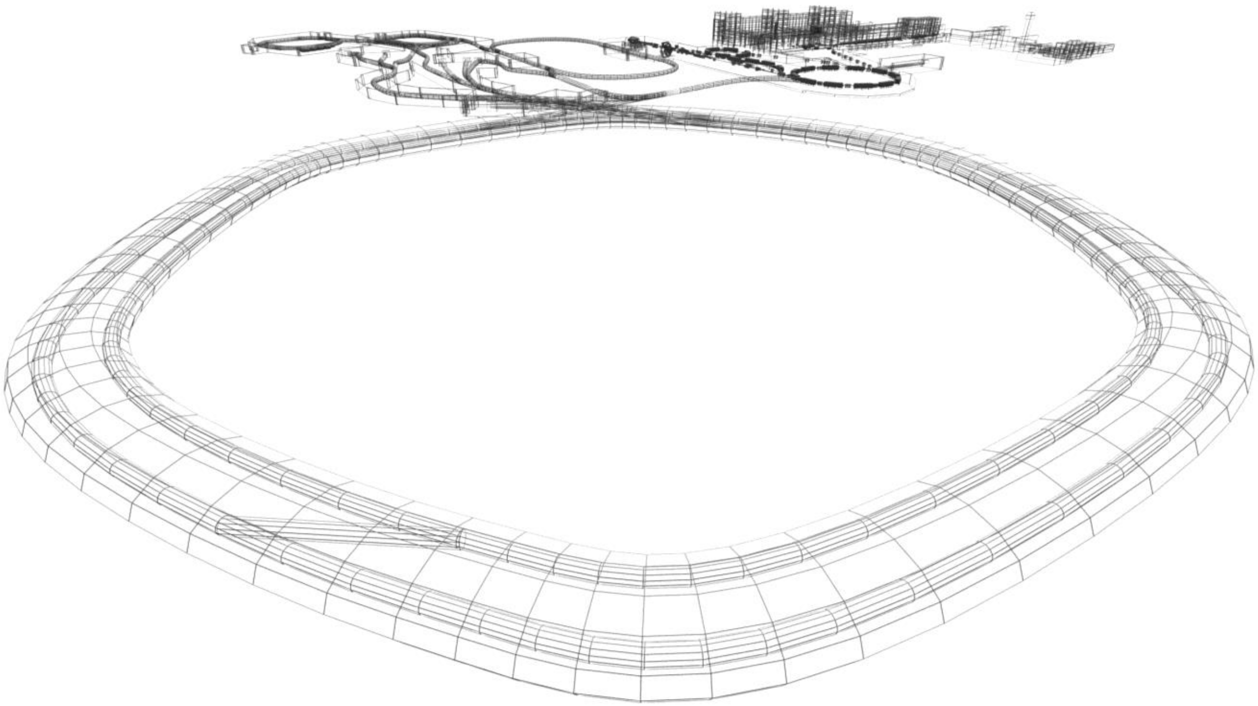
Talk

The vacuum system of the heavy ion synchrotron SIS100 at FAIR



EuCARD-2 workshop on
"**Beam Dynamics meets Vacuum, Collimations, and Surfaces**"
March 8th - 10th, 2017 ▪ Karlsruhe, Germany

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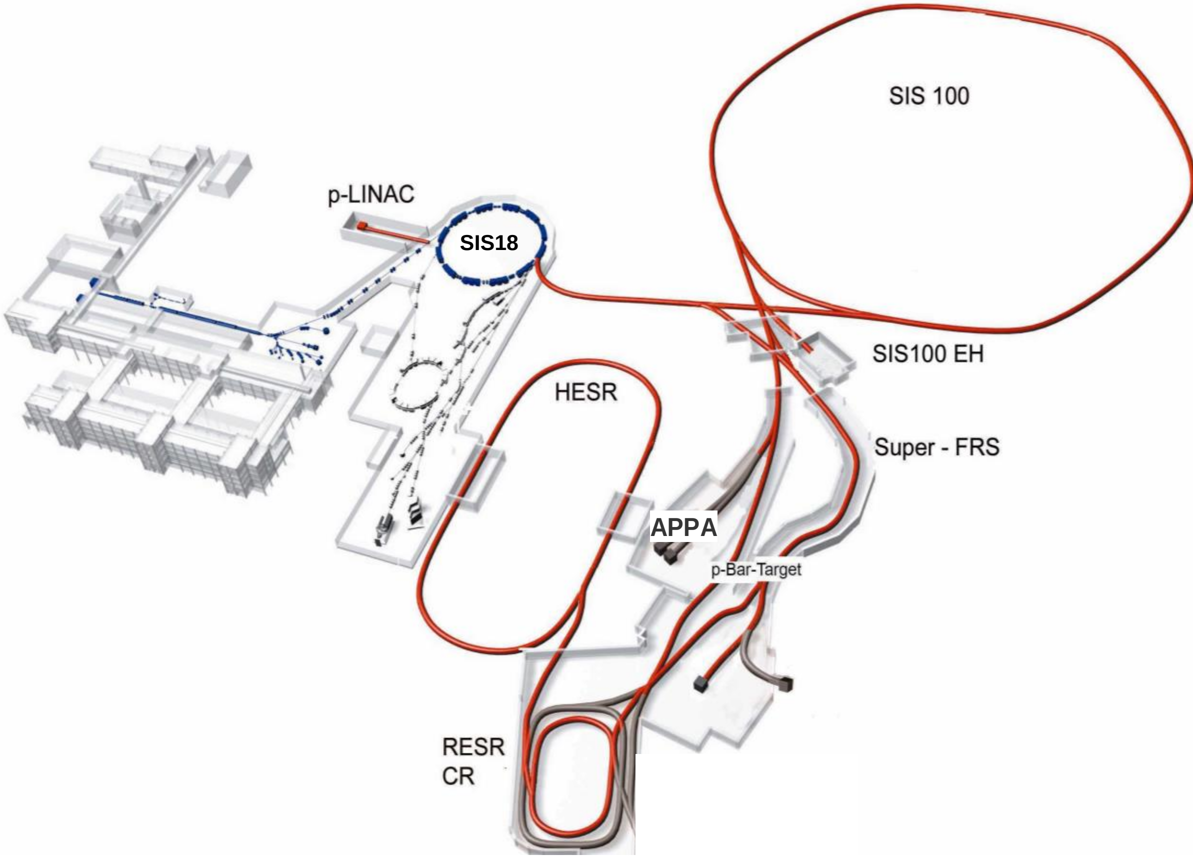
Overview on FAIR – Facility for Antiproton and Ion Research

Germany Russia Finland France India Poland Romania Slovenia Sweden UK



Beams

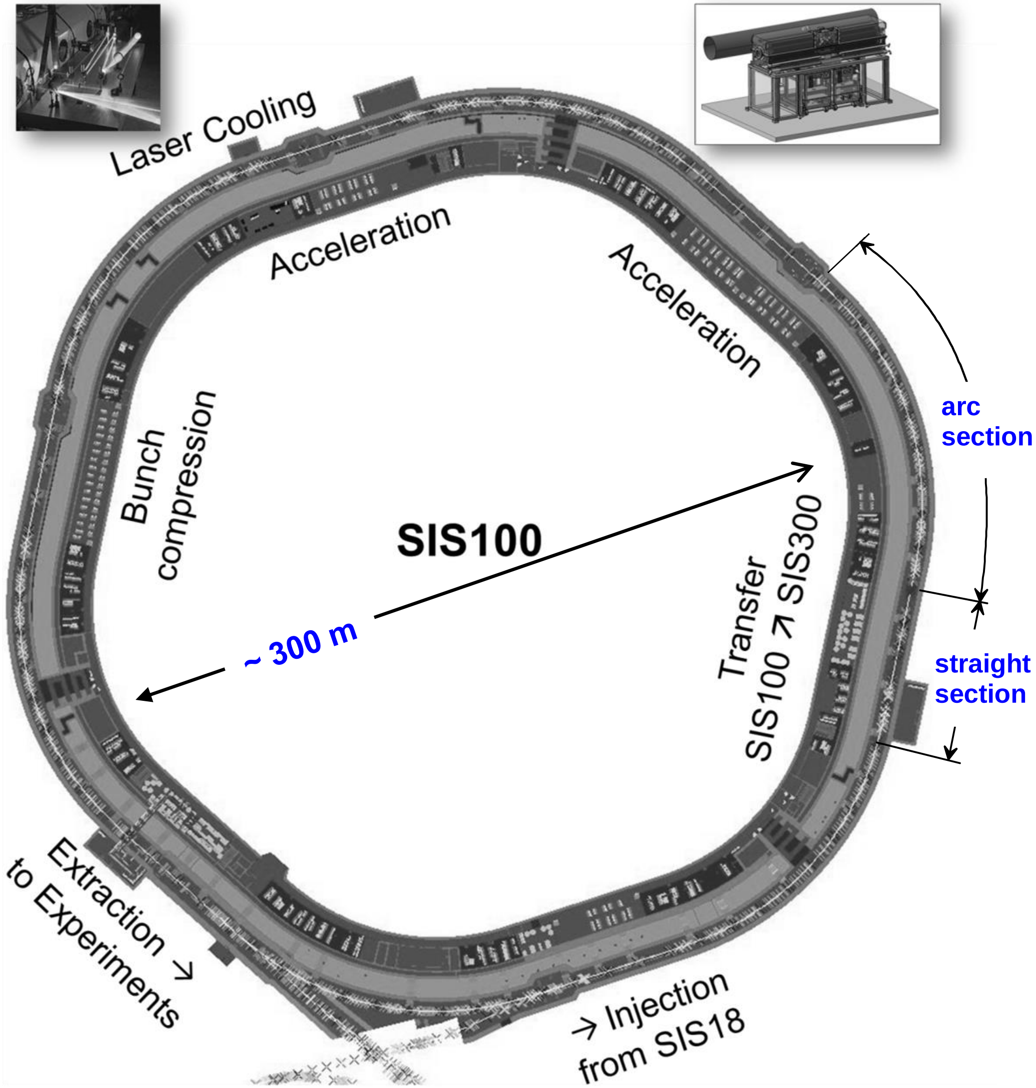
- 10^{12}/s 4 GeV/u $^{238}U^{28+}$ (Factor 100 over present intensity)
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 2×10^{13}/s 30 GeV protons
- Antiprotons 3 - 30 GeV
- broad range of radioactive beams up to 1.5 - 2 GeV/u;
- cooled beams

Experiments

Four Pillars of physics at FAIR

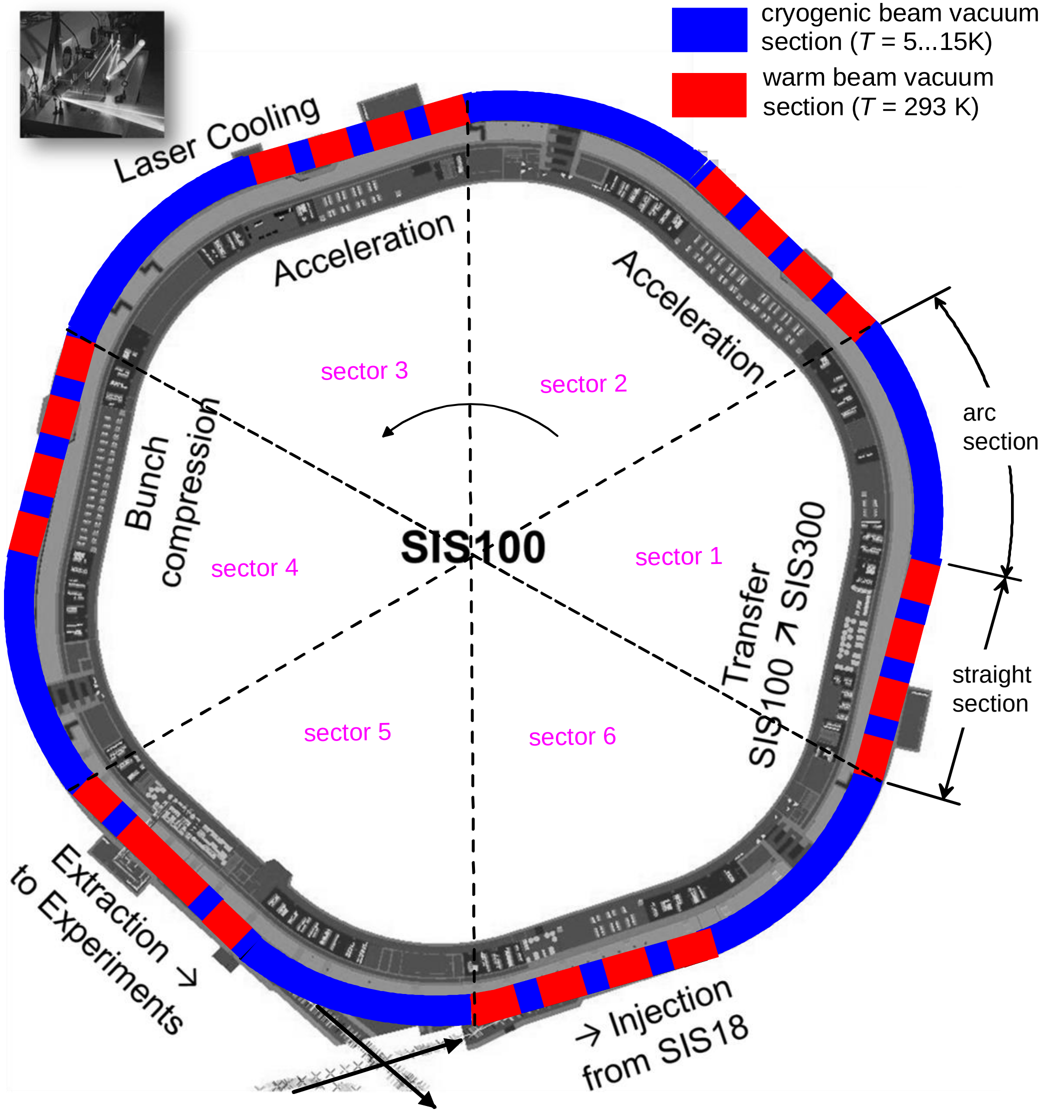
1. NUSTAR Physics (NUclear Structure, Astrophysics & Reactions)
2. Physics with high energy antiprotons: PANDA (AntiProtonen aNnihilation experiment at DArmstadt)
3. Nuclear matter physics: CBM experiment (Compressed Baryonic Matter)
4. APPA physics (Atomic, Plasma Physics and Applications)

SIS100 heavy ion synchroton



- main accelerator
- hexagonally-shaped synchrotron with 6-fold symmetrical ion optical lattice
- is situated 10m below ground level
- total circumferential length: **1083.6 m**
- 6 sectors, each ~ 180m long
- each sector contains one straight section (*l* ~ 45m) and one cryogenic arc section (*l* ~ 135m)
- on the straight sections alternating warm and cryogenic structures (cryomagnetic modules)
- 108 cryomagnetic dipole modules
- 83 cryo-magnetic quadrupole modules with 11 various configurations will be housed in the arc & straight sections
- rapidly-cycled superconducting magnets

