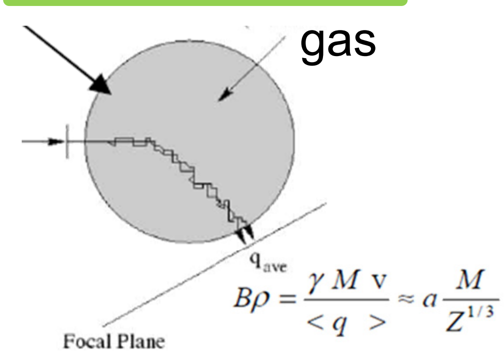


What are we fighting for?

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**	**Large acceptance Gas-filled Separator**



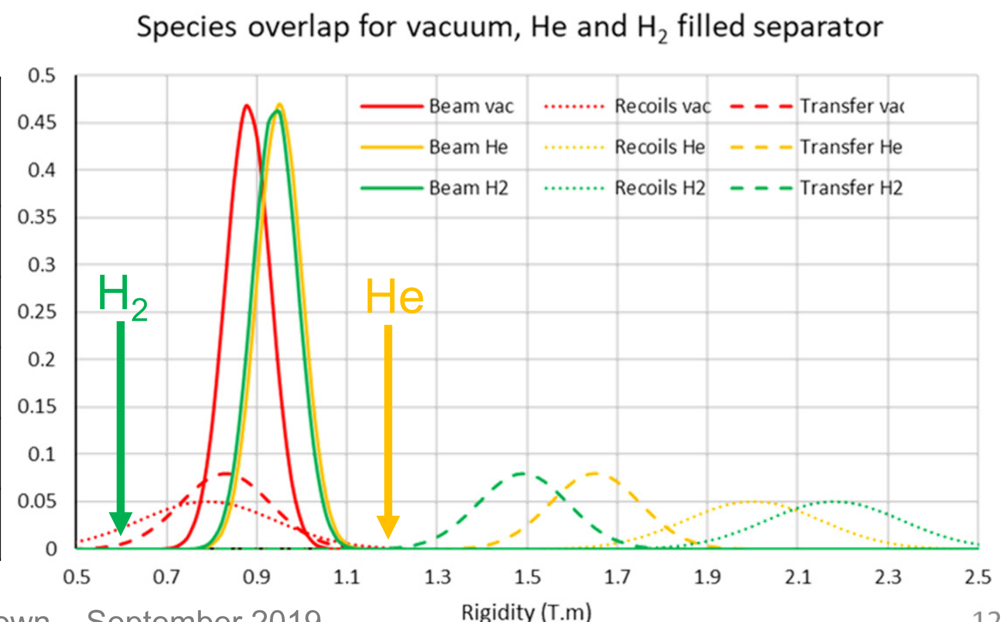


Discriminating from background

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

$$^{48}Ca(236MeV) + {}^{244}Pu(300mg/cm^2, PuO2) \rightarrow {}^{292}Fl^*$$

Nucl.	E(MeV)	Bρ vac (T·m)	Bρ He (T·m)	Bρ H_2 (T·m)
^{48}Ca	236	0.88	0.94	0.94
^{292}Fl	38.8	0.79	2	2.18
^{244}Pu	129.7	0.83	1.65	1.49
^{4}He	67		1.2	
$^{1}H_2$	18.8			0.62



What GF separators are not so good at

Asymmetry: $A_p/(A_p+A_t)$

Completely symmetric reactions
Asym = 0.5

$^{136}Xe + ^{136}Xe \rightarrow ^{272}Hs^*$

Nucl.	E(MeV)	Bρ vac (T·m)	Bρ He (T·m)	Bρ H_2 (T·m)
^{136}Xe	600	1.1	1.38	1.38
^{272}Hs	300	0.95	1.39	1.21
^{136}Xe	600	1.1	1.38	1.38
^{4}He	66.6		1.2	
$^{1}H_2$	17.4			0.6

Very asymmetric reactions
Asym = 0.085

$^{22}Ne + ^{238}U \rightarrow ^{260}No^*$

Nucl.	E(MeV)	Bρ vac (T·m)	Bρ He (T·m)	Bρ H_2 (T·m)
^{22}Ne	112.4	0.76	0.76	0.76
^{260}No	9.5	0.74	1.82	2.45
^{238}U	34.8	0.72	1.89	2.01
^{4}He	58.5		1.1	
$^{1}H_2$	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 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"

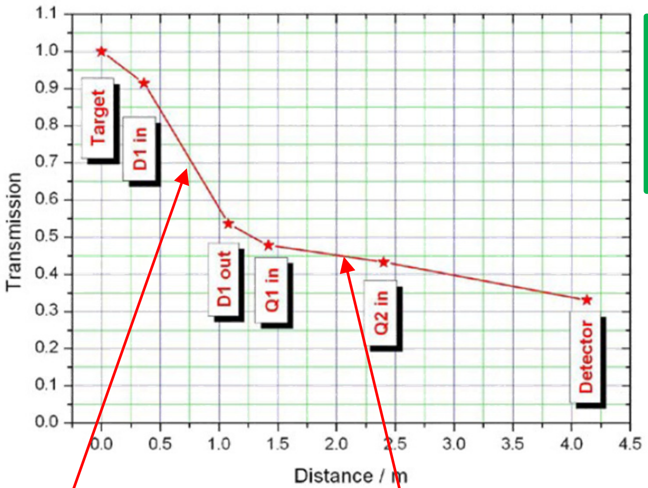
Excerpt from the Wikipedia webpage on Oganesson
https://en.wikipedia.org/wiki/Oganesson

Expectations

Rationale for new layout

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

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



40% loss in dipole

15% loss in quads

MUST IMPROVE TRANSMISSION

Increase dipole gap

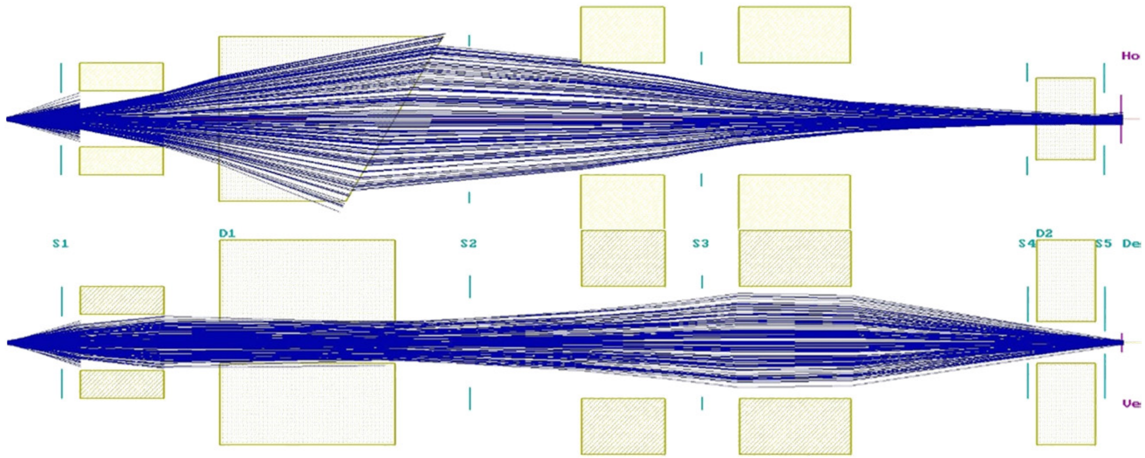
Q_1 V to enter dipole

Refocus H asap

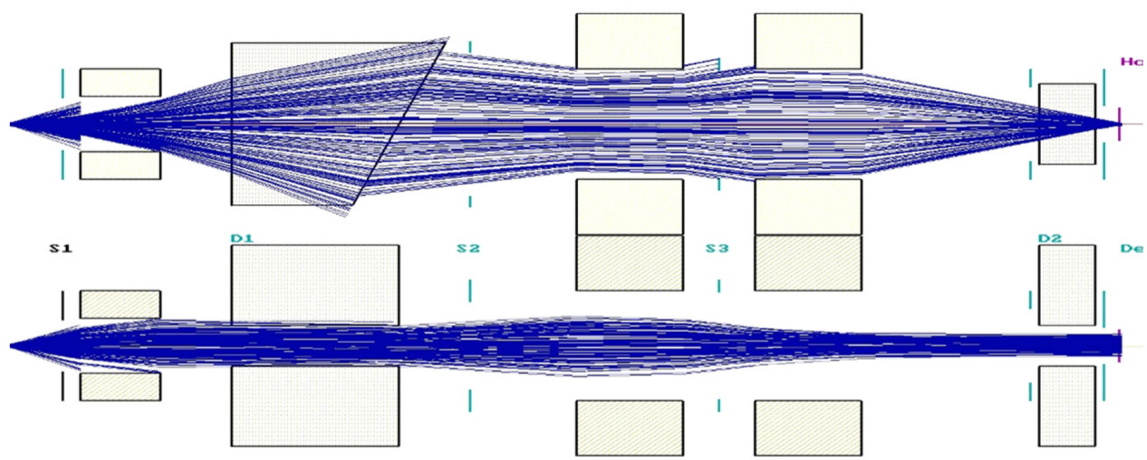
Large exit pole edge angle

Large aperture quads

Transmission or Resolution ?