Overview on SIS100 beam vacuum system



Average residual hydrogen density must be

$\overline{N}_{max} < 8 \cdot 10^{+11}\ m^{-3}\ (H_2)$

accepting 2% beam losses (aim for reference cycle RIB cycle 2.7GeV U^{28+})

Maximum allowed average beam **vacuum pressure must be**

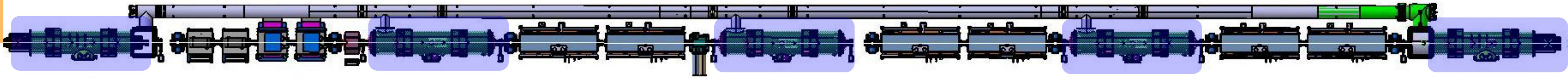
→ $\overline{p}_{cold}\ (H_2) < 1 \cdot 10^{-12}$ mbar ($\overline{T}$ = 10K)

→ $\overline{p}_{warm}\ (H_2) < 3 \cdot 10^{-11}$ mbar (T = 293K)

- sectored vacuum system
- appr. 895 m (82%) of the 1083.6 m beam vacuum system will be operated at cryogenic temperatures (5…15K),
  → 23 cryogenic sections (= 6 long arcs à 135m + 17 short straights à ~5 m)
- appr. 187 m (18%) are designed as bakeable room temperature UHV system
  → 25 straight warm sections (= 24 à ~7 m + 1 à ~19 m)
- completely CF-type flanged
- cryogenic and RT sections are separated by 46(+4) all-metal gate valves

The cryogenic SIS100 beam vacuum system

Some technical facts

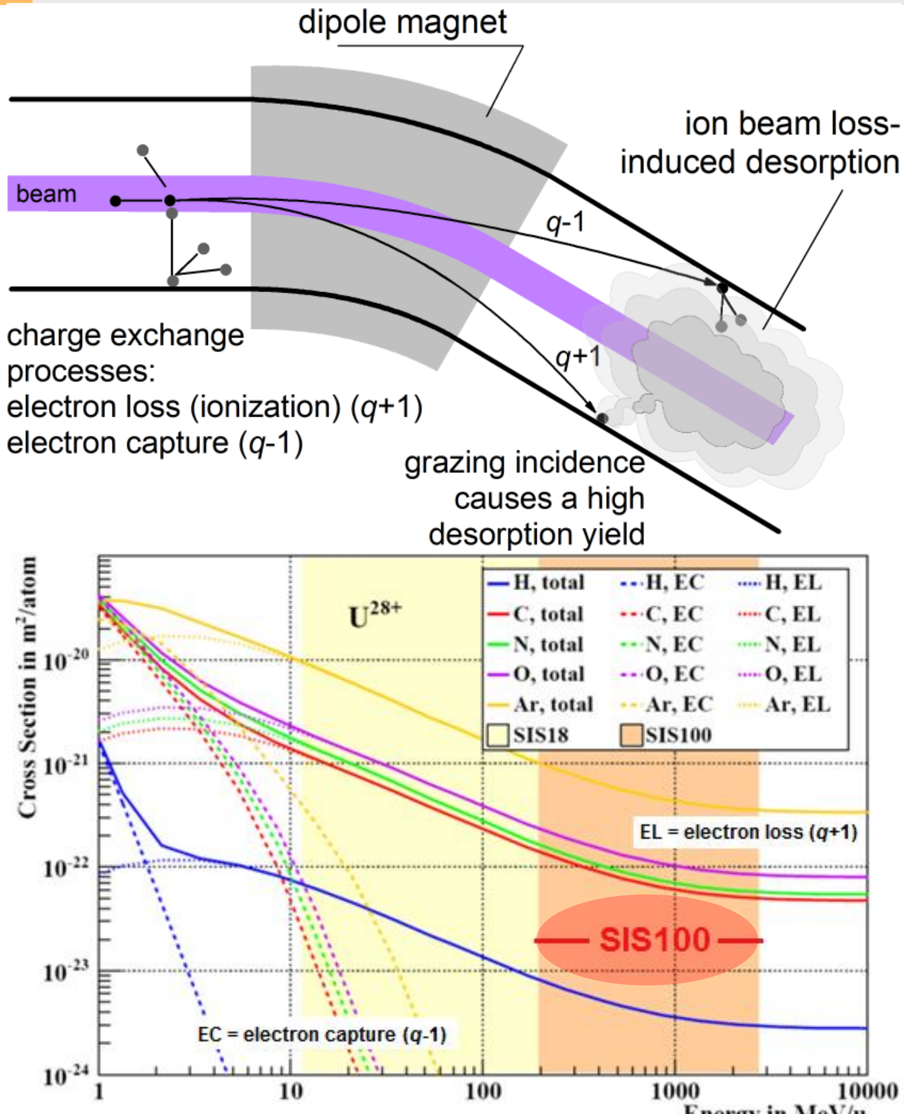


23 cryogenic sections (= 6 long arcs à 135m + 17 short straights à 5 m)

Vacuum chambers	108 DN160CF dipole chambers 12 DN160CF missing dipole chambers 164+4 DN160CF quadrupole chambers (incl sextupole + correctors) with elliptical cross section 6 DN160CF quadrupole chambers (incl sextupole) with star-shaped cross section 29 DN160CF short cryogenic drift tubes 2 DN100CF long cryogenic drift tubes 60 DN160CF drift tubes (interconnecting dipoles) 120 DN160CF cryogenic bellows 60 DN160CF ion catcher chamber 83 DN160CF Cryogenic Beam position monitors (BPM)	**631 chambers**
Cold-Warm-Transitions	42 DN160CF CWTs (Beam Vacuum) elliptically-shaped inner tube 6 DN160CF CWTs (Beam Vacuum) star-shaped inner tube 47 DN100CF CWTs (Roughing) 1 DN160CF+DN100CF combined CWT (Beam vacuum)	**96 CWTs**
Vacuum pumps	85 DN100CF customized cryosorption pumps	
Vacuum diagnostic	77 DN40CF cold-cathode gauges (operated in room temperature environment)	
Burst disks	30 DN40CF burst disk per arc (p_{over} ~ 0.3 bar) 17 DN40CF burst disk per quadrupole module on the straights (p_{over} ~ 0.3 bar)	**47 burst disks**

The cryogenic SIS100 beam vacuum system

Main issue - dynamic vacuum instabilities driven by beam losses and ion stimulated desorption



L Bozyk, PhD thesis, University Darmstadt (Germany), 2012

Most critical: beam loss stimulated desorption effects due to charge exchanged ions

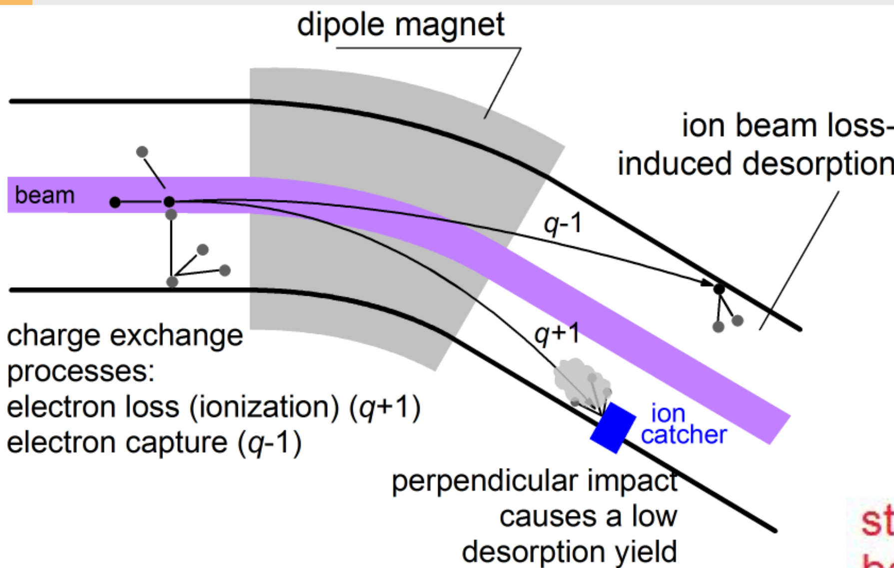
Probability for **beam ionization (electron loss)** depends on residual gas density, gas composition, and beam energy.

→ **Ionized ions will get lost on the wall**

- **desorption yield η**
- $\eta_{\angle}$ **~ 3...30·10³ molecules/ion**
- $\eta_{\perp}$ **~ 10² molecules/ion scales with (d^2E/dx^2)**
- Losses drive a local **pressure bump due to ion stimulated desorption**
- **Self amplification** can develop up to **complete beam loss**
- Maximum number of accelerated ions is limited → **beam intensity limitation**

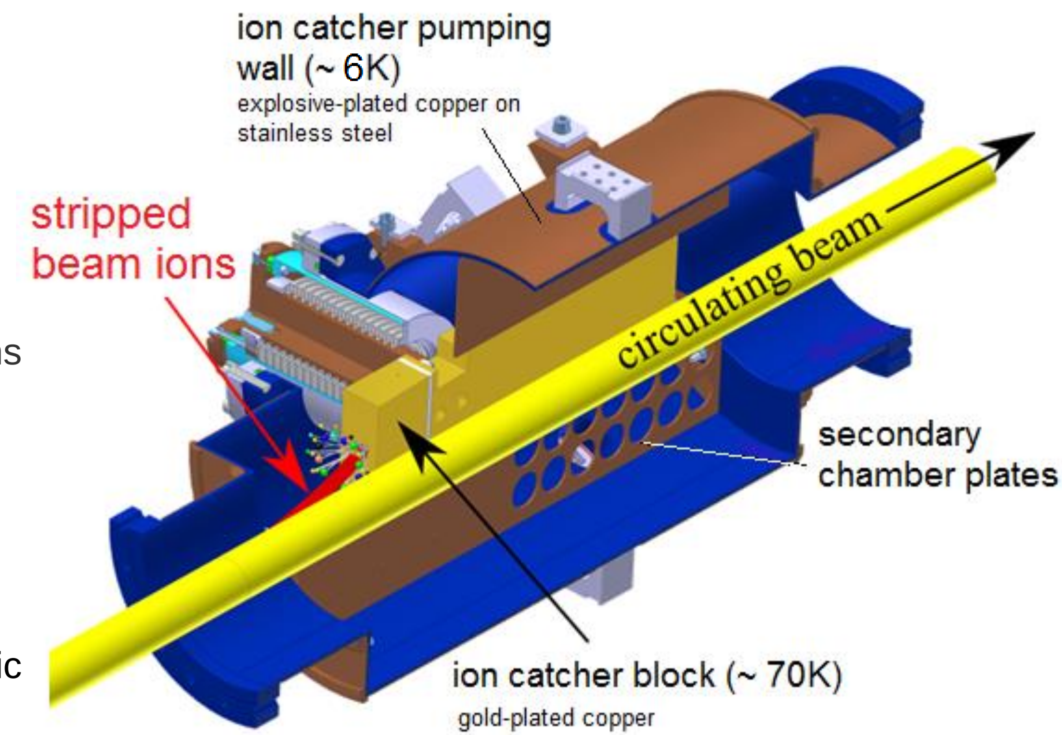
The cryogenic SIS100 beam vacuum system

Ion catcher system for suppression of dynamic vacuum instabilities



Solution: Controlled collection of charge-exchanged ions at exactly defined ring positions using an ion catcher system

- Controlled catching of ionized ions on surfaces with low desorption yield (gold) → most ionized ions are caught by the ion catcher
- Surrounding cold chamber acts as cryopump quickly removing desorbed gases
- Cryocatcher block will be kept at a higher temperature to prevent gases from cryosorbing on the surface of incidence
- Significant reduction of gas desorption → dynamic vacuum effects are suppressed effectively
- Activation and radiation damage of magnets by beam losses are reduced



developed by L Bozyk (GSI)
PhD thesis, University Darmstadt (Germany), 2012

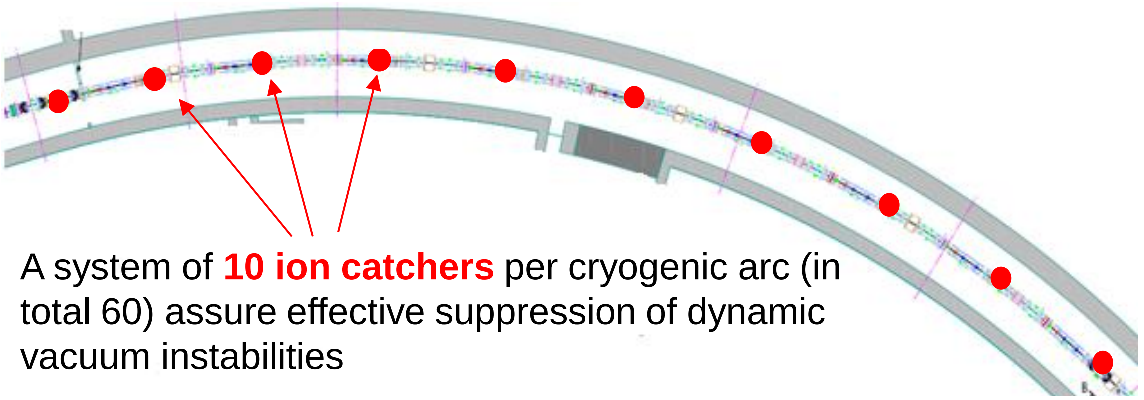
The cryogenic SIS100 beam vacuum system

Ion catcher system for suppression of dynamic vacuum instabilities

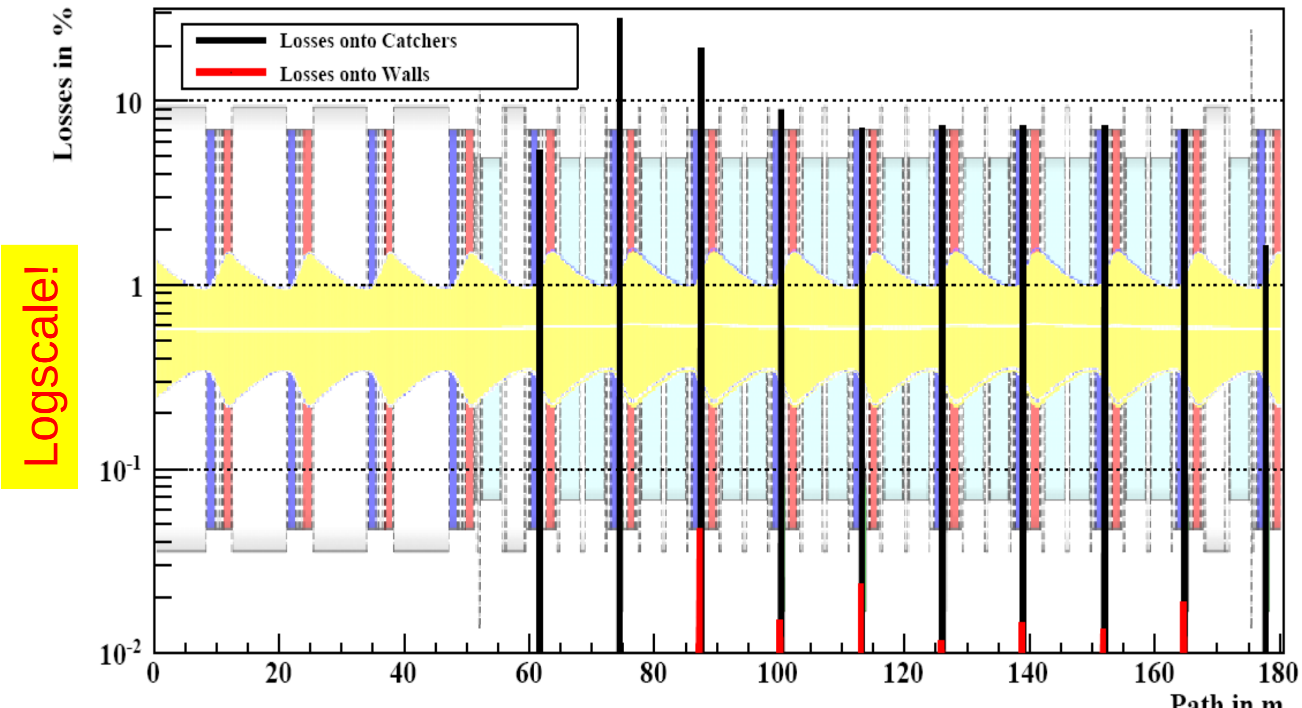
Losses normalized to one cryogenic arc, $U^{28+} \rightarrow U^{29+}$