VHHV
Transmission +
Resolution -
Separator

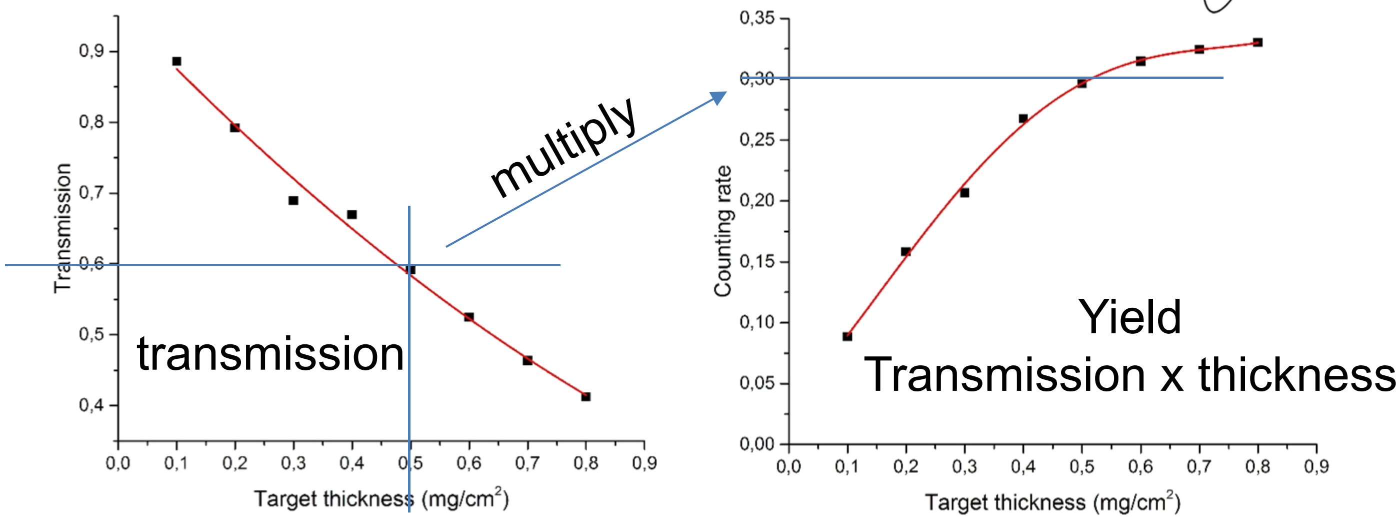


VHVH
Transmission –
Resolution +
Spectrometer

Some other role players

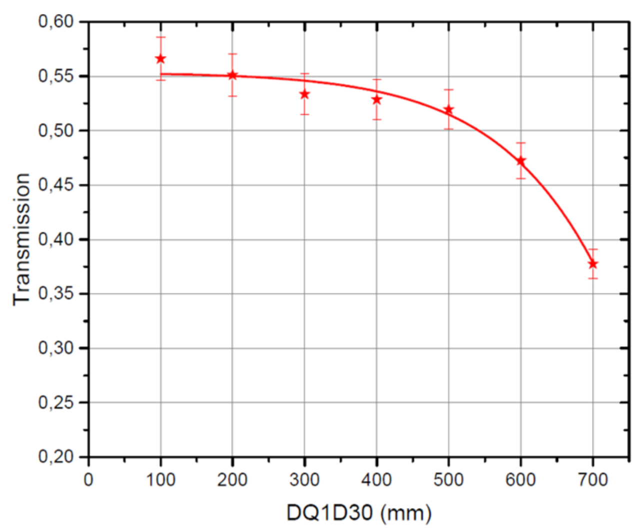
The target

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



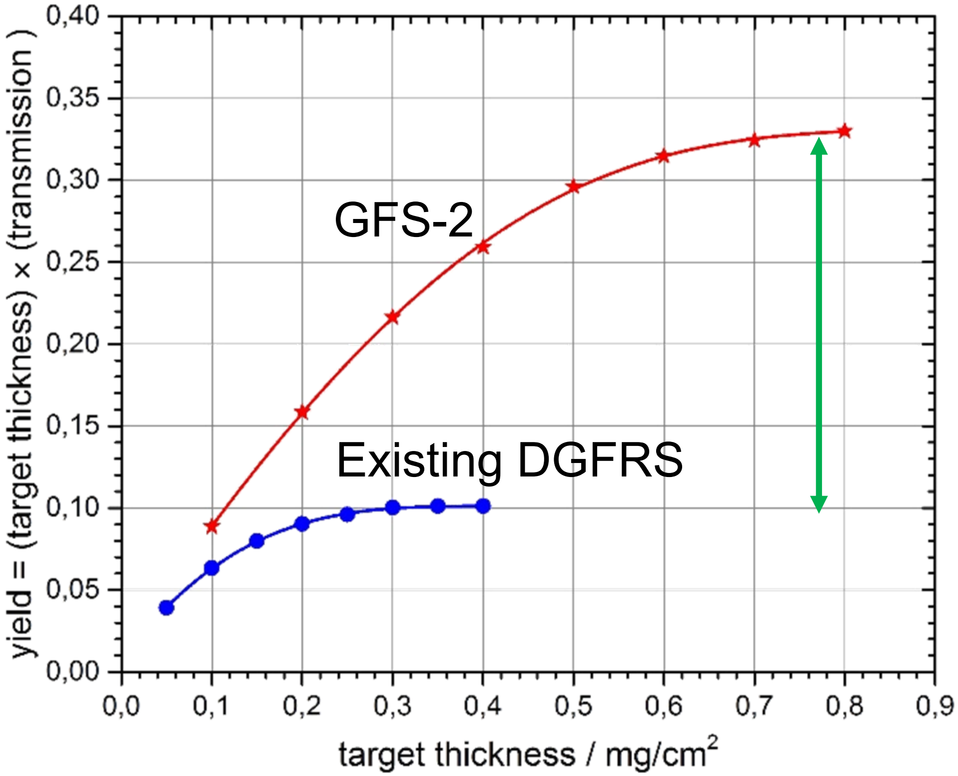
Distances

Length of elements
Drifts between elements



Expected gain

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



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

Over 3 times more !!

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

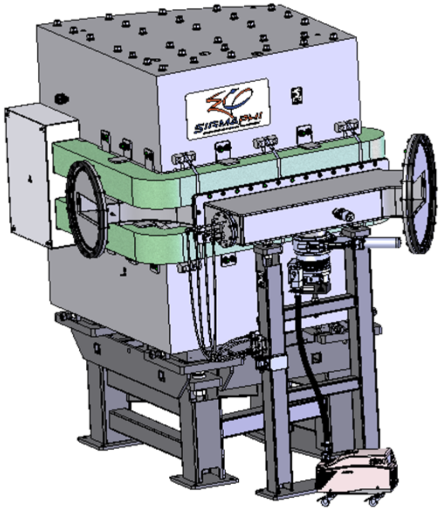
Can I trade this for that ?

I can improve. Is it worth ?

…

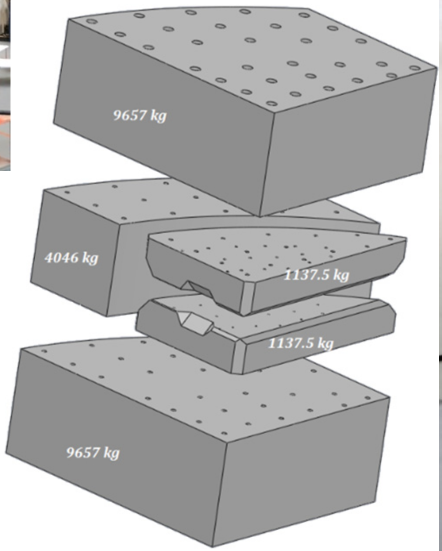
The big guy – 30° D1

D1 General



Factory assembly

Assembly on site



Hall probe measurement

Each part must be less than 10 tons

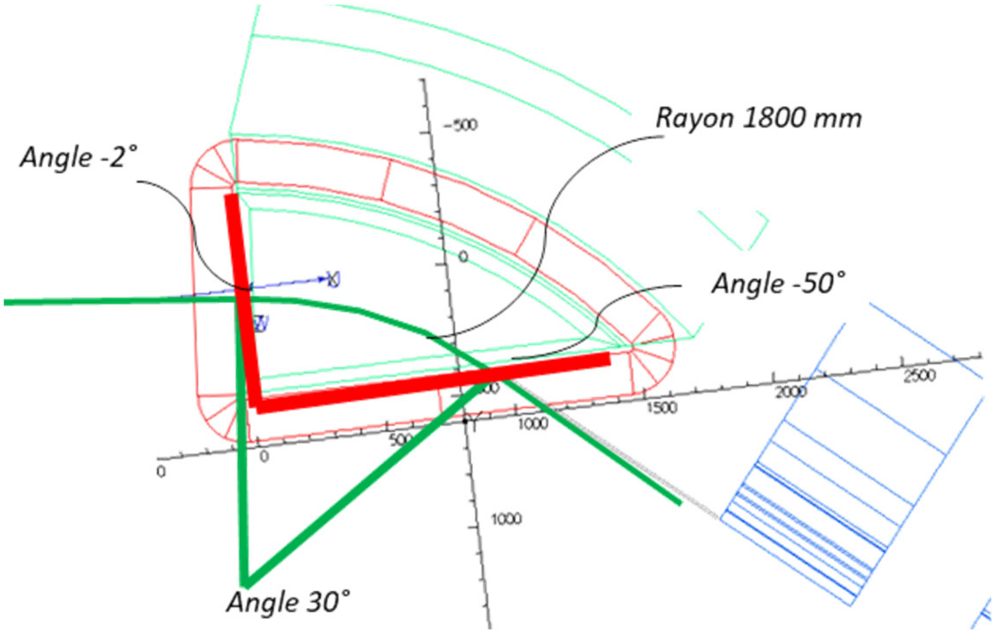
D1 parameters

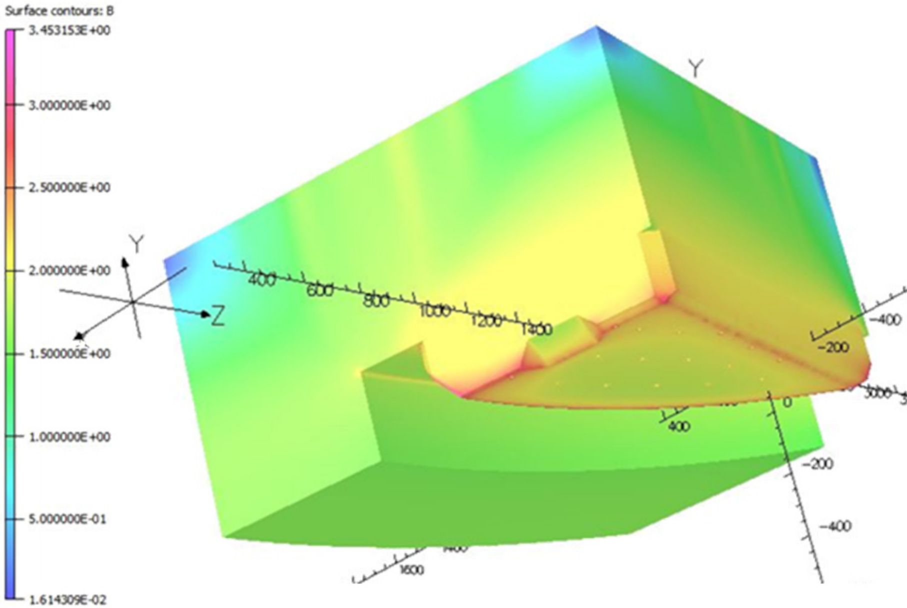
Beam free aperture	**120**	mm
Magnet gap	**132**	mm
Curvature radius	1800	mm
Entrance face angle	-7 (-2)	°
Exit face angle	**-44** (-50)	°
Deviation angle	31.5	°
Effective length	1007	mm
Good Field region	440	mm

Max field	1.8	T
Max current	919	A
# turns (1 coil)	120	
Max current density	7.4	A/mm^2
Magnet power	139	kW
Yoke weight	25.7	ton
Copper weight	1.24	ton

D1 design (1)

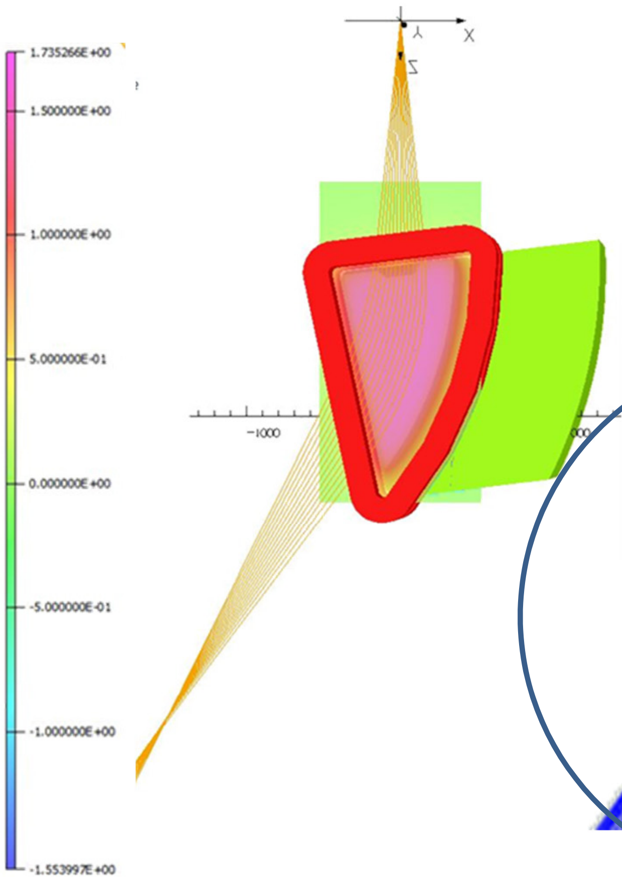
Large exit angle makes a conventional structure very difficult.
Entrance and exit faces side by side
Change on one generate change on the other -> joint optimization
Complex profile on entrance face