99.6% catching efficiency

- Intensity limitation by self-amplification due to ionization losses can be shifted to higher beam currents by ion catcher
- Without the use of the ion catcher system, a reliable and stable beam operation with high intensity intermediate charge state ions wouldn't be possible



A system of **10 ion catchers** per cryogenic arc (in total 60) assure effective suppression of dynamic vacuum instabilities

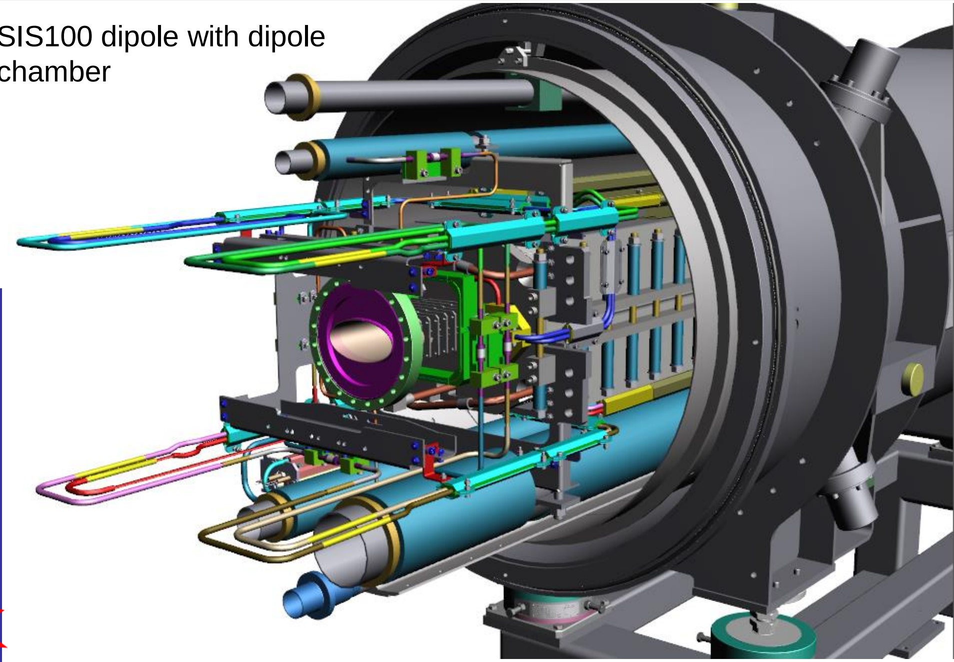


L Bozyk (GSI), PhD thesis, University Darmstadt (Germany), 2012

The cryogenic SIS100 beam vacuum system
Dipole chambers

- all dipole chambers represent 46% of the total cold surface in the cryogenic arc of SIS100
- appr. 373 m are represented by dipole chambers ~ 1/3 of complete beam line length

SIS100 dipole with dipole chamber



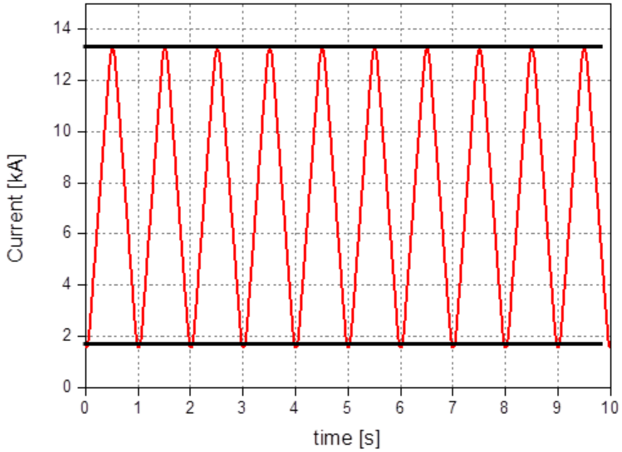
critical issue: fast magnet ramping with 4T/s and 1Hz repetition frequency causes eddy current-induced heating up of the chamber walls

- **Temperature increase reduces significantly the cryosorption capacity for H_2**
- **harmonics generation**

!

chamber design had be optimized in terms of

- field quality (avoiding the distortion of main guidance field)
- low wall temperatures during magnet ramping in order not to lose the effectiveness of cryopumping (wall temperatures should be as low as possible, T_{max} < 15K are required)
- beam dynamics aspects (e.g. impedances)



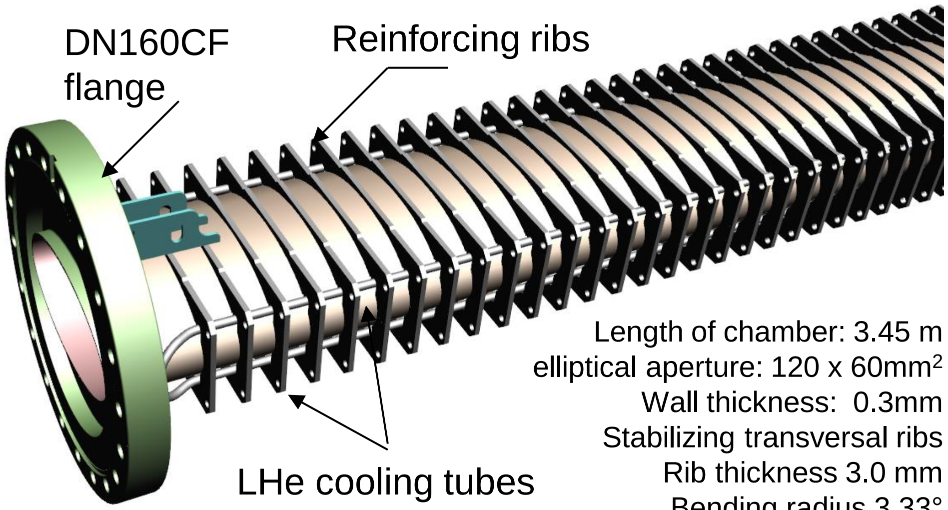
B_{max}

B_{max} = 1.9T
dB/dt = 4 T/s
f_{rep} = 1 Hz
B_{min} = 0.23 T

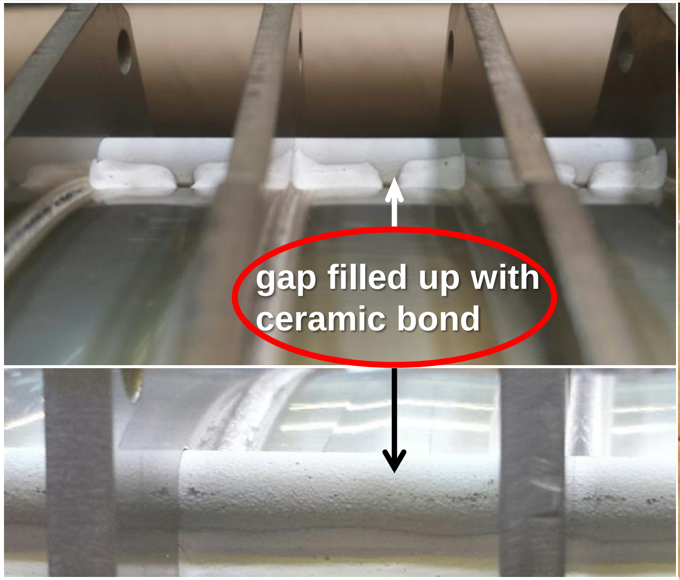
magnet cycle, /\ cycle

The cryogenic SIS100 beam vacuum system

Dipole chambers

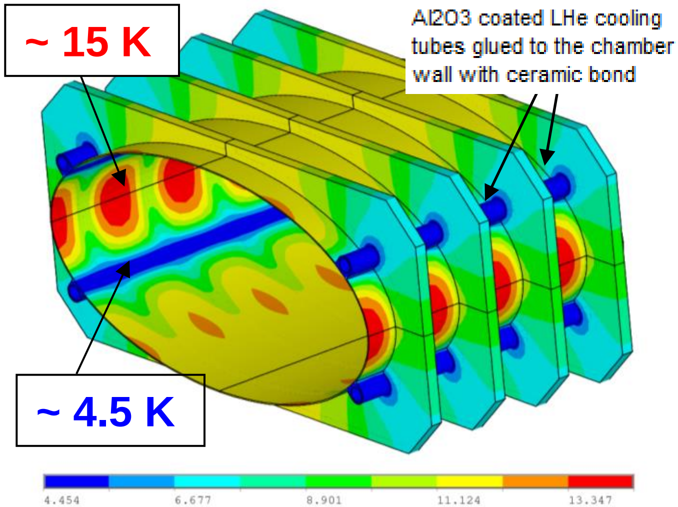


SIS100 dipole chamber with supplementary cooling tubes



Problem: metallic cooling tubes connected electrically with chamber wall generate additional unwanted harmonics (multipoles) in the magnetic beam guidance field!

- the **outer surface of the cooling tubes** has to be covered with a thin ceramic film (e.g. 200µm aluminium oxide Al_2O_3)
- electrical loop represented by a closed metallic LHe cooling circuit must be electrically interrupted by the use of an electrical insulating voltage breaker



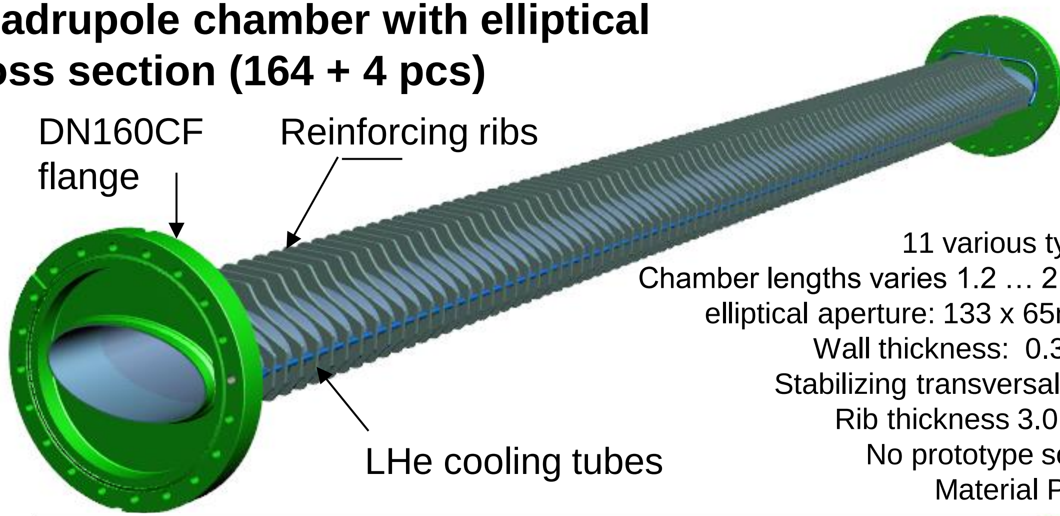
Temperature profile during magnet operation

Calculated by Y Shim (GSI)

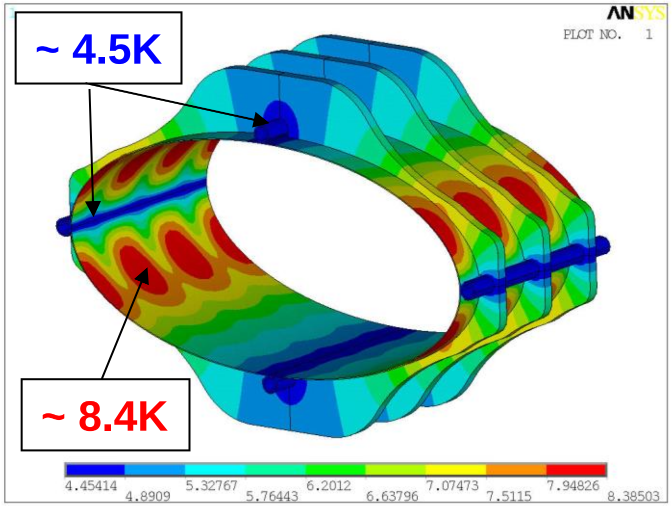
The cryogenic SIS100 beam vacuum system

Quadrupole chambers

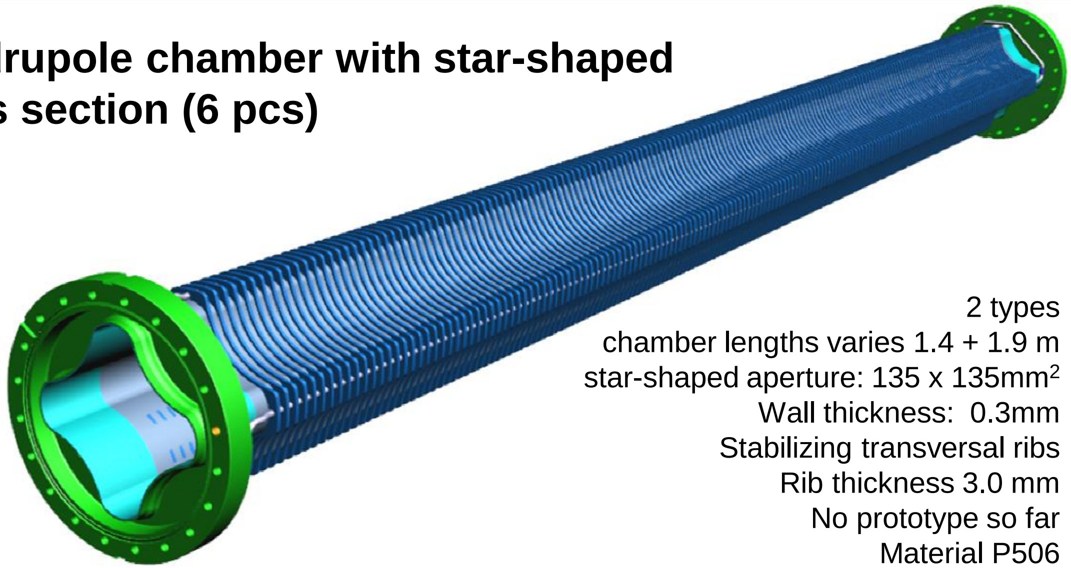
Quadrupole chamber with elliptical cross section (164 + 4 pcs)