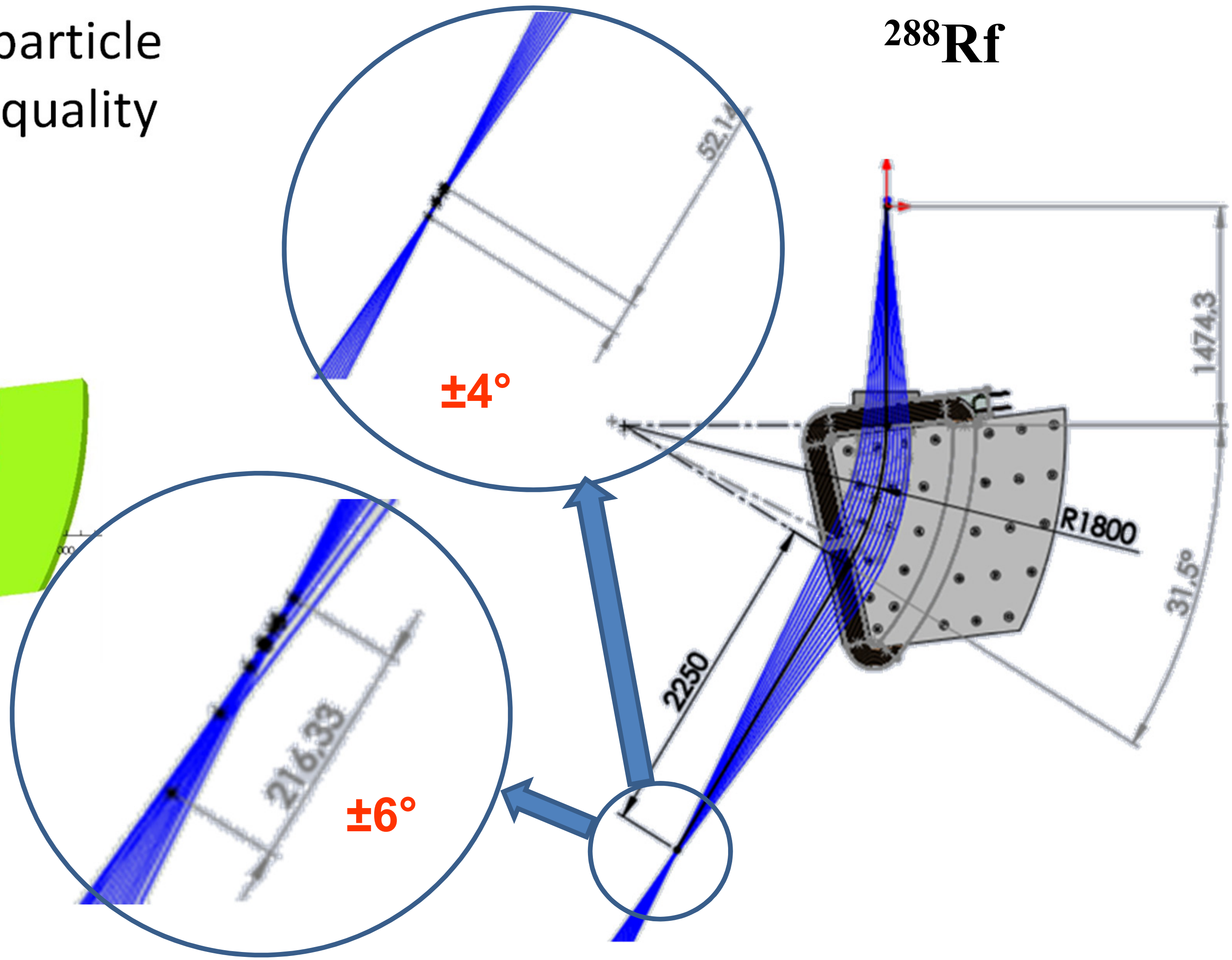


D1 design (2)

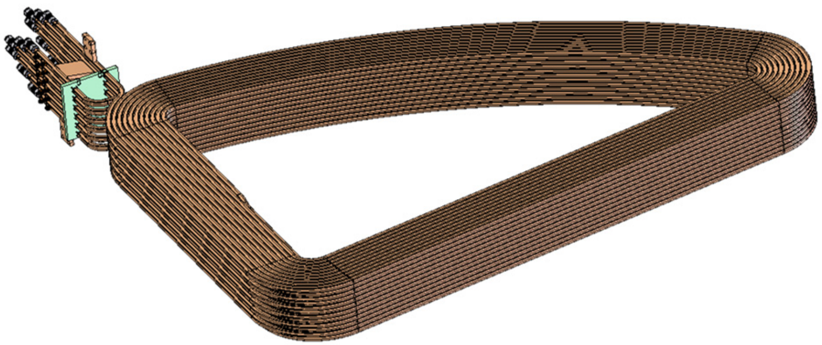
Design driven by particle tracking focusing quality

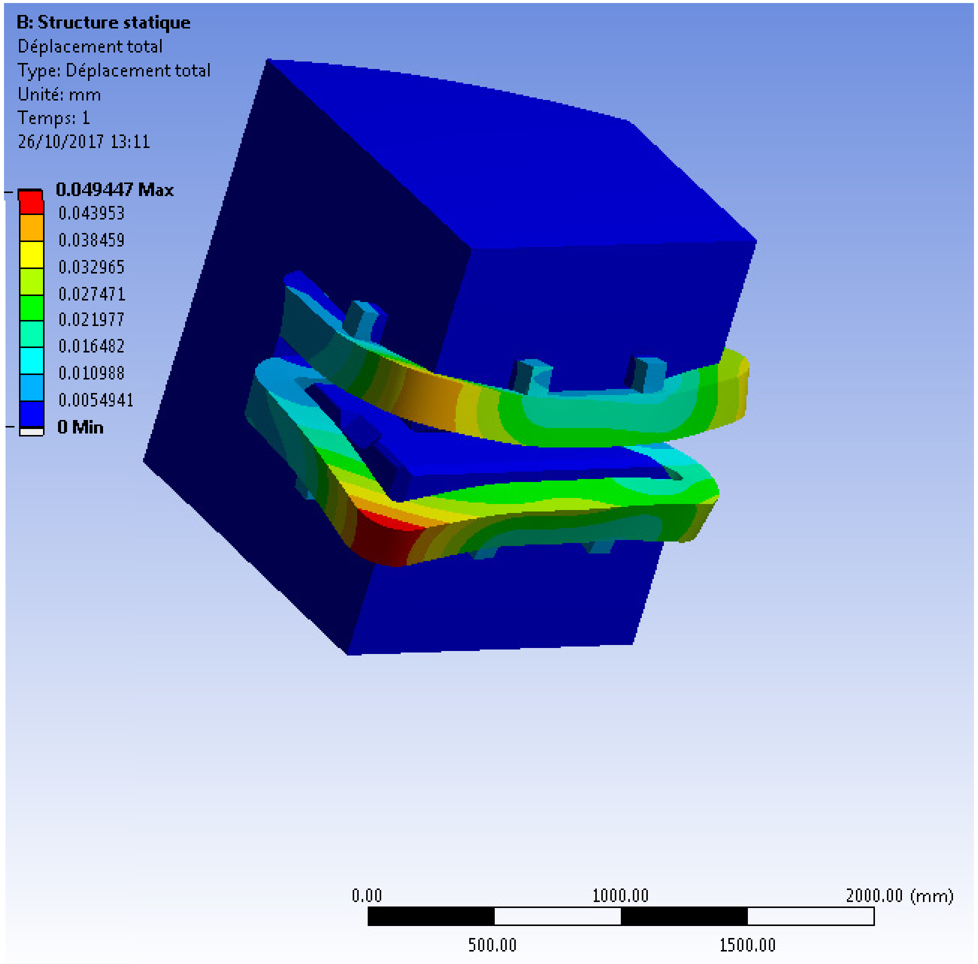


^{288}Rf

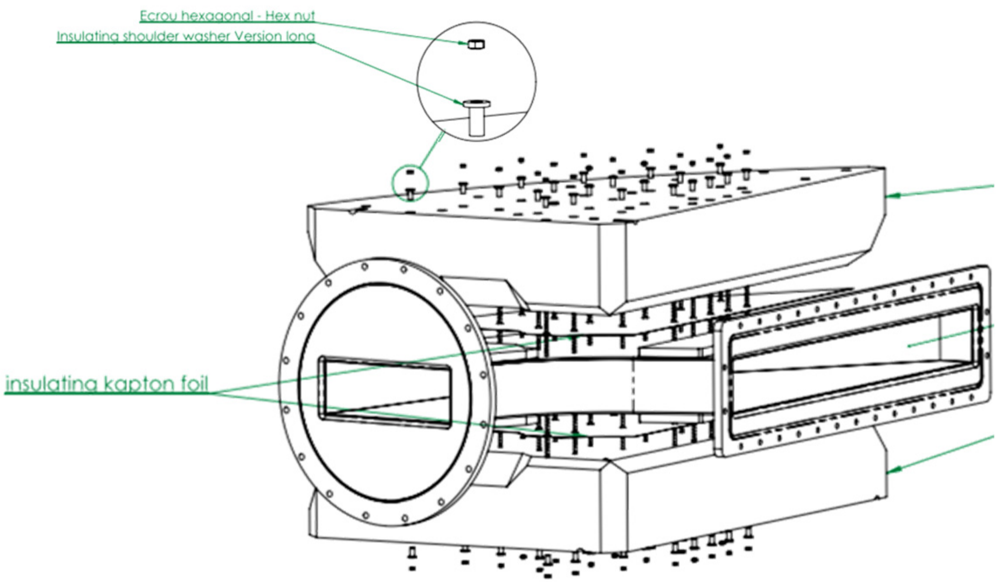


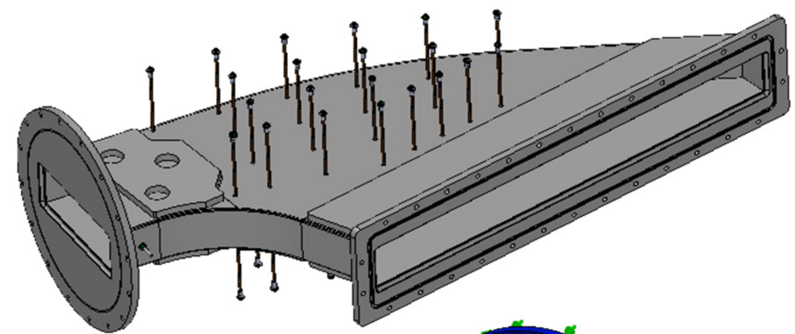
D1 coils

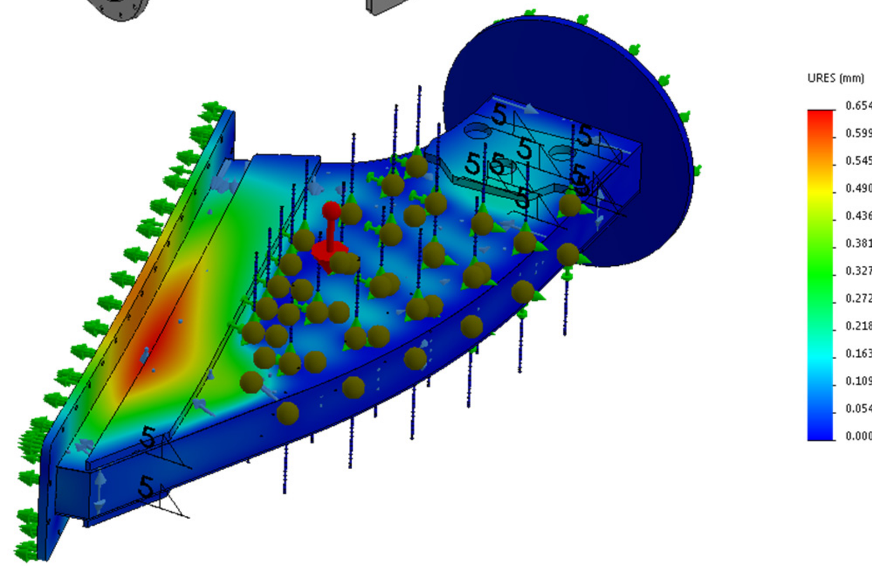



B: Structure statique
Déplacement total
Type: Déplacement total
Unité: mm
Temps: 1
26/10/2017 13:11
0.049447 Max
0.043953
0.038459
0.032965
0.027471
0.021977
0.016482
0.010988
0.0054941
0 Min
0.00
1000.00
2000.00 (mm)
500.00
1500.00

D1 chamber (1)







Very large surface ~4000 cm²
Wall must be thick to prevent deformation
21 struts + edge reinforcement allow thin walls
0.65 mm max displacement

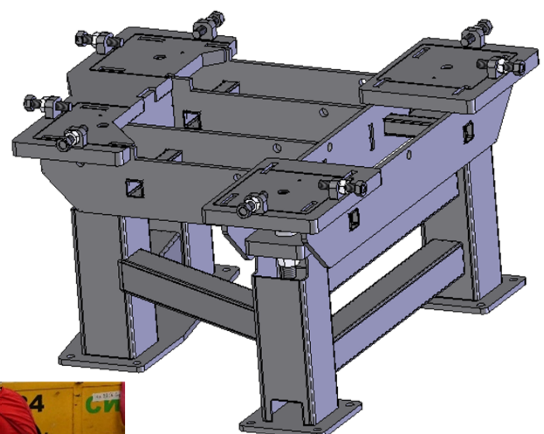
D1 chamber (2)

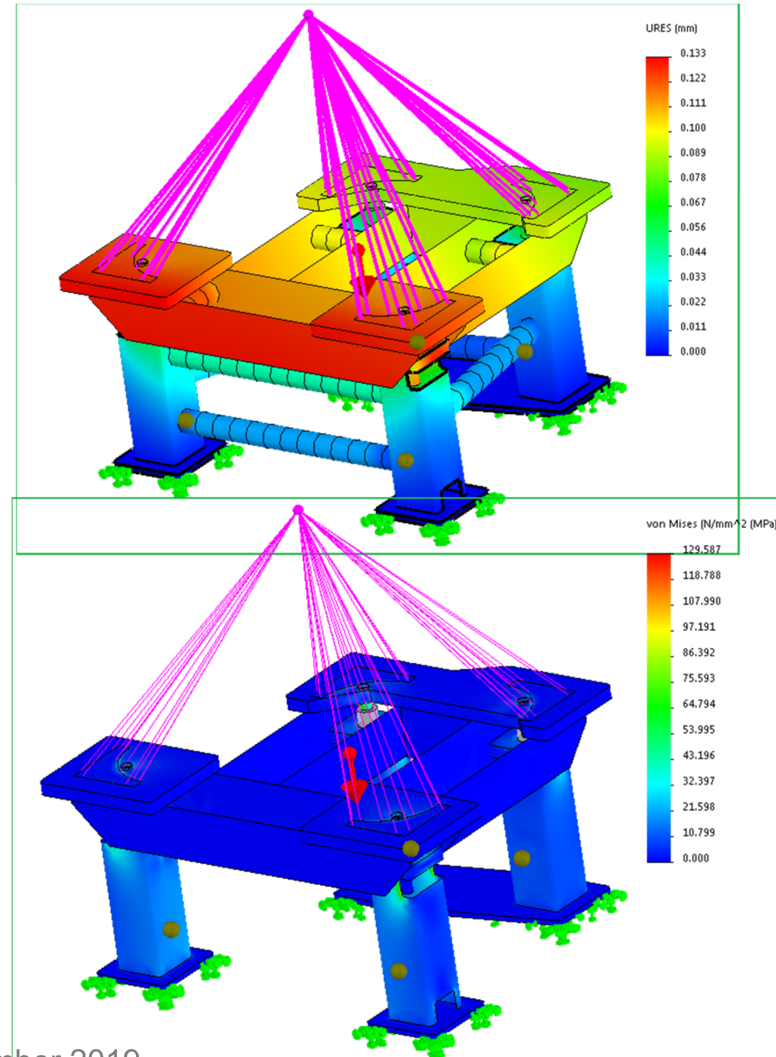
Chamber is electrically insulated

Chamber assembly and testing in factory

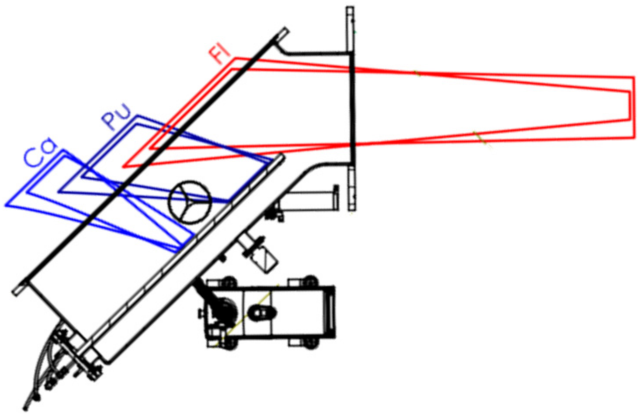
D1 Stand

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

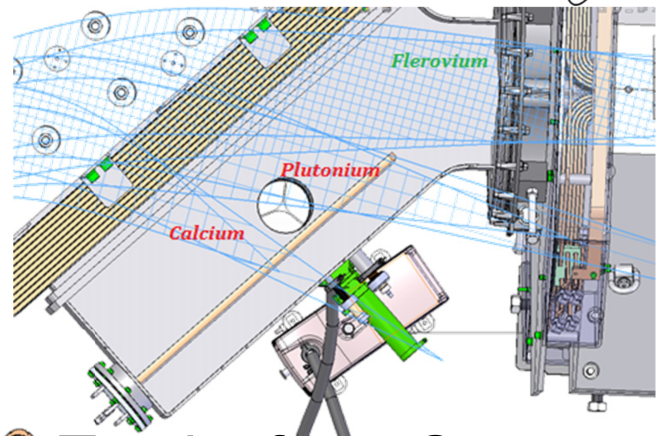




D1 Beam stop

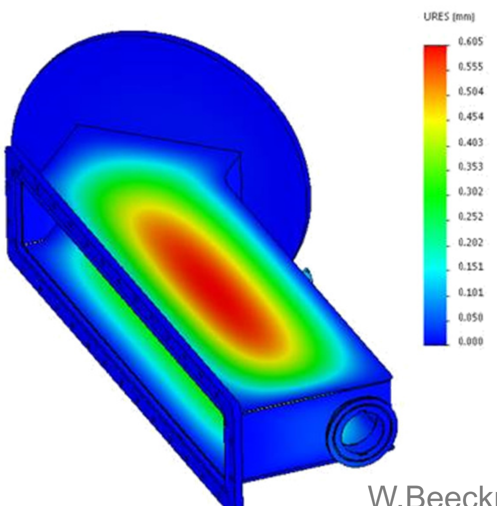


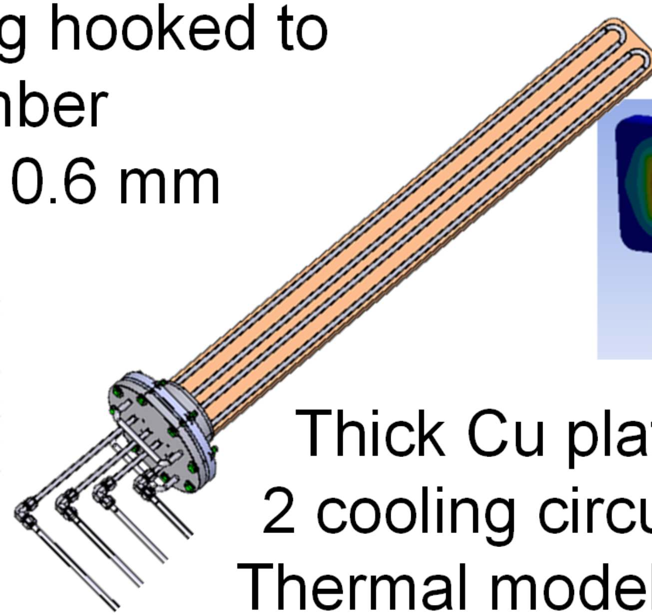
block most background species and let EVR pass

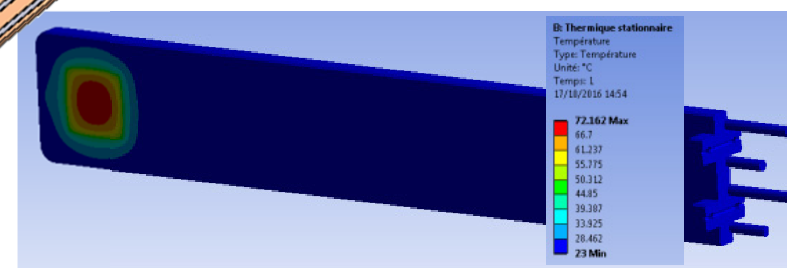


Tracks from Opera model

Beam stop housing hooked to main chamber
Deformation < 0.6 mm







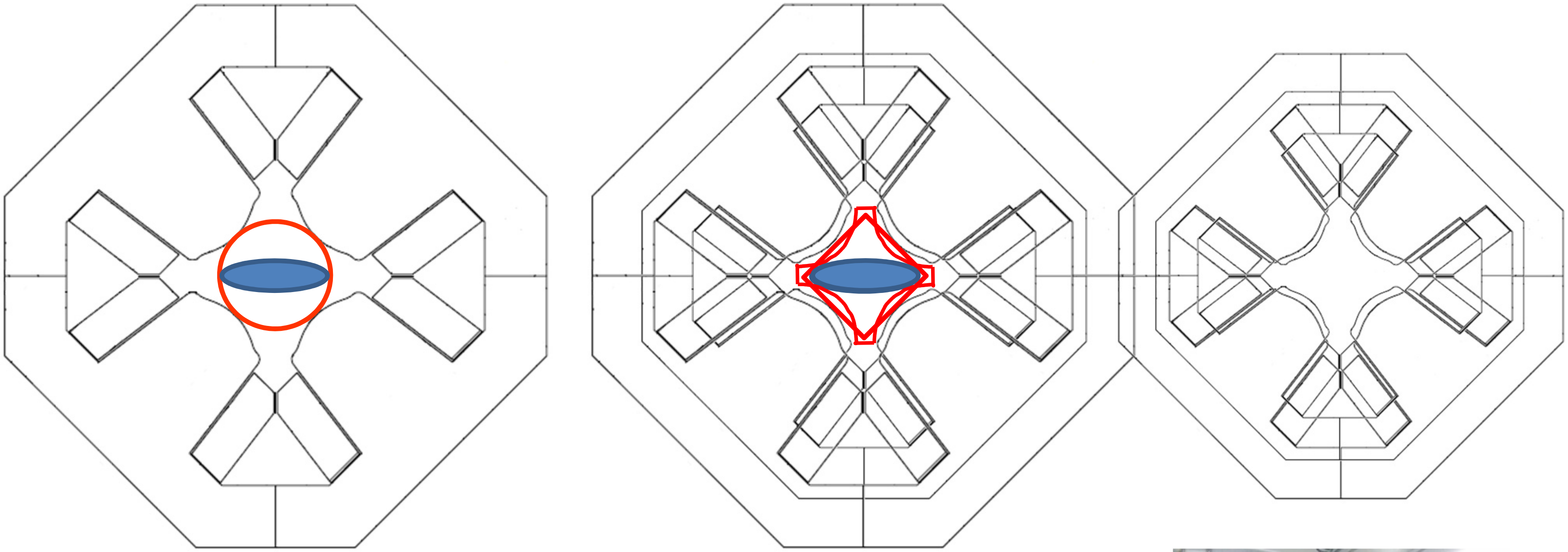
Thick Cu plate
2 cooling circuits
Thermal modelling **crucial**