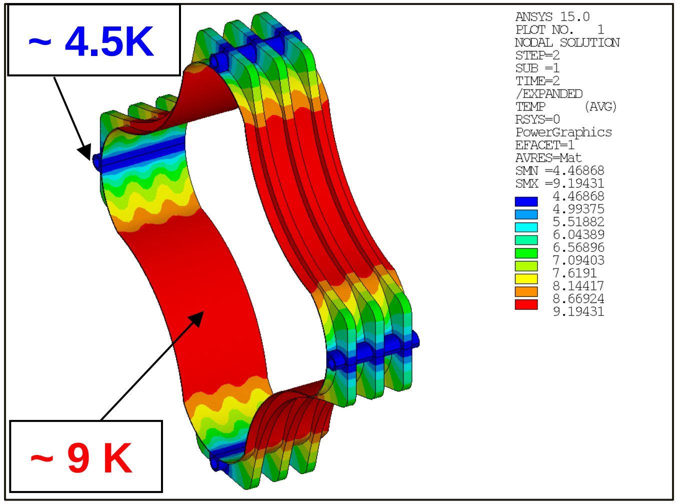
11 various types
Chamber lengths varies 1.2 … 2.7 m
elliptical aperture: 133 x 65mm^2
Wall thickness: 0.3mm
Stabilizing transversal ribs
Rib thickness 3.0 mm
No prototype so far
Material P506



Quadrupole chamber with star-shaped cross section (6 pcs)



2 types
chamber lengths varies 1.4 + 1.9 m
star-shaped aperture: 135 x 135mm^2
Wall thickness: 0.3mm
Stabilizing transversal ribs
Rib thickness 3.0 mm
No prototype so far
Material P506



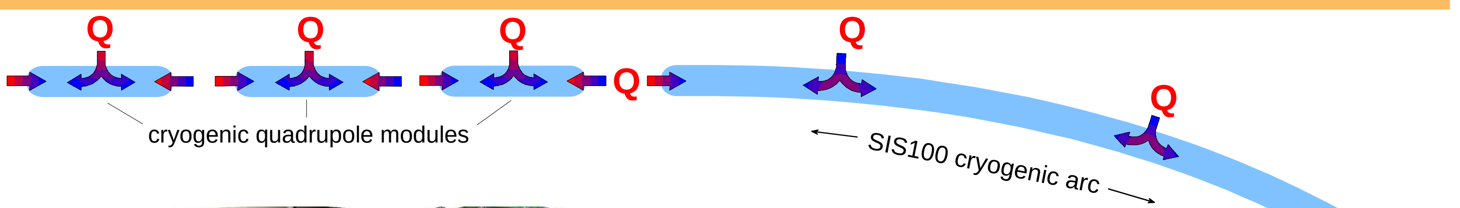
Temperature profile during magnet operation
Calculated by Y Shim (GSI)

The cryogenic SIS100 beam vacuum system

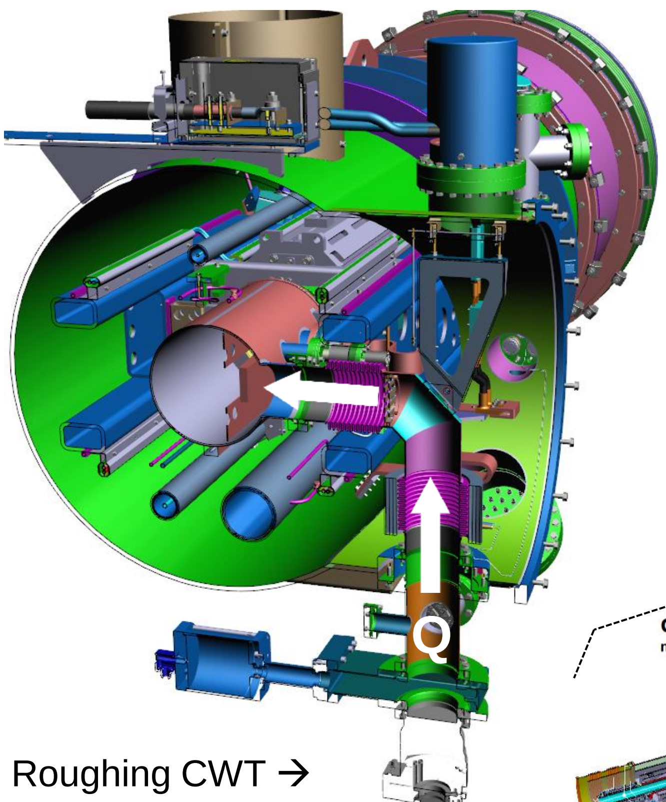
Operational issues

Chamber wall temperature during normal machine operation

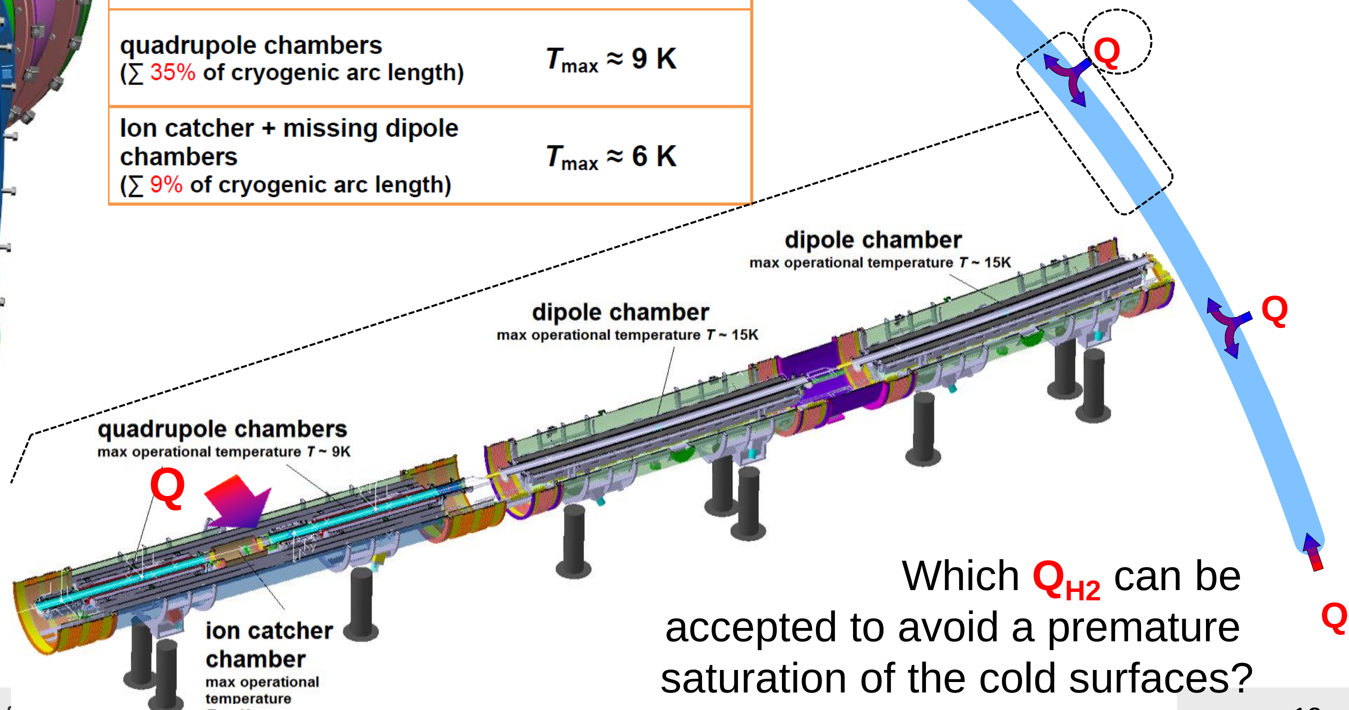
Q – permanent H_2 flux from the room temperature sides into the cryogenic beam vacuum sections



	Triangular CBM cycle (extremal U^{92+} cycle)
dipole chambers (∑ 46% of cryogenic arc length)	$T_{max} \approx 15$ K
quadrupole chambers (∑ 35% of cryogenic arc length)	$T_{max} \approx 9$ K
Ion catcher + missing dipole chambers (∑ 9% of cryogenic arc length)	$T_{max} \approx 6$ K



Roughing CWT → permanent H_2 load **Q**

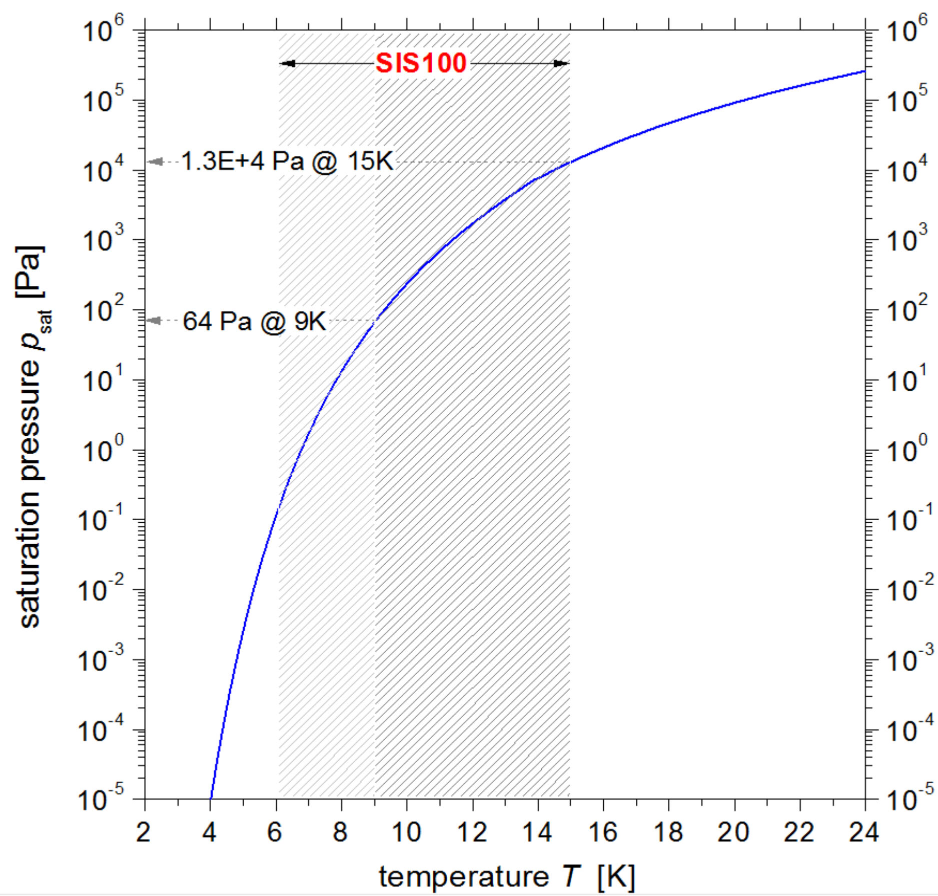


Which Q_{H2} can be accepted to avoid a premature saturation of the cold surfaces?

Are the wall temperatures low enough to maintain sufficiently long the required low residual gas densities in the cold sections of SIS100 for the long-term beam operation?

- hydrogen as the expected dominant residual gas component in the cryogenic sections (and He in case of a cryo-leak) cannot be pumped by cryo-condensation at these temperatures, but only by **cryosorption (sub- monolayer coverage)**
- problem: the higher the wall temperature, the lower the cryosorption capacity
- experimentally verified adsorption isotherms (i.e. relation between surface coverage σ and vapor pressure p) for hydrogen on stainless steel in this temperature range were not available yet **→ must be known → measurements were needed**
- calculation of hydrogen density profiles in cryogenic systems with H_2 loads from room temperature sides **→ no simulation code for long time scales (i.e. years) is available yet → new code was needed**

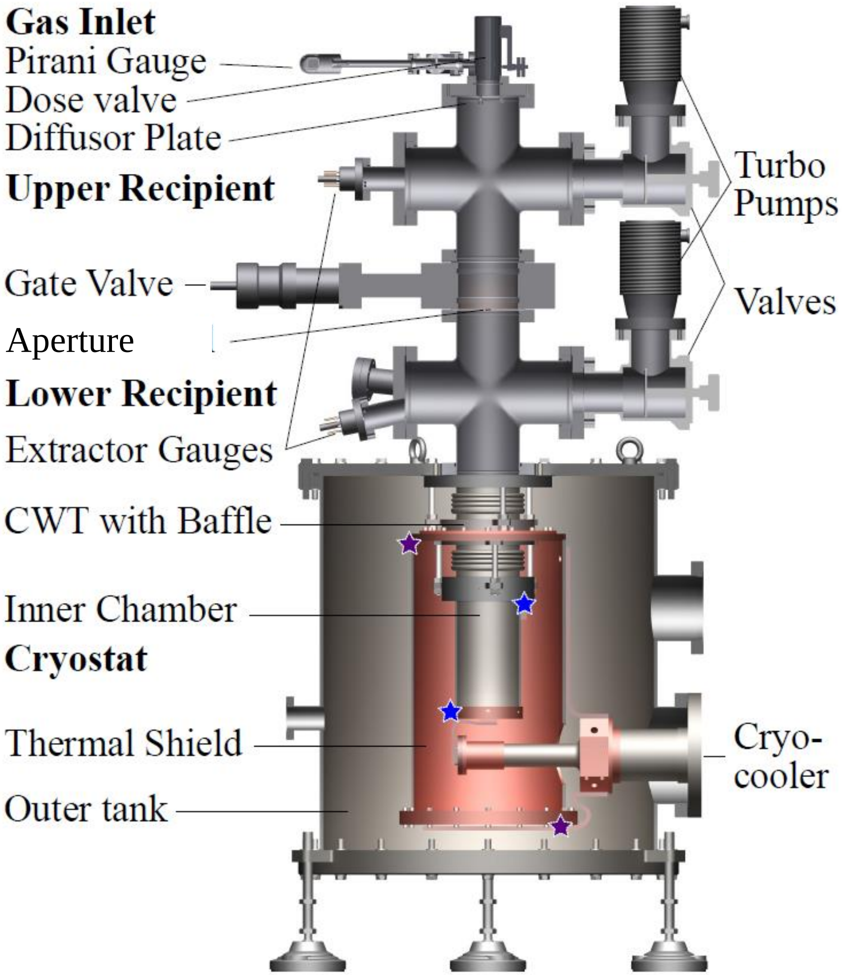
Saturation vapour pressure vs. temperature relation for hydrogen



The cryogenic SIS100 beam vacuum system

Measurement of the H_2 cryosorption behavior on electro-polished stainless steel surface between 7...20K

Experimental set-up for studying the H_2 adsorption isotherms



Experimental data & setup: Courtesy by F Chill (GSI), PhD thesis, University Frankfurt (Germany) (2016)

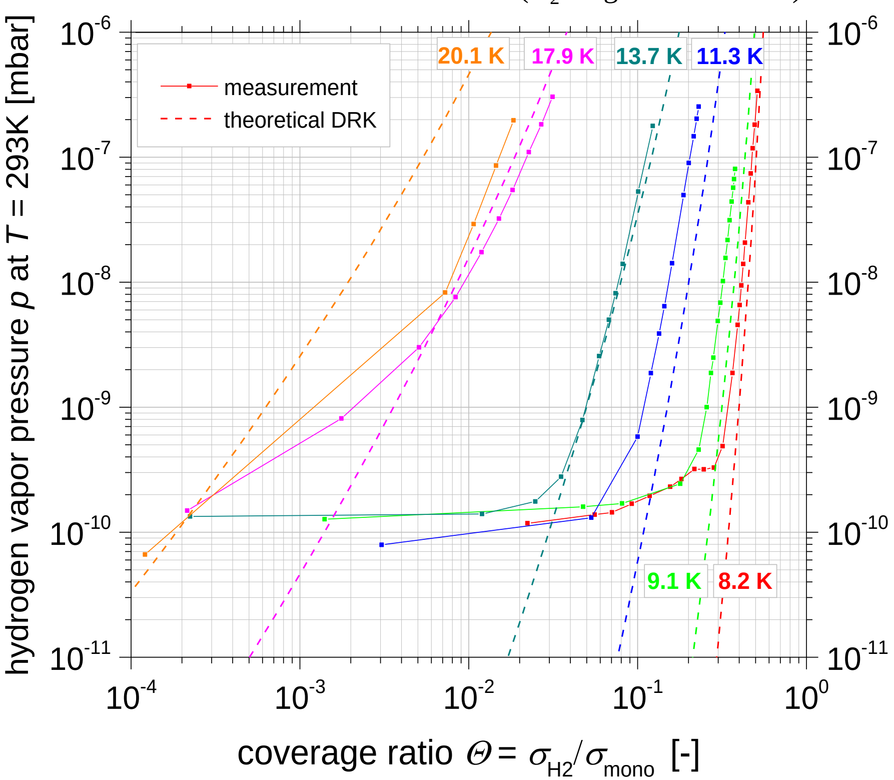
Dubinin-Radushkevich-Kaganer isotherm (DRK)

$$\Theta(T) = \frac{\sigma_{H2}(T)}{\sigma_{mono}} = \exp\left\{-B\left(k_B T \ln\frac{p}{p_S(T)}\right)^2\right\}$$

$B = 3075$ eV^{-2}, $\sigma_{mono} = 6.95\text{E}+14$ H_2/cm^2 [1)]

van Itterbeck[2)]: $B = 1907.5$ eV^{-2} (H_2 on glass)

Haefer[3)]: $B = 1976.3$ eV^{-2} (H_2 on gas condensates)



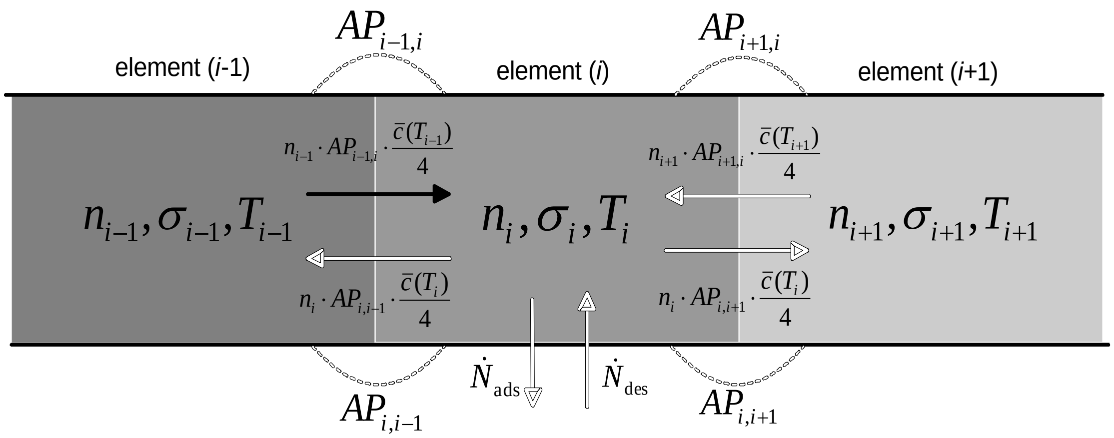
1) Redhead, Hobson, Kornelsen, *The Physical Basis of Ultrahigh Vacuum,* AVS (1997)
2) Van Itterbeck et al, Physica 30(1964), 324 3) Haefer, *Cryopumping* (1989), 3)

The cryogenic SIS100 beam vacuum system

TransVAC Code – Analytical calculation of H_2 density profiles in longitudinal non-isothermal vacuum systems

TransVAC was developed by F Chill (GSI)

TransVac was developed to predict time-dependent H_2 density profiles in longitudinal, non-isothermal vacuum systems for long time scales



Element characteristics:

position x	[m]
volume V	[m^3]
surface area A	[m^2]
temperature T	[K]
static pumping speed S	[m^3/s]
H_2 static outgassing/ H_2 inflow Q	[H_2 molec/s]

Variables:

time t	[s]
time step Δt	[s]
surface coverage σ	[H_2 molec/m^2]
hydrogen density n	[m^{-3}]

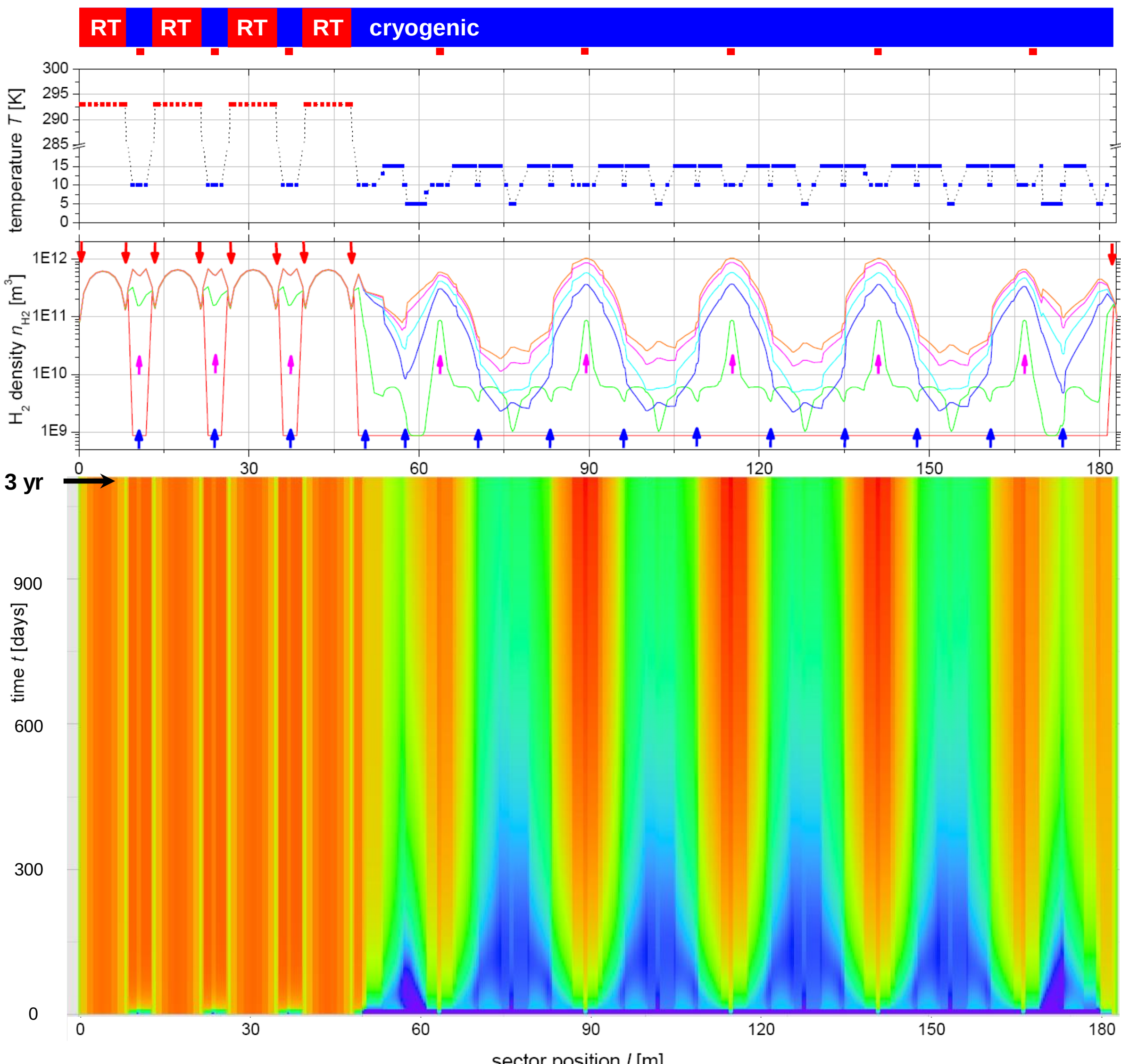
- based on *Vakdyn* code developed by V Ziemann
- **Concept of TransVac:** vacuum system is considered as a chain of discretized vacuum elements connected to the adjacent element via a **temperature-independent** geometric conductance → $A \cdot P$ [m^2] (= cross section area A x transmission probability P).

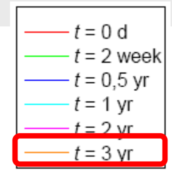
- thermal transpiration correction
- uses for calculation the measured sojourn times of H_2
- vacuum elements between 5...18 K are considered as cryopumping elements

The cryogenic SIS100 beam vacuum system

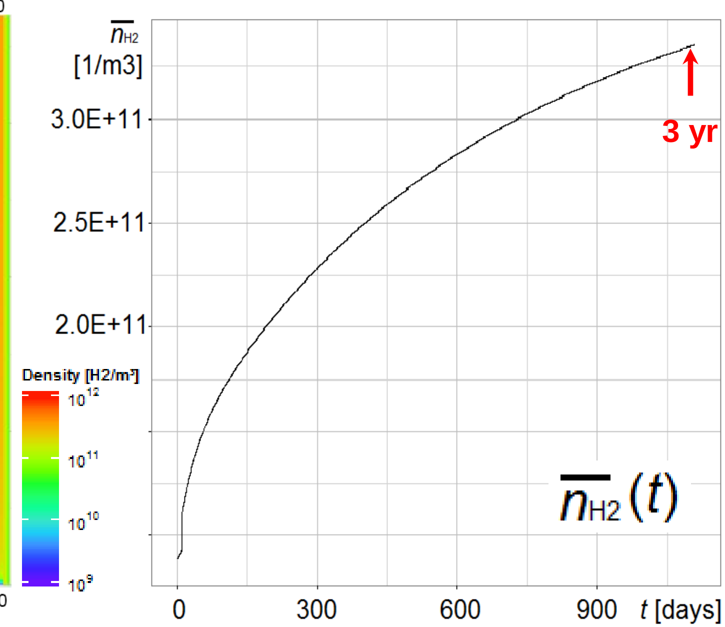
Simulation of time and position dependent hydrogen density profiles in a SIS100 sector using TransVAC code

TransVAC was developed by F Chill (GSI)





	H_2 outgassing room temperature sections	1E-12 mbar.ℓ/s.cm^2
↑	Cryosorption pumps (not capacity-limited)	S_{H2} = 60 ℓ/s (T = 5K)
↓	RT NEG + ion pumps (not capacity-limited)	S_{H2} = 2200 ℓ/s (T = 293K)
↑	H_2 load due to Roughing Cold-Warm-transition (RCWT) ■ (baked out + NEG pumps)	Q = 5E-10 mbar·ℓ/s (T = 293K)
	Initial H_2 coverage	Θ = 1E-4 (corresponds to a roughing pressure of about 1E-5 mbar prior cool down)



The cryogenic SIS100 beam vacuum system

Simulation of time and position - dependent hydrogen coverage profiles in a SIS100 sector using TransVAC code