Quadrupoles

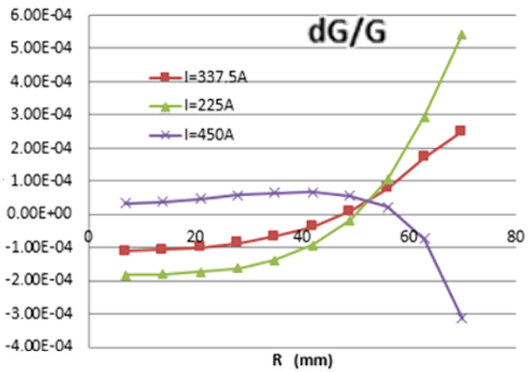
Quadrupoles parameters

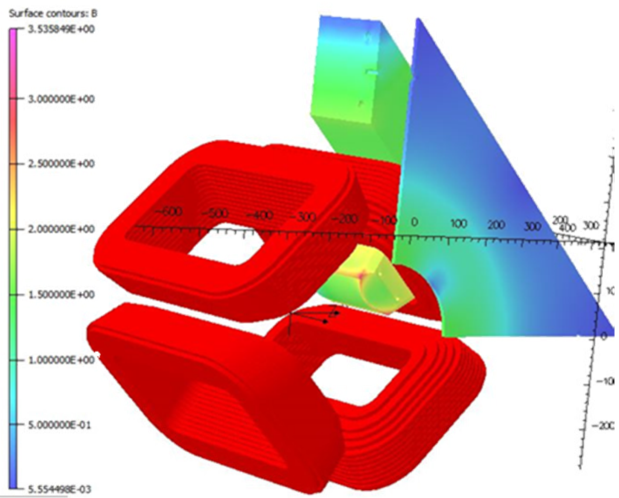
	Q1	Q2/Q3	
Bore diameter	150	300	mm
Iron length	420	520	mm
Effective length	456.6	600	mm
Max gradient	13.2	5.34	T/m
Max current	450	362	A
# turns (1 coil)	88	138	
Max current density	6.35	6.6	A/mm^2
Magnet power	28.2	61.6	kW
Yoke weight	2.07	6.65	ton
Copper weight	0.39	0.68	ton