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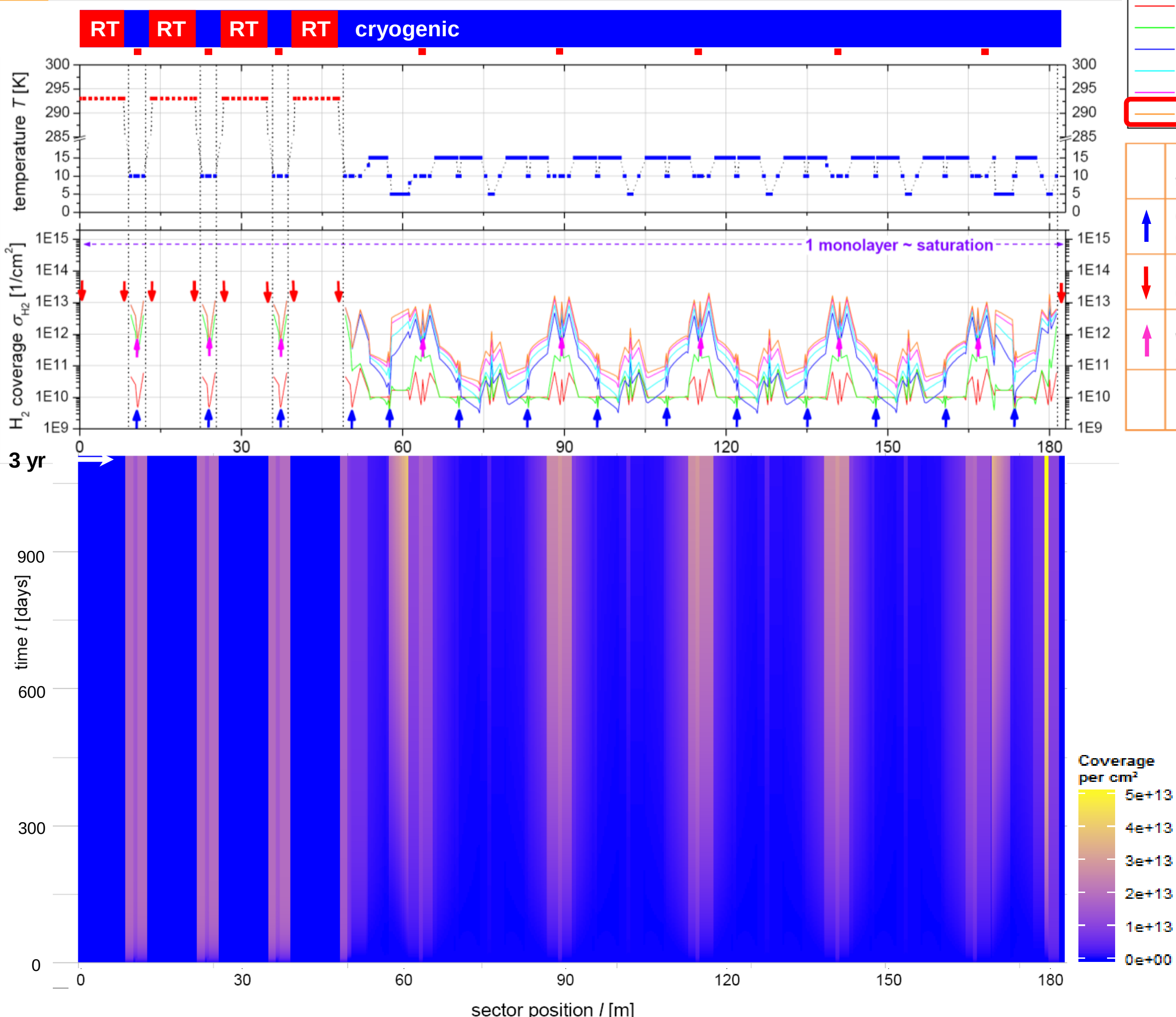

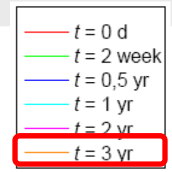

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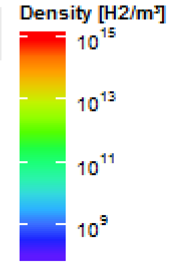
The cryogenic SIS100 beam vacuum system

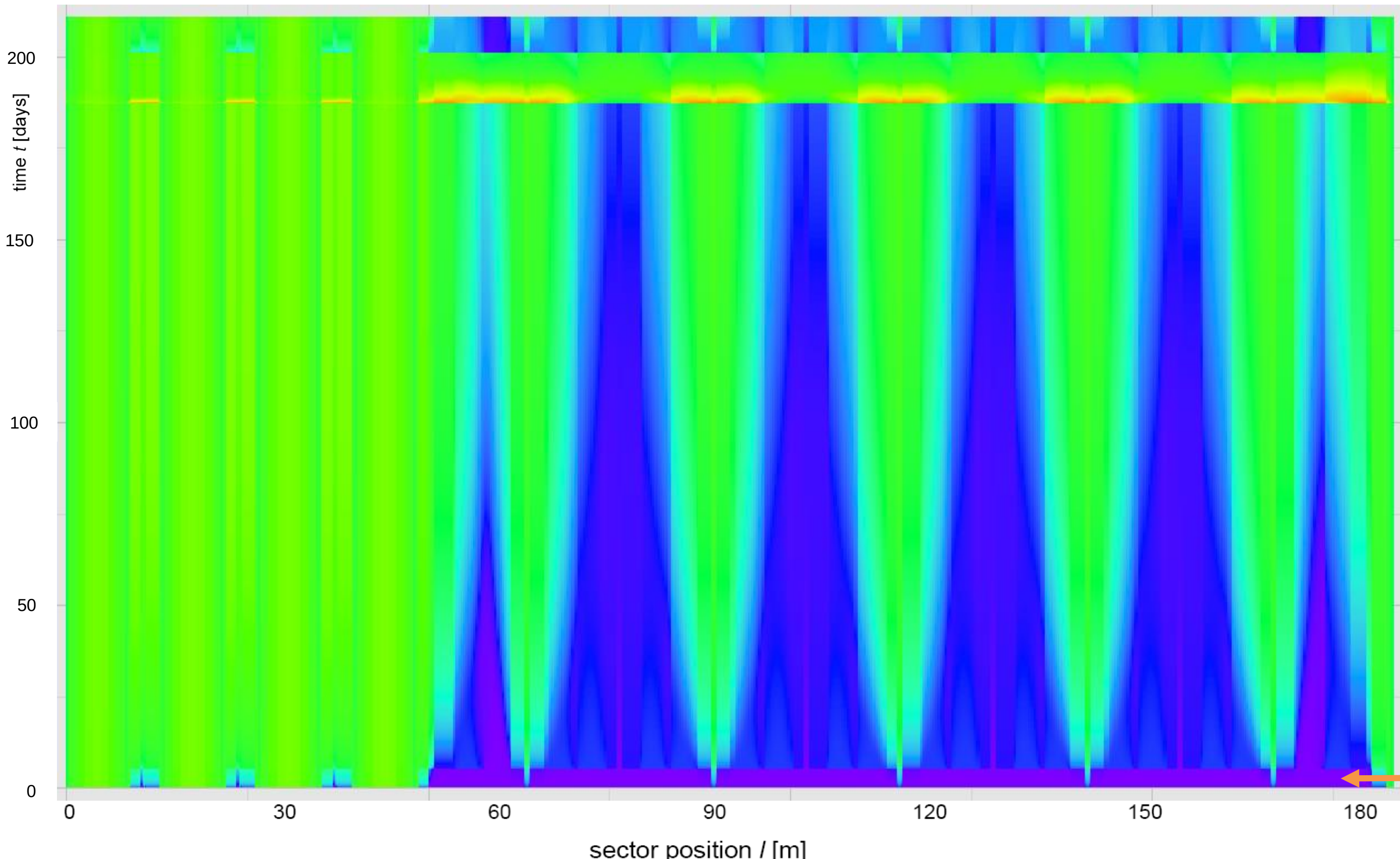
Simulation of time and position - dependent hydrogen coverage profiles in a SIS100 sector during a „cryogenic bake-out“ using TransVAC code

TransVAC was developed by F Chill (GSI)

What is a „cryogenic bake-out“?

Warming up the cryogenic beam chambers up to T ~ 18K → H_2 desorbs from the cold surfaces → H_2 amount must be pumped by external pumps → re-cool down → → recovering of the initial H_2 coverage → starting conditions are nearly recovered





Re-cool down, external TMPs switchd off, starting conditions are nearly recovered

T_{quad} = 9K, T_{dip} = 15K

Cryogenic bake out: the entire cryogenic vacuum system is at 18K for 14 days, external TMPs (S_{H2} = 100 ℓ/s at RT) mounted on the RCWTs pump simultaneously the desorbing H_2 amount

Standard operational chamber wall temperatures for 0.5 yr = 182d

T_{quad} = 9K, T_{dip} = 15K

Starting condition
The entire cryogenic vacuum system is at 5K for 5 days, initial H_2 coverage Θ = 1E-5

The cryogenic SIS100 beam vacuum system

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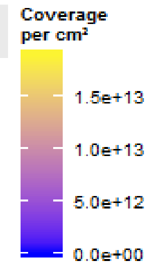

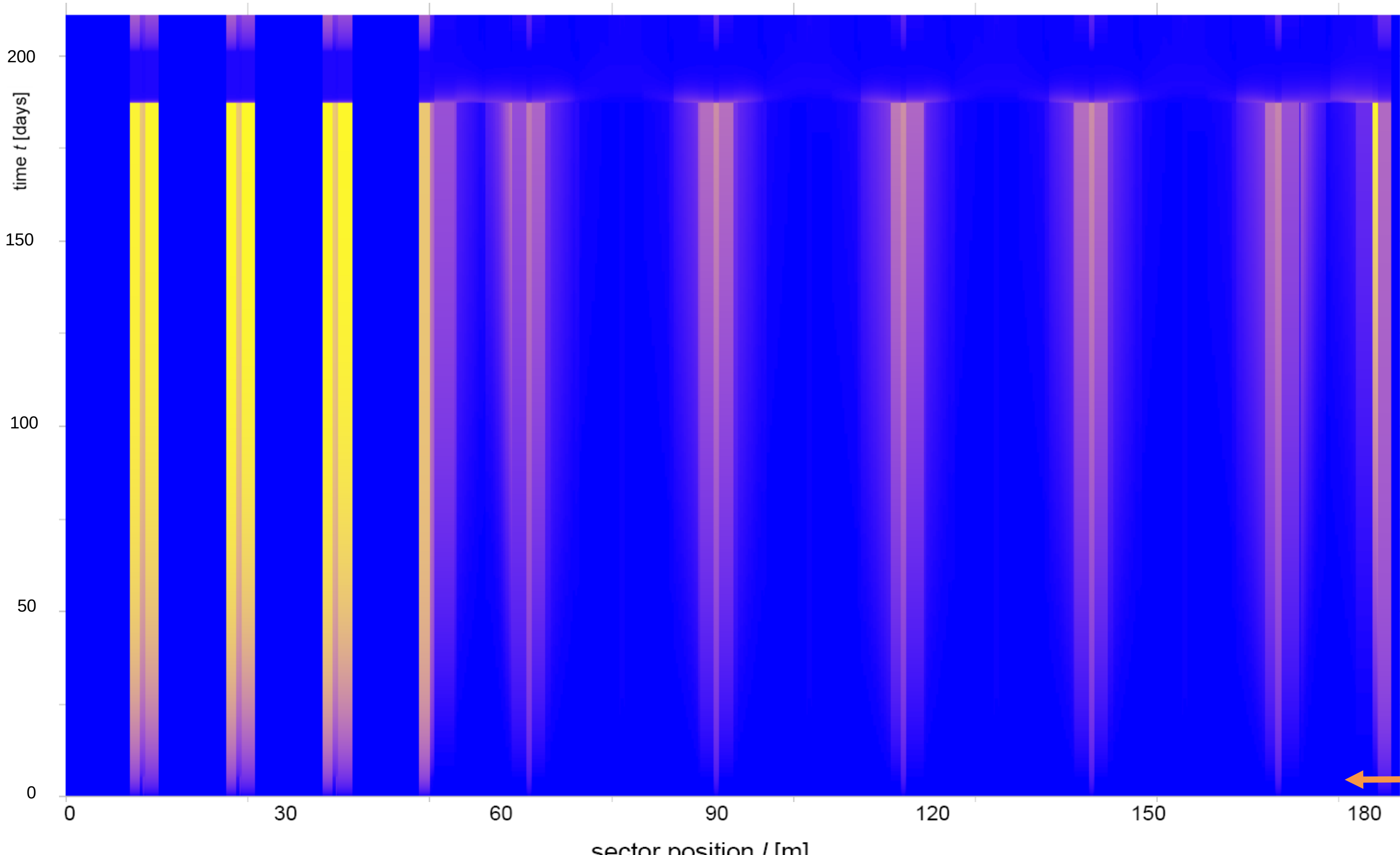

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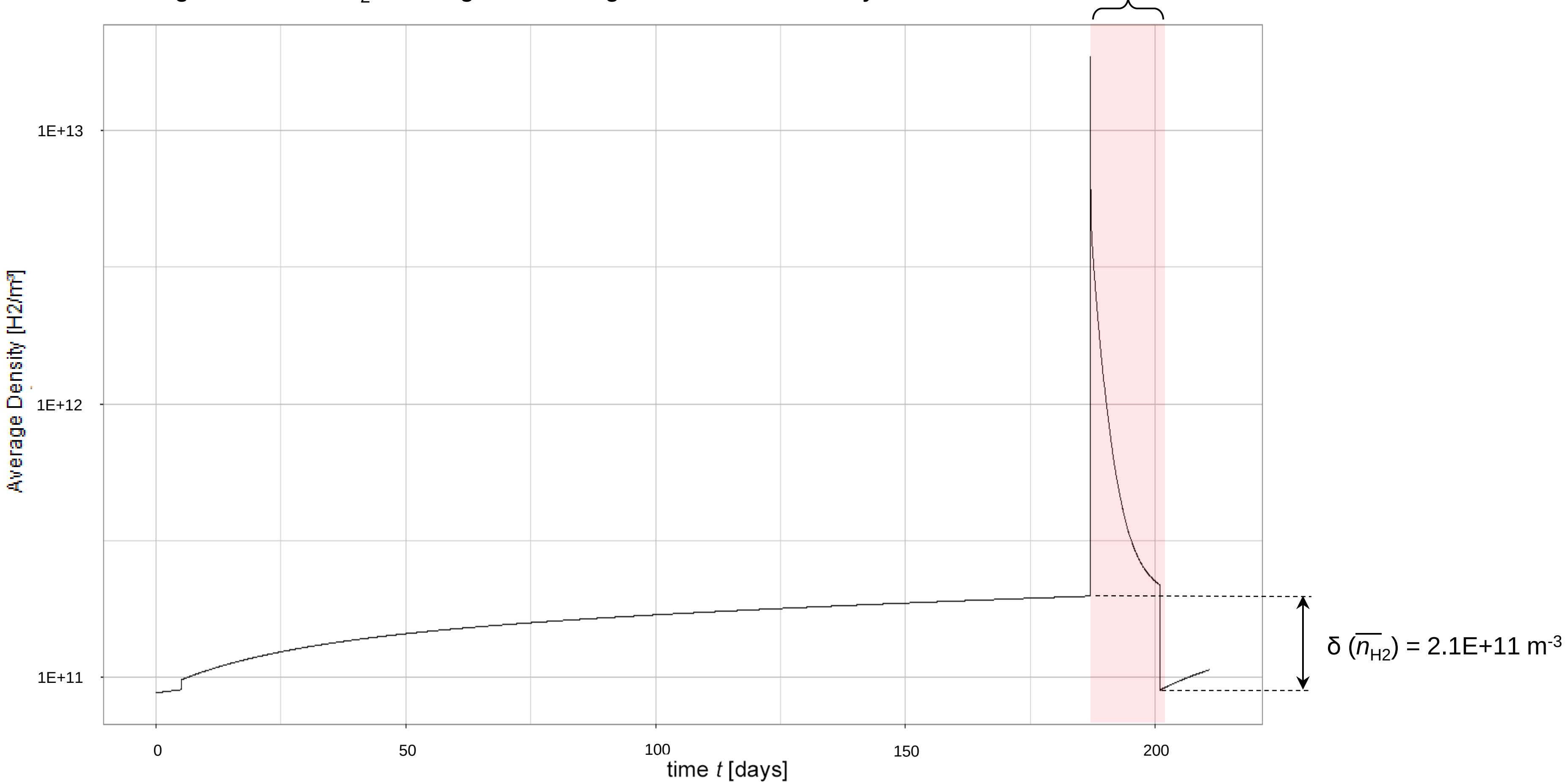
→ H_2 amount must be pumped by external pumps → re-cool down →
→ recovering of the initial H_2 coverage → starting conditions are nearly recovered

Cryogenic bake out: cryogenic vacuum system is at 18K for 14 days, and external pumping



The cryogenic SIS100 beam vacuum system

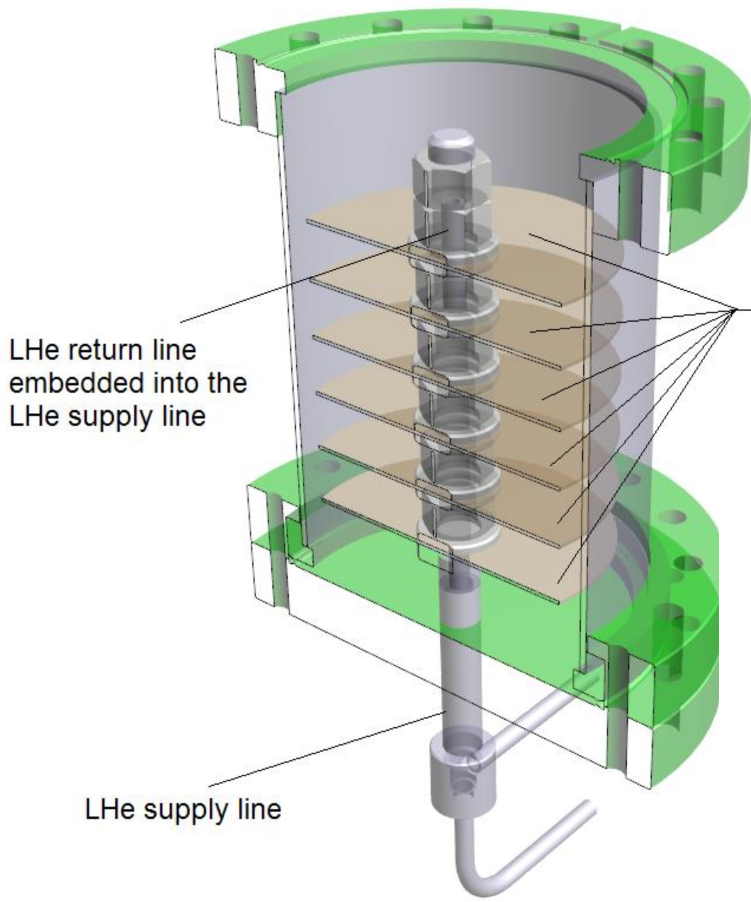
Development of SIS100 cryosorption pumps

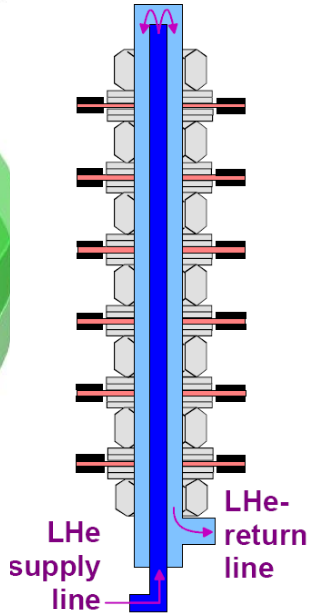
Additional cryosorption pumps in the cryogenic SIS100 beam vacuum section are crucial because

- they stabilize the pressure conditions in the cryogenic sections in long-term operation when the cryosorption capacity of the bare chamber walls (9...15K) for hydrogen gradually decreases (in long time scales)
- nearly no pumping action of the bare chamber walls (9...15K) for He (in case of He leaks)

Additional pumping speed for H_2 and He must be provided by lumped cryosorption pumps at selected ring positions

- requirements: simple design and no loosely packed adsorbens → well defined thermal contact
- Pumping elements are six circular copper cryopanels coated with charcoal type AQUACARB 208C (US mesh size 12x30) produced by Chemviron® (high adsorption capacity)
- screwed onto a central common axial LHe cooling tube
- pump is mounted on a DN100CF flange and installed into a standard nipple





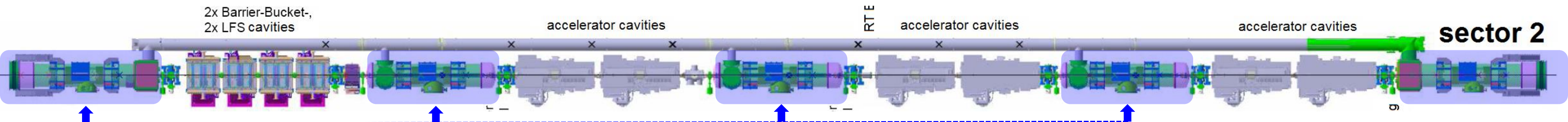
Cooling principle of the pump

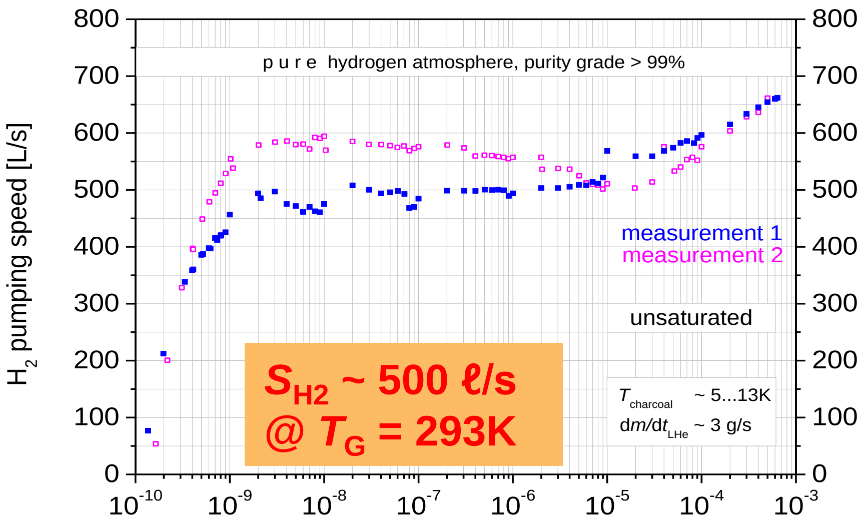
Pump parameters

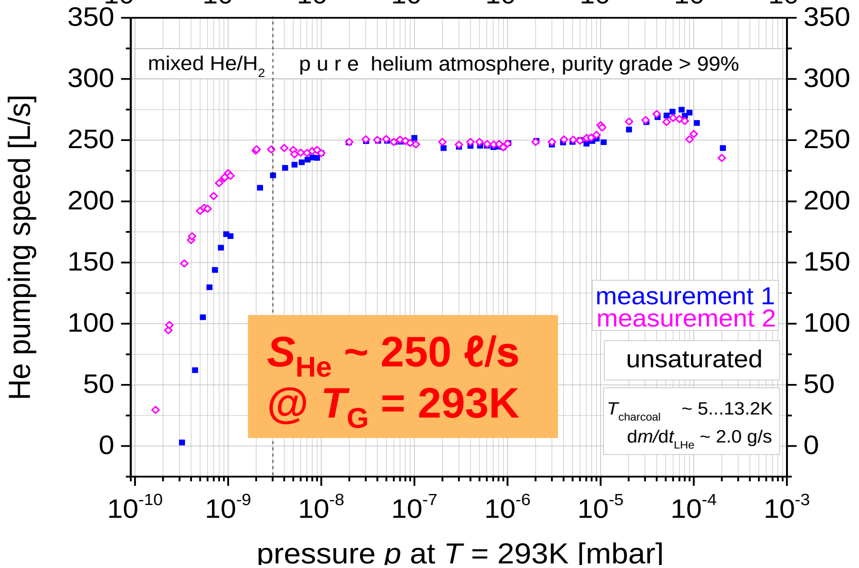
LHe flux @ 4.5K	Total charcoal mass per pump	Theoretical sorption capacity @ 4.5K
1 g_{LHe}/s	30 g ± 25 %	~ 200 mbar·ℓ

The cryogenic SIS100 beam vacuum system

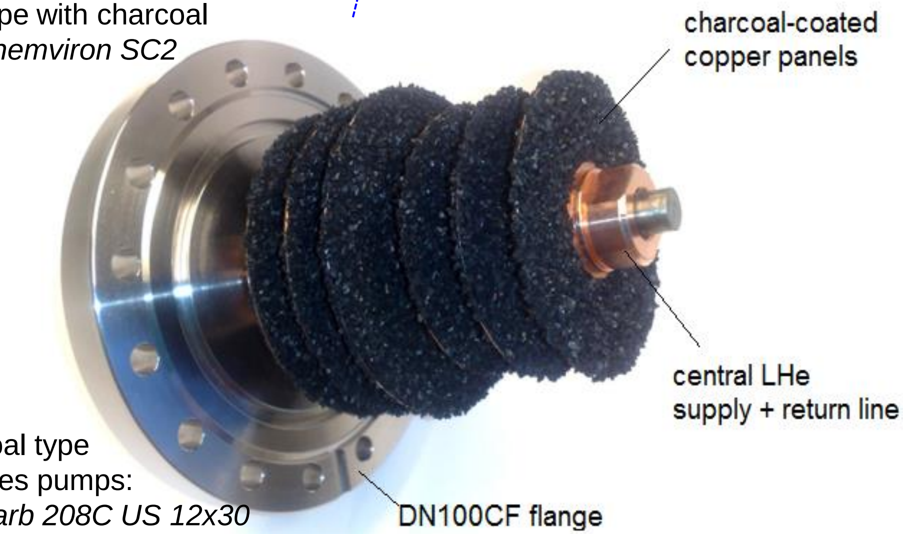
Development of SIS100 cryosorption pumps







In-house development of a pump prototype with charcoal type *Chemviron SC2*



Charcoal type for series pumps: *Aquacarb 208C US 12x30*

What will be the pumping performance at T_G = 5K?

$$S = \frac{\bar{c}}{4} sA = \frac{1}{4}\sqrt{\frac{8k_B T_G}{m\pi}}\, sA$$

$$\frac{S(T_G = 5\text{K})}{S(T_G = 293\text{K})} = \sqrt{\frac{5\text{K}}{293\text{K}}} = 0{,}13$$

$$S(T_G = 5K) \approx \frac{1}{8} S(T_G = 293\text{K})$$

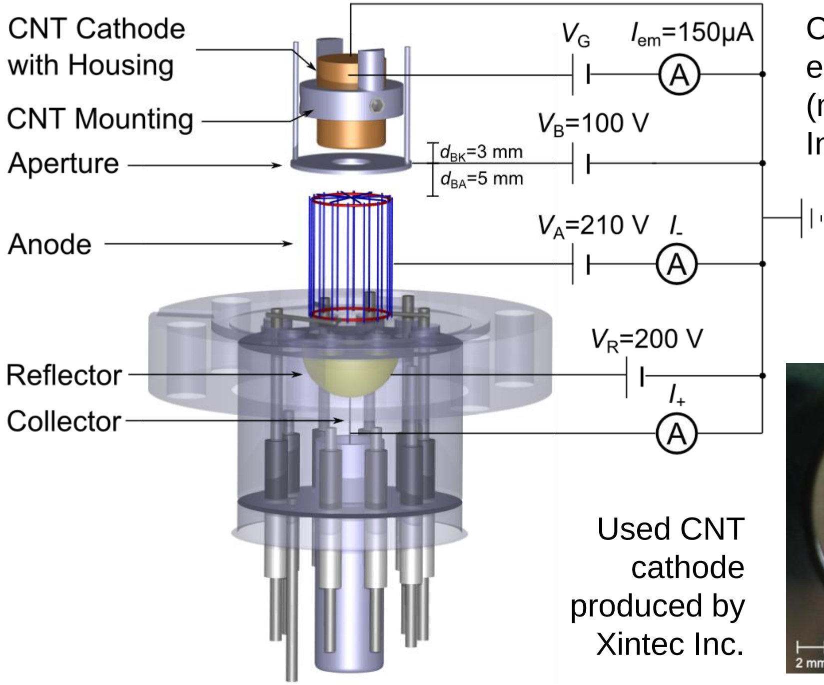
S_{H2} ~ 60 ℓ/s @ T_G = 5 K

S_{He} ~ 30 ℓ/s @ T_G = 5 K

Wilfert St, Hackler T, Wengenroth M, GSI Scientific report (2012), 241

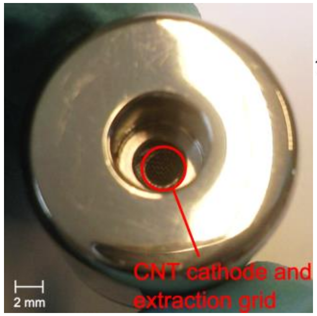
The cryogenic SIS100 beam vacuum system

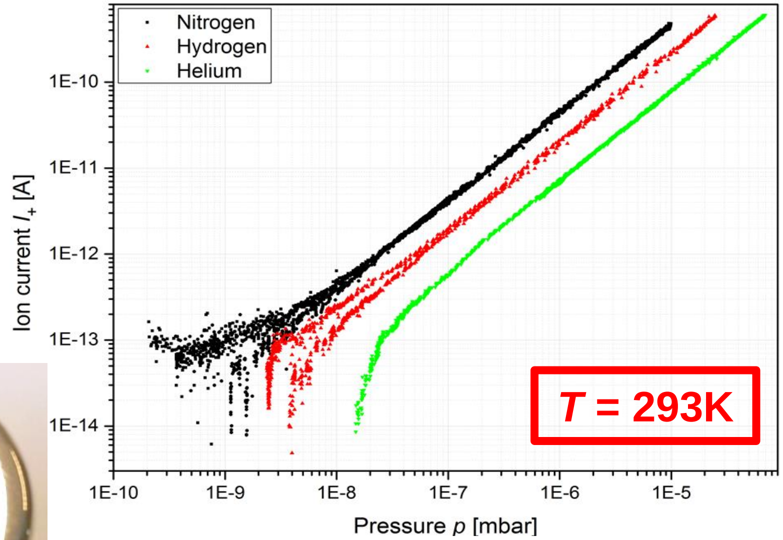
Development of ‚Cold' extractor ion gauge for the use in cryogenic UHV/XHV environments

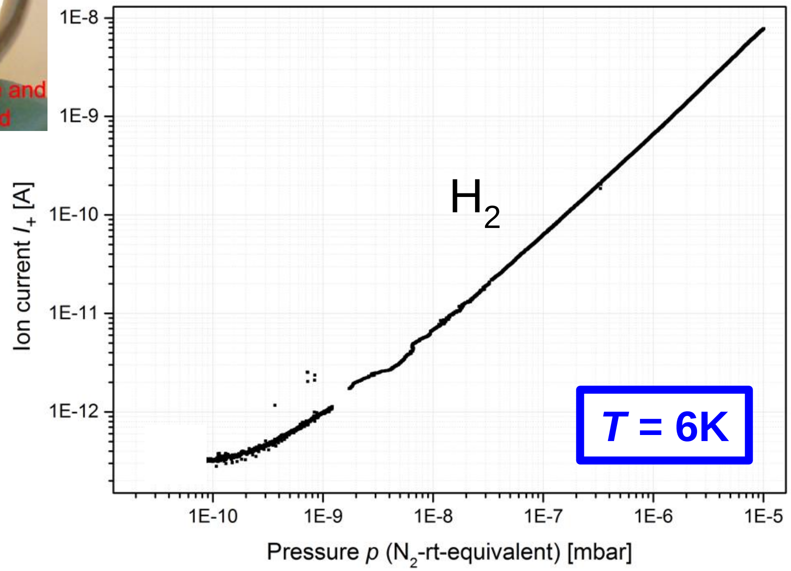


CNT-based extractor gauge (modified IE514, Inficon)

Used CNT cathode produced by Xintec Inc.