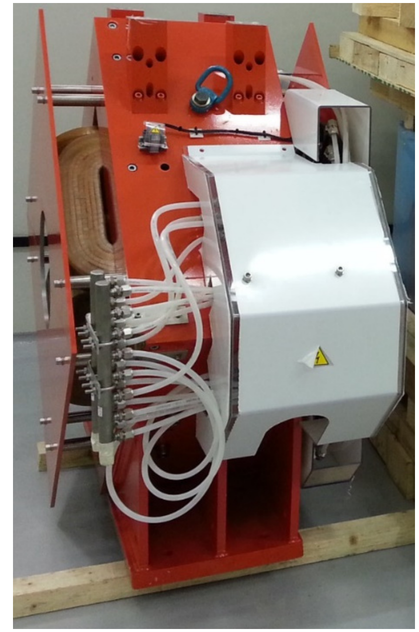
Shaping chambers to reduce bore

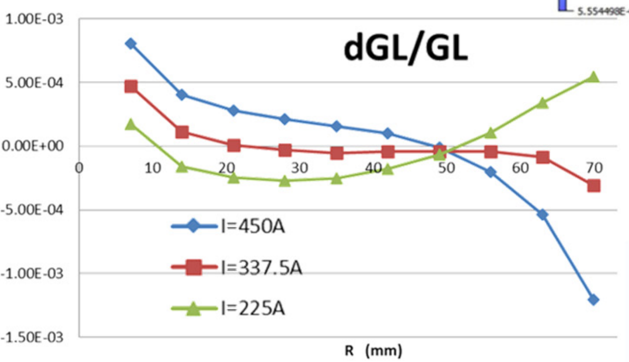


Q1

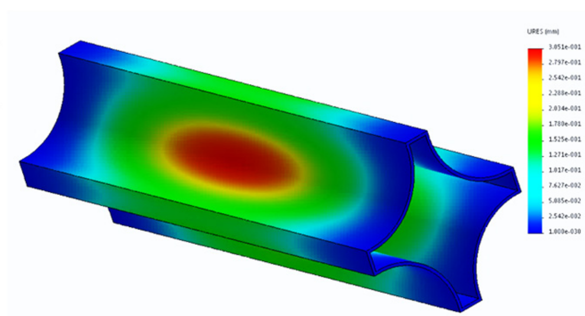


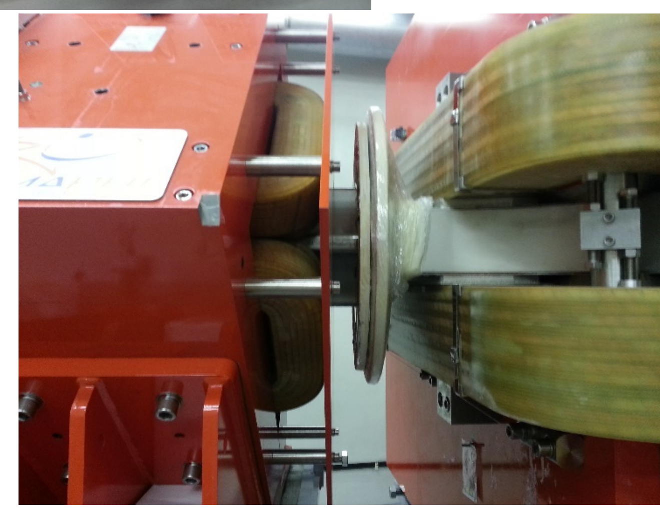






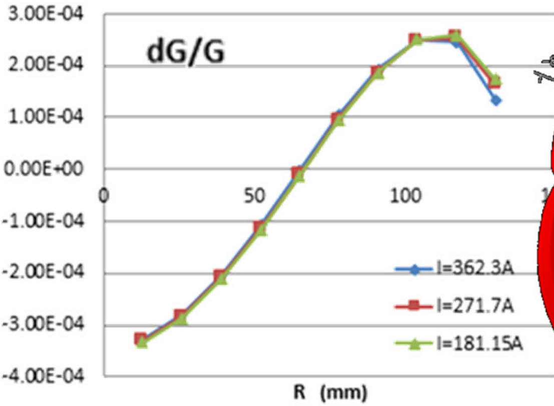
ϕ=150mm
G=13.2 T/m

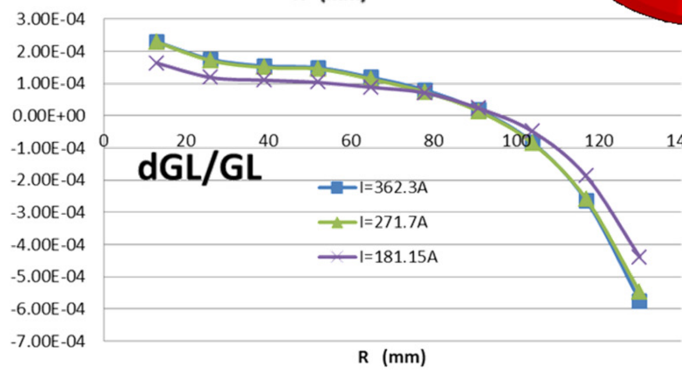


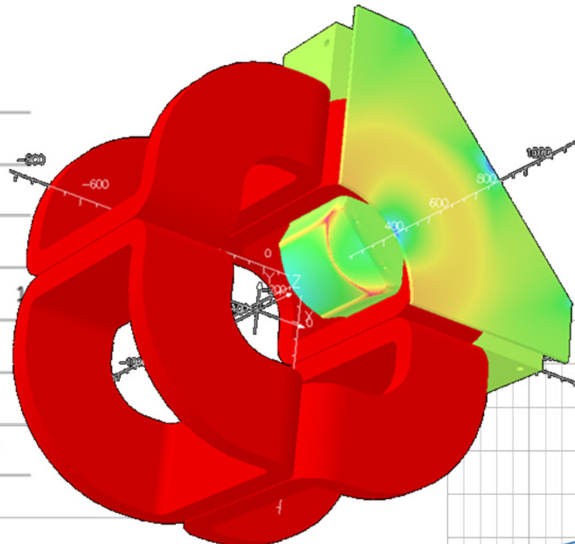


Local & integrated gradient homogeneity along radius

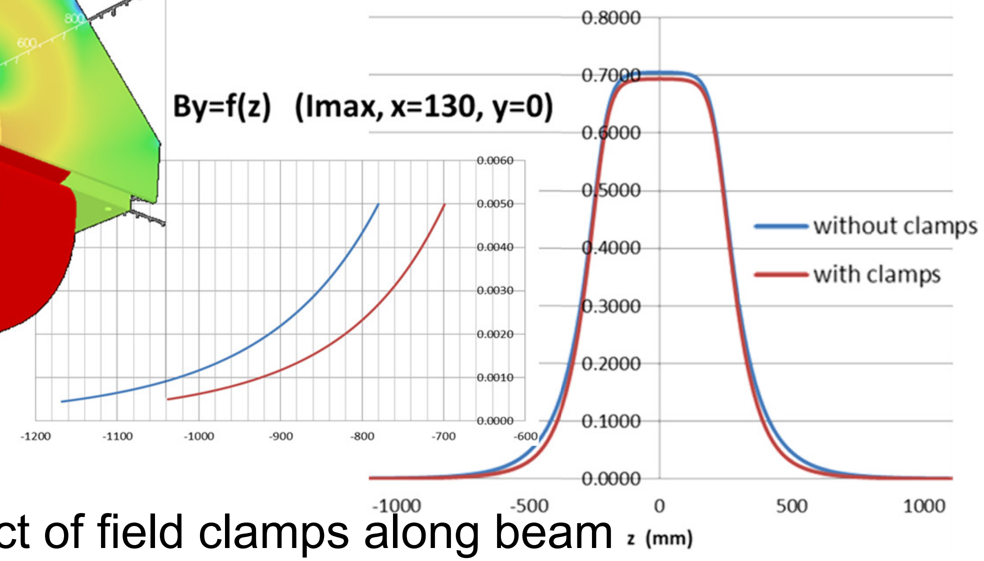
Q2/Q3



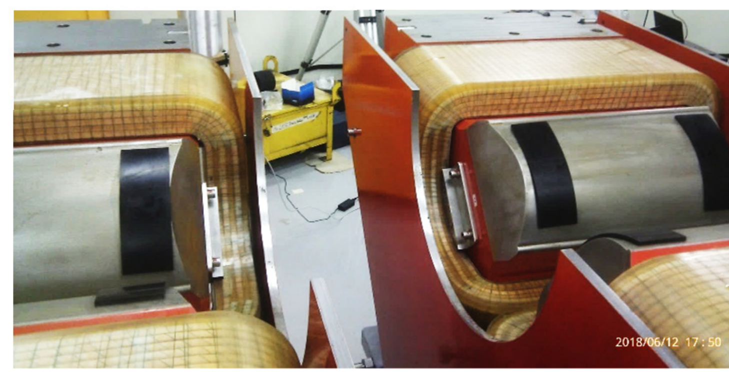




ϕ=300mm
G=5.34 T/m

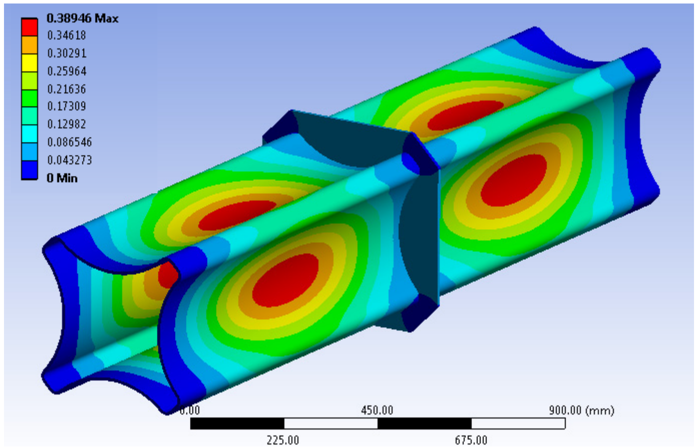


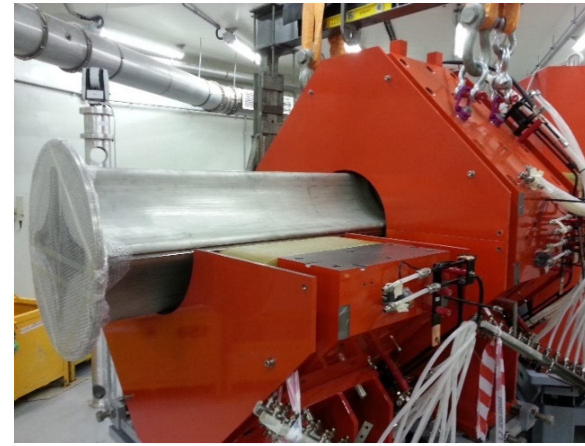
Effect of field clamps along beam

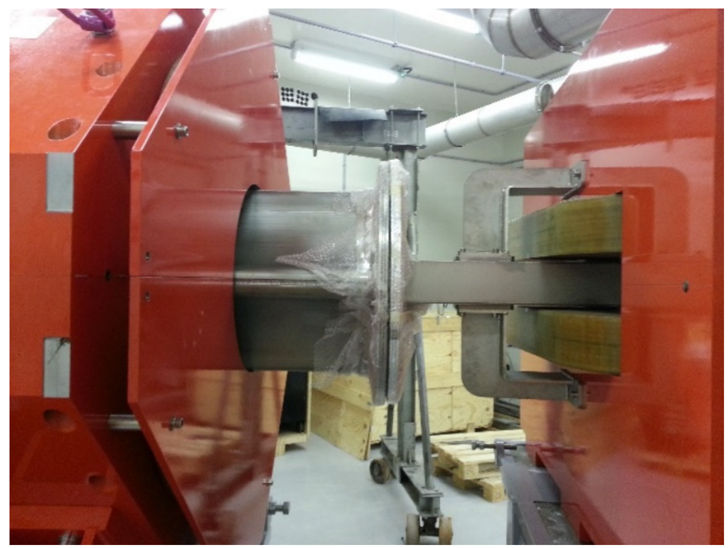


Local & integrated gradient homogeneity along radius

Q2/Q3 Vacuum chamber





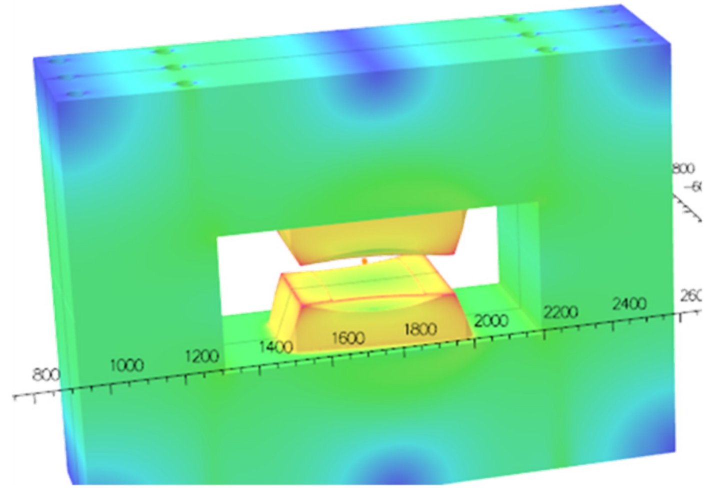


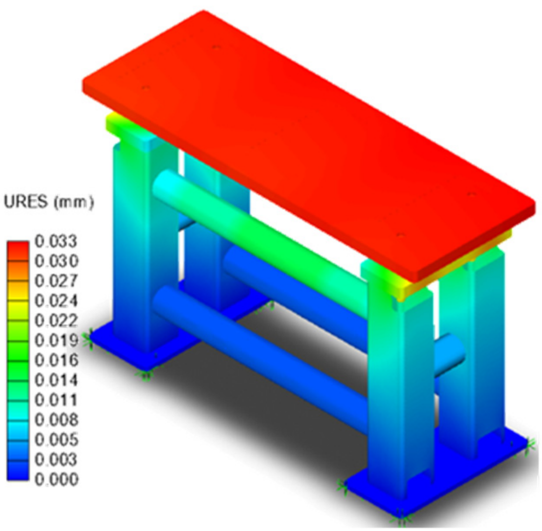
SIGMAPHI
MAGNETS AND BEAM TRANSPORT

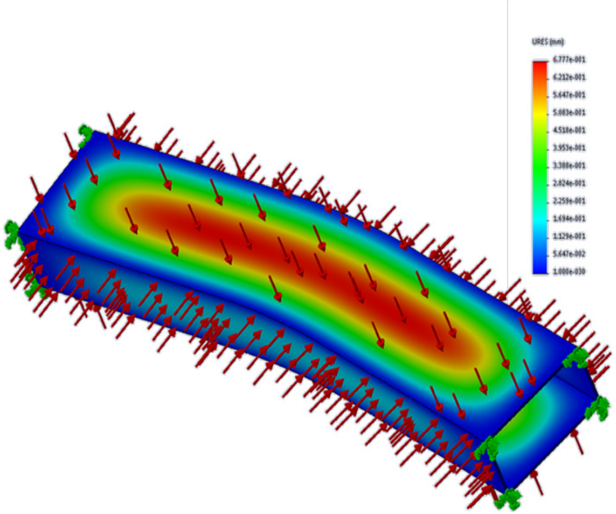
D2

JINR
FLNR
114 Flerovium
Dubna

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





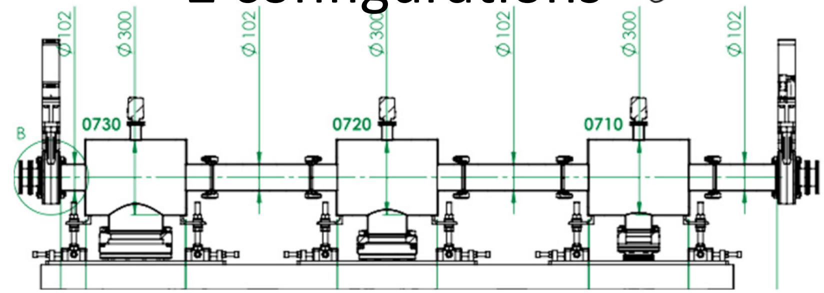


Differential pumping system

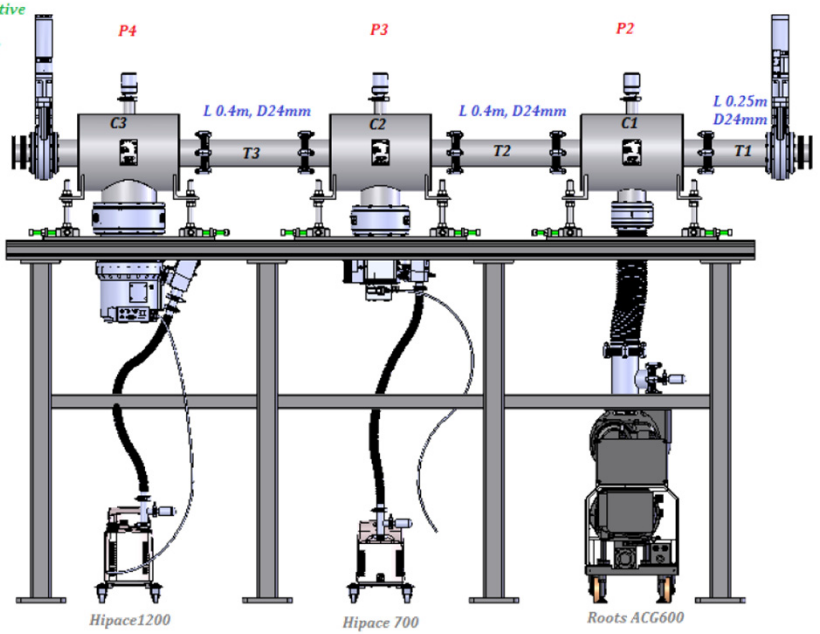
Differential pumping (1)

- 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



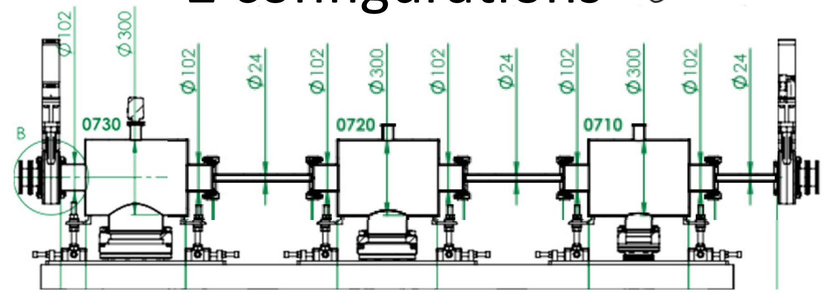
Pressure profile (case of He)

	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

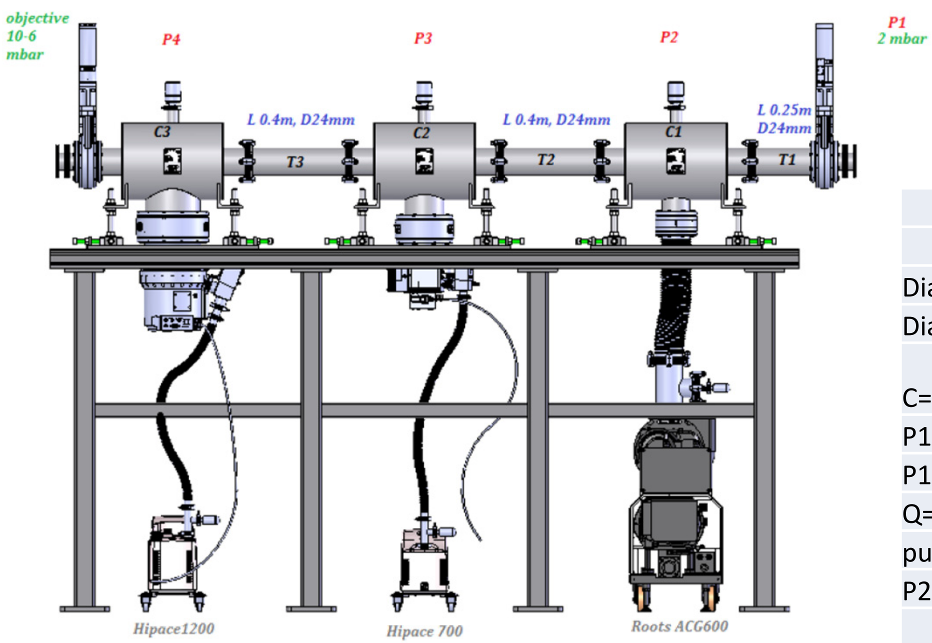
Differential pumping (1)

- 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

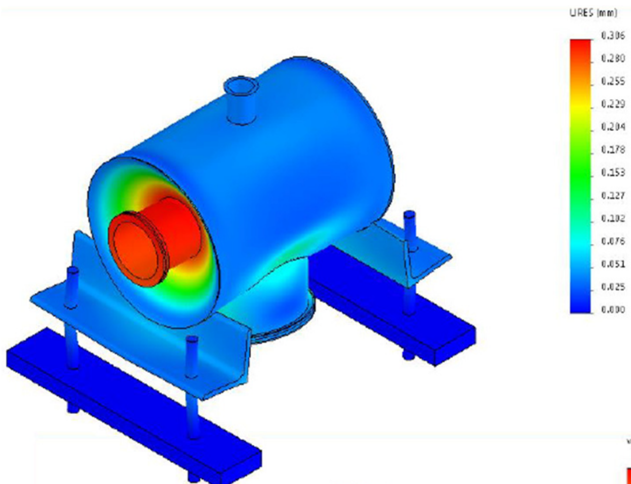


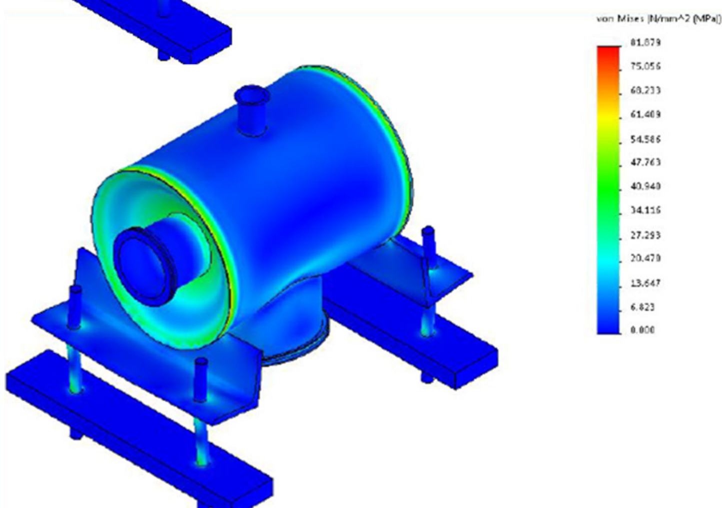
Pressure profile (case of He)

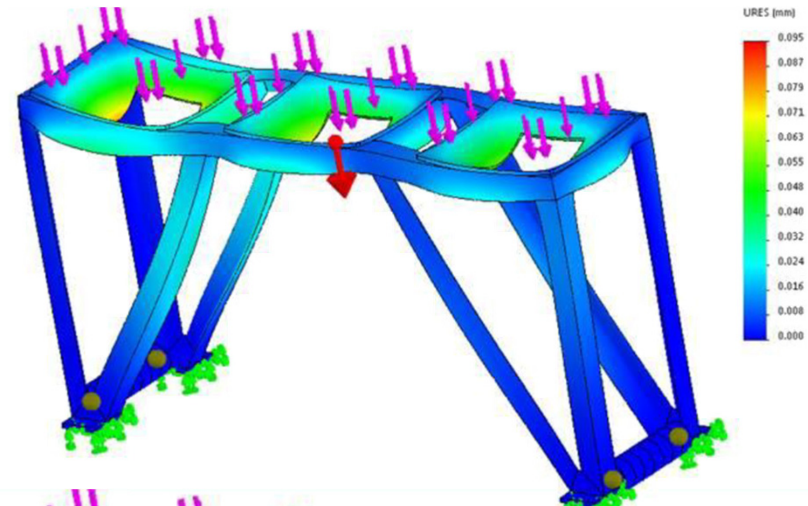
	P1	2.00E+00	P2	1.04E-01	P3	6.47E-04	mbar
	P2 goal	1.00E-03	P3 goal	1.00E-03	P4 goal	1.00E-06	mbar
Diaphragm diameter		24		24		24	mm
Diaphragm length		0.25		0.4		0.4	m
C=1.22 $10^{-4}*(D^3/L)$		6.75E+00		4.22E+00		4.22E+00	l/s
P1-P2		2.00E+00		1.03E-01		6.46E-04	mbar
P1-P2		1.97E-03		1.01E-04		6.37E-07	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

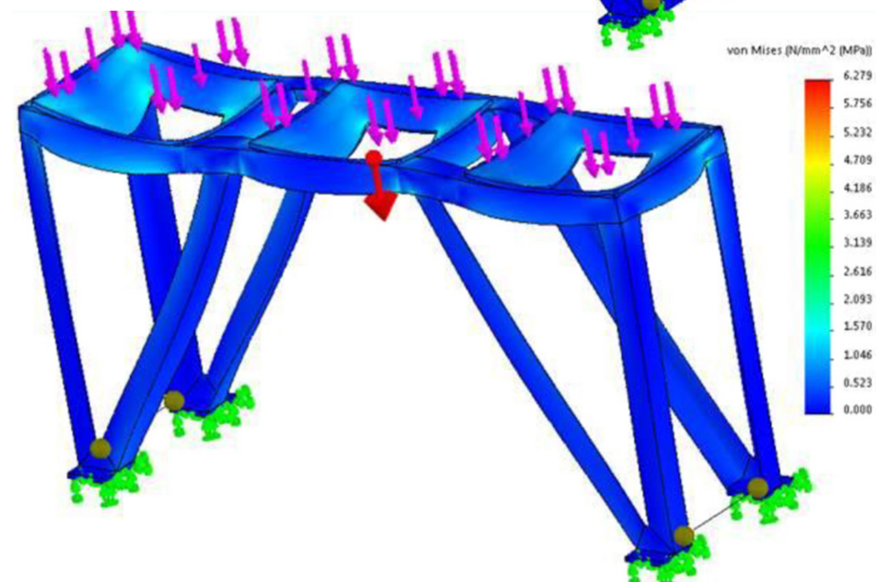
Differential pumping (2)

Mechanically sound



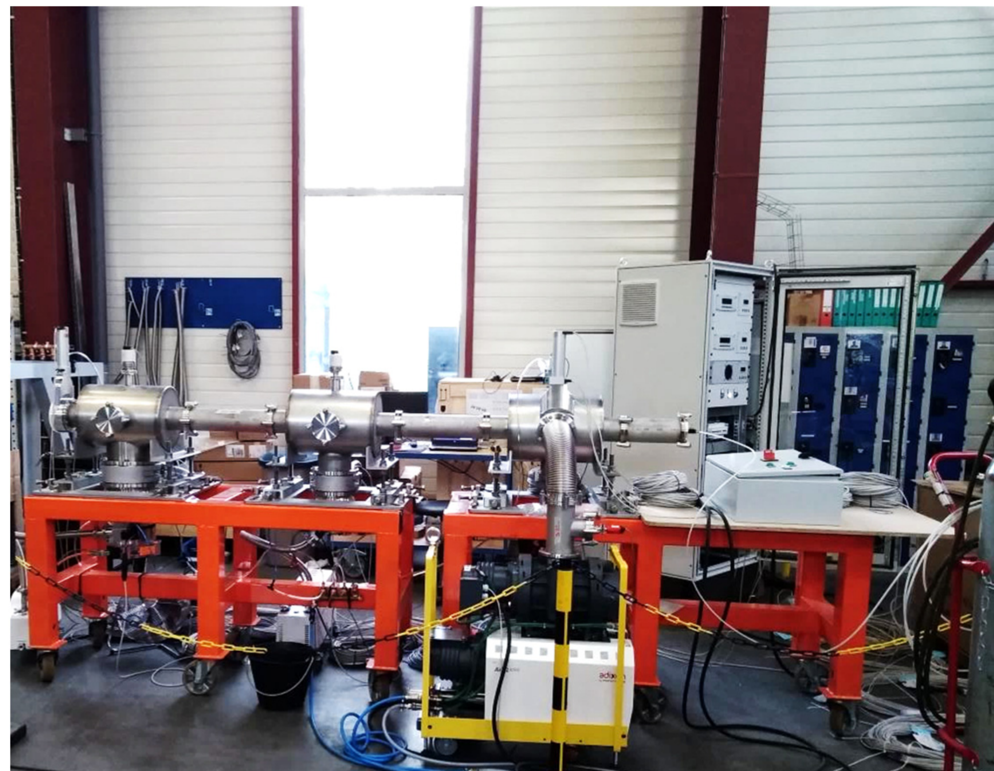






Differential pumping (3)

Factory testing



Power supplies

Power supplies

	Q1	D1	Q2	Q3	D2
I (A)	400	520	260	260	730
U (V)	70	260	230	230	160

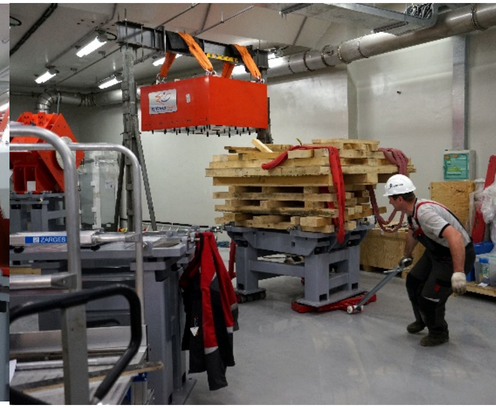
Installation
June 05th-14th 2018

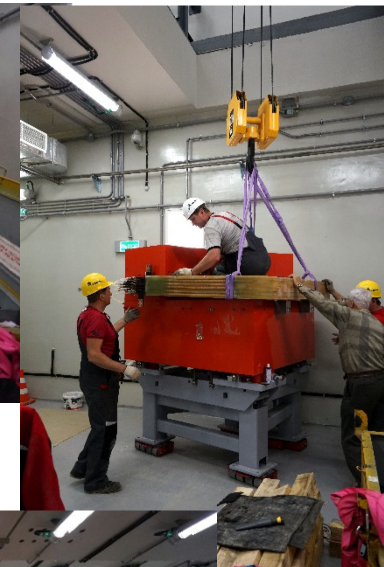
No crane! So what? (1)

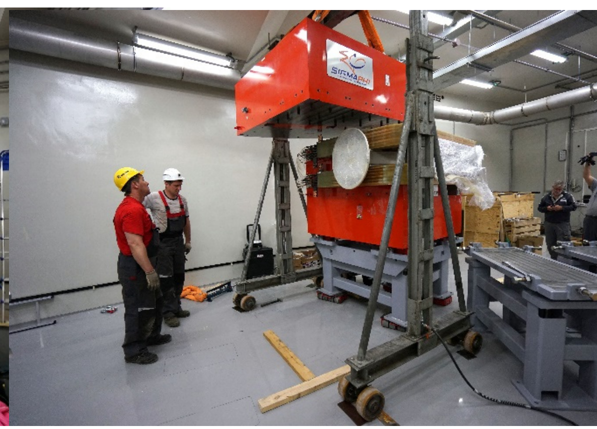
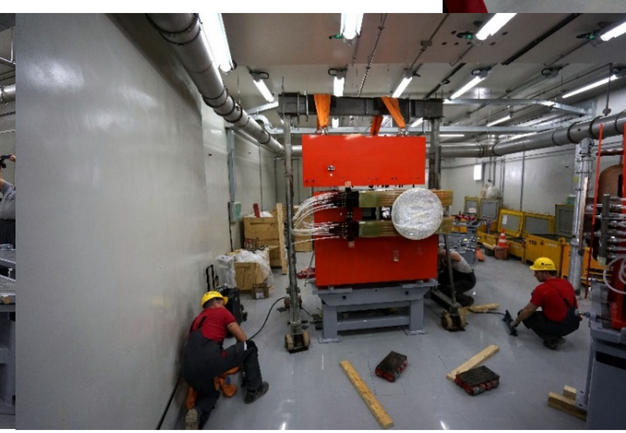
SIGMAPHI
MAGNETS AND BEAM TRANSPORT

No crane! So what? (2)

JINR
114 Flerovium
FLNR
Dubna



Alignment

Alignment

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

Present status and near future

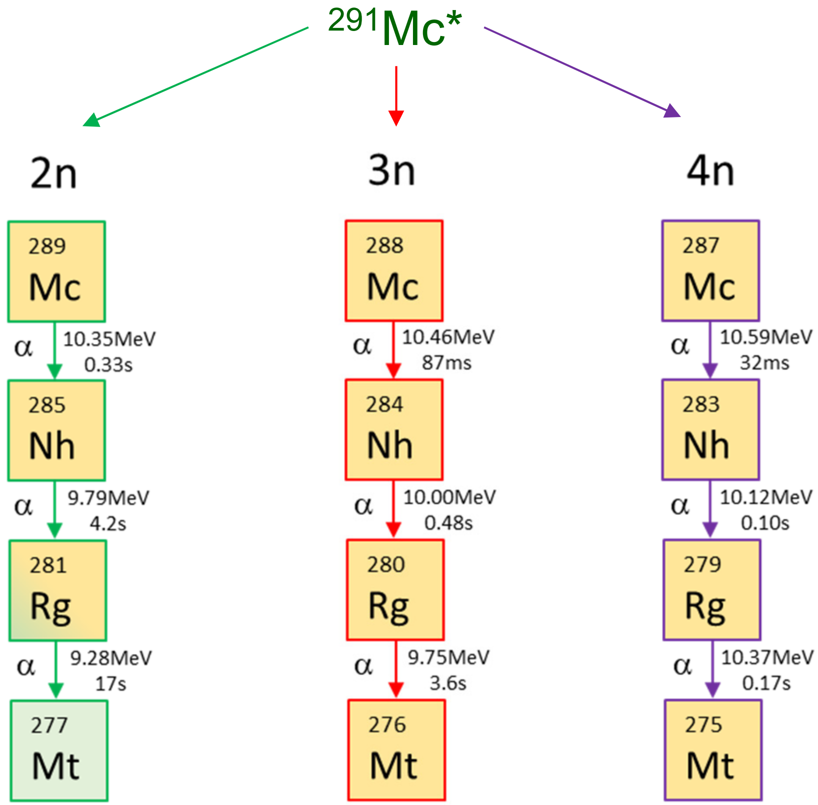
2018 GFS-2 acceptance tests
2019 GFS-2 first beam tests

2019 GFS-3 manufacturing
2020 GFS-3 installation

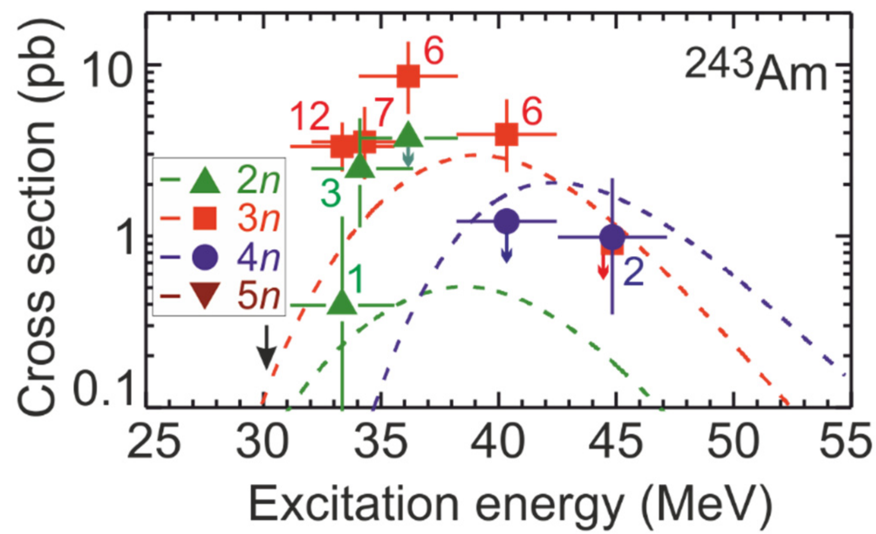
SHE Factory test reaction
$^{243}Am + ^{48}Ca \rightarrow ^{291}Mc^*$

σ=8.5 pb, h_t=0.5 mg/cm^2, ε_{coll}=0.6, I_{beam}= 1 pµA → ≈ 3/day

^{48}Ca from U400 at 235-250 MeV - 1.0-1.5 pµA
Consumption: 0.5-0.8 mg/h @ 80 USD/mg



Excitation functions for x*n*-evaporation channels



Observation of a decay of ^{281}Rg

Two decay times of ^{276}Mt

Figures close to points give the number of Mc atoms produced

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

Ongoing & planned tests

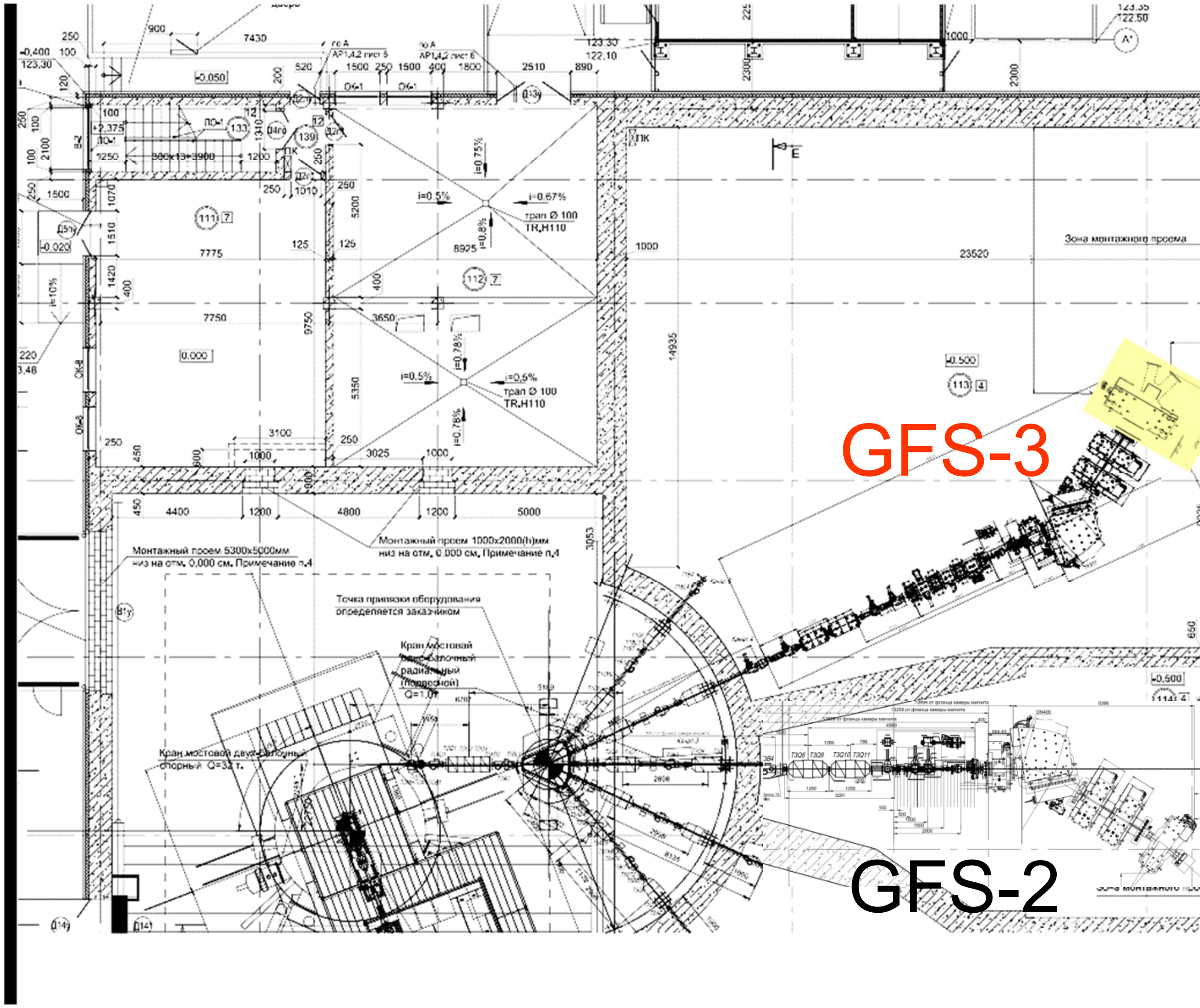
Ar(+6) 5 MeV/A beam transmission from accelerator to beam stop is 95%.

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

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

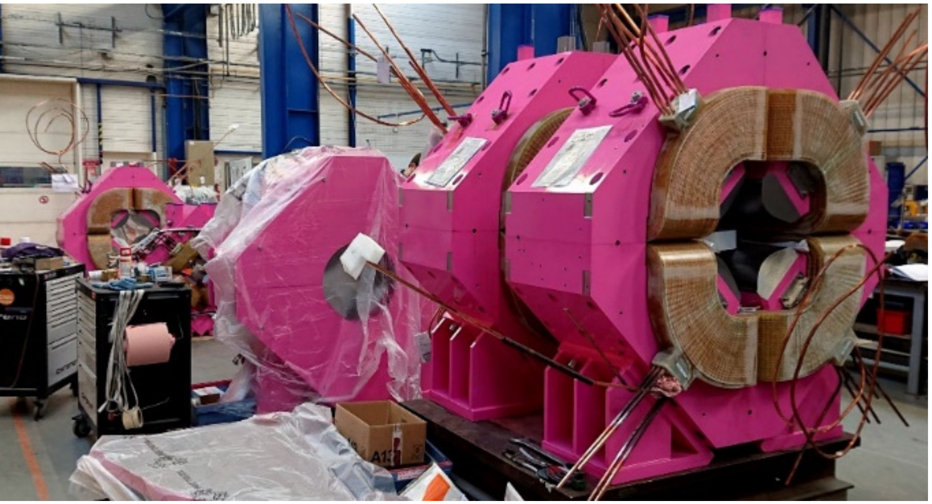
Future plans

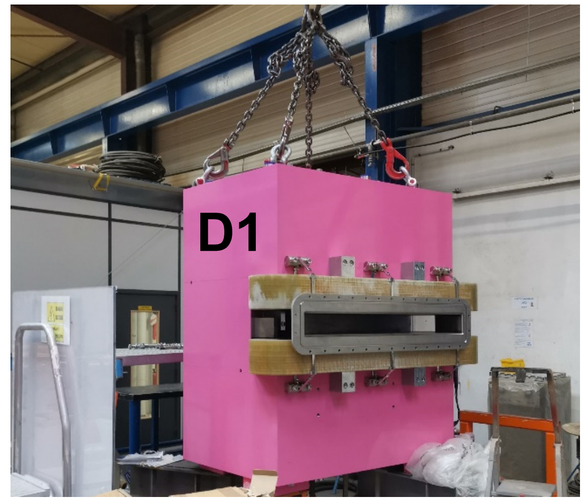


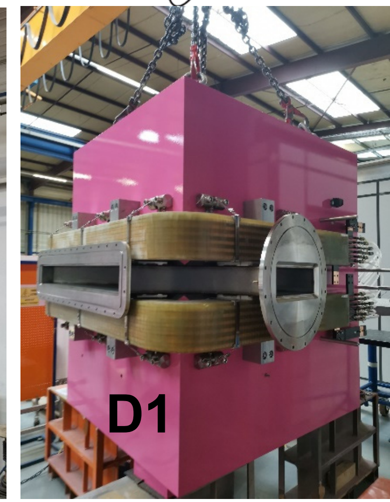
SIGMAPHI
MAGNETS AND BEAM TRANSPORT

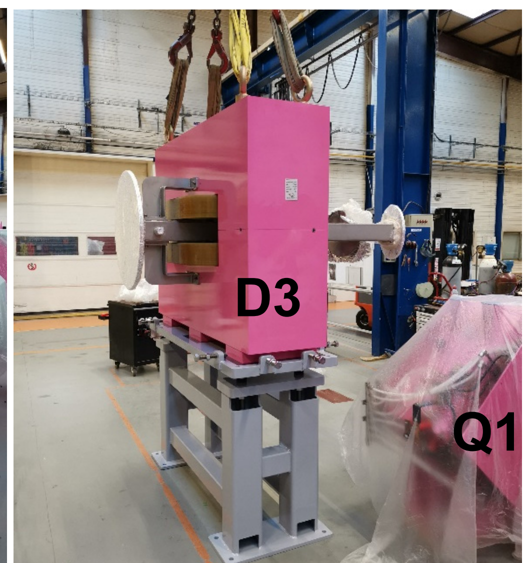
GFS-3 in the factory

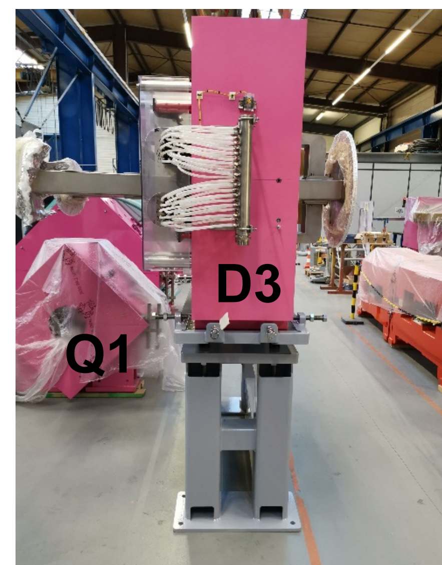
JINR
114 Flerovium
FLNR
Dubna











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!

SIGMAPHI
MAGNETS AND BEAM TRANSPORT

Thank you for your attention

JINR
114 Flerovium
FLNR
Dubna

The essence of the beautiful is unity in variety

W. Somerset Maugham