- Field emission-based ion gauges have been proven to work well under cryogenic vacuum conditions and deliver meaningful pressure (density) reading
- most promising field emission source: CNT cathode
- I_{em} ≈ 150μA → I_{anode} ≈ 50μA
- anode current is still too low for pressure reading in lower UHV or XHV range => improved design and higher emission currents are needed

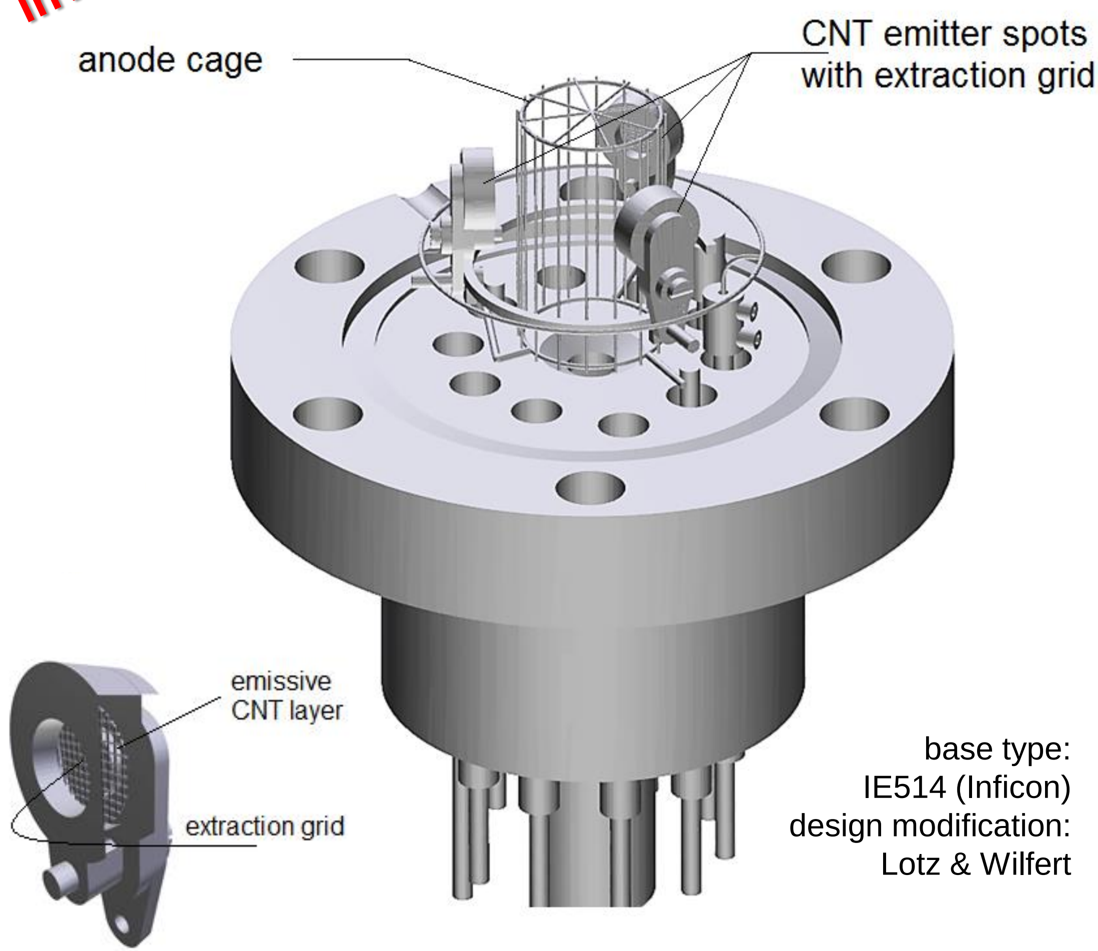
Lotz, M, Wilfert, St, et al. IPAC2014, Proc. IPAC2014,Dreseden (Germany),WEPME029, 2320-2322
Lotz, M; Wilfert, St, et al. Vakuum in Forschung & Praxis 27(4)(2015),34-40

The cryogenic SIS100 beam vacuum system

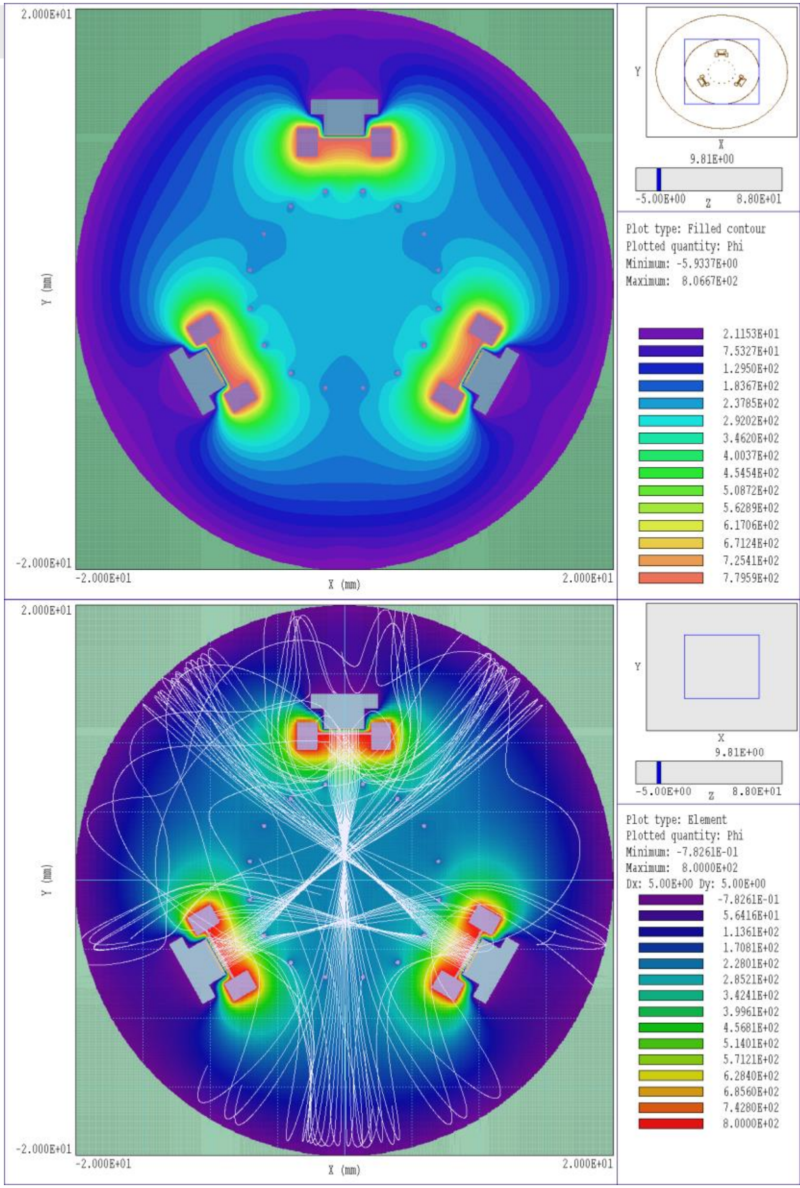
Development of a ‚cold‘ extractor ion gauge for the use in cryogenic UHV/XHV environments

under investigation!

CNT-based extractor gauge



base type:
IE514 (Inficon)
design modification:
Lotz & Wilfert



simulation by M Lotz (GSI+University Frankfurt)
Courtesy by M Lotz

The room temperature SIS100 beam vacuum system

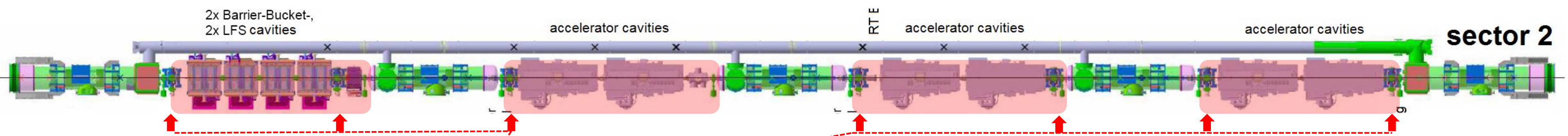
Some technical facts

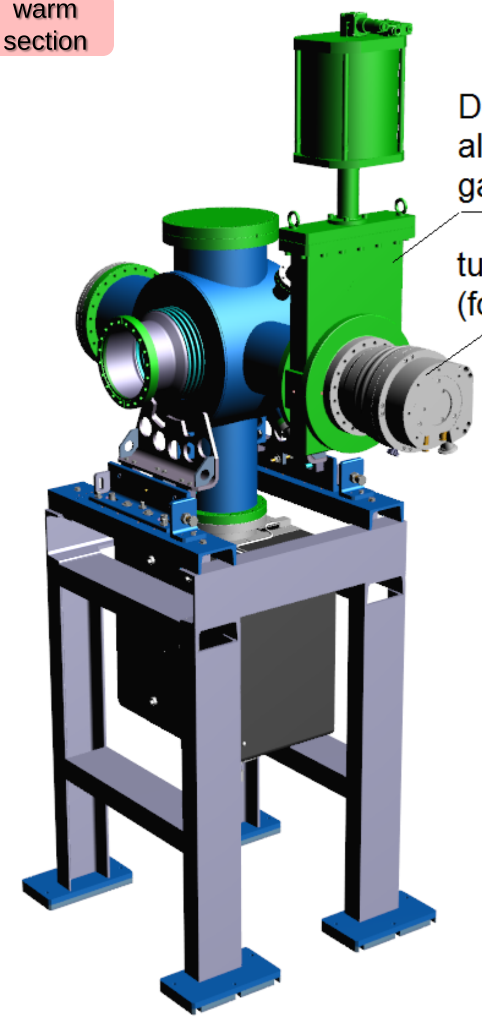
25 straight warm sections (= 24 à 7 m + 1 à 19 m)

Vacuum chambers	33 Standard pumping and roughing chambers 11 Diagnostic chambers 6 Resonance sextupole chambers 16 Bunch compressor cavity chambers 20 accelerator cavity chambers 2 Barrier-Bucket cavity chambers 2 Longitudinal feedback cavity chambers 2 RT quadrupole chambers (radiation-resistant) 70 Interconnection bellows 3 magnetic extraction septa 2 magnetic injection septa 3 RT Beam position monitor		**169 individual vacuum chambers**
Large-volume vacuum tanks	**Extraction line (sector 5):** BTF exciter tank 2-fold extraction kicker 3-fold magnetic extraction kicker Electrostatic septa K.O. exciter tank	**Injection line (sector 6):** Magnetic extraction kicker tank 6-fold electrostatic kicker tank 2-fold electrostatic septa tank Q-kicker tank	**9 individual large-volume vacuum tanks**
Vacuum pumps	60 ion getter pumps ($S \geq 500$ ℓ/s N_2) 96 NEG/Ion getter pumps ($S \geq 500$ ℓ/s H_2) 63 NEG pumps ($S \sim 3500$ ℓ/s H_2) 30 mobile roughing pump stations (TMP+SCR) (700 ℓ/s N_2)		**249 vacuum pumps**
Gate valves	25 DN160CF gate valves (Roughing) 47 DN100CF gate valves (Roughing) 34 DN160CF gate valves (beam vacuum system separation) 12 DN160CF fast valves (beam vacuum system separation) 1 DN350CF gate valves (beam vacuum system separation) 1 DN350CF fast valve (beam vacuum system separation) 2 DN100CF gate valves (beam vacuum system separation SIS100 – HEBT)		**122 all metal-gate valves**
Vacuum diagnostic	53 Extractor ion gauges 25 Pirani gauges 6 residual gas analyzers		

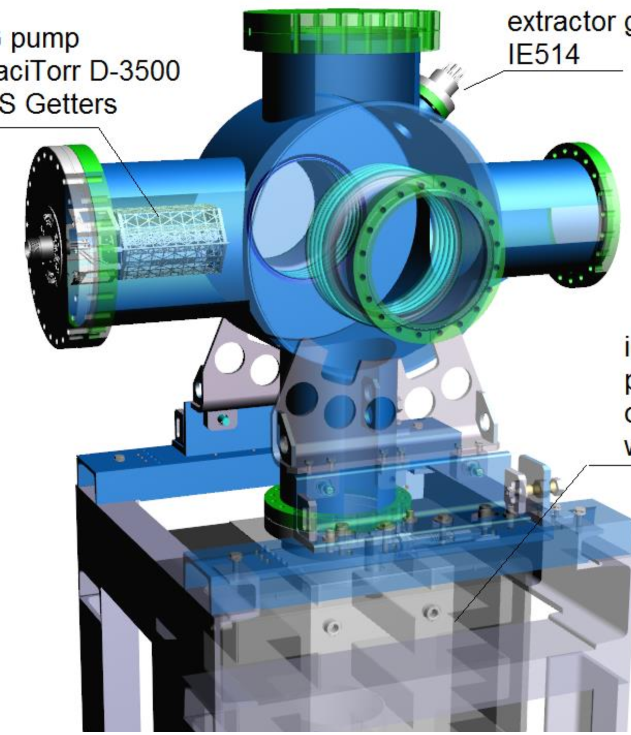
The room temperature SIS100 beam vacuum system

Standard pumping and roughing chambers





- 33 standard pumping chambers will be distributed throughout the entire ring, two will be installed in each room temperature section, DS+US
- 11 RT diagnostic chambers are designed such that they can be used simultaneously as pumping chambers
- Roughing the RT sections will only be done at the pumping chamber on downstream side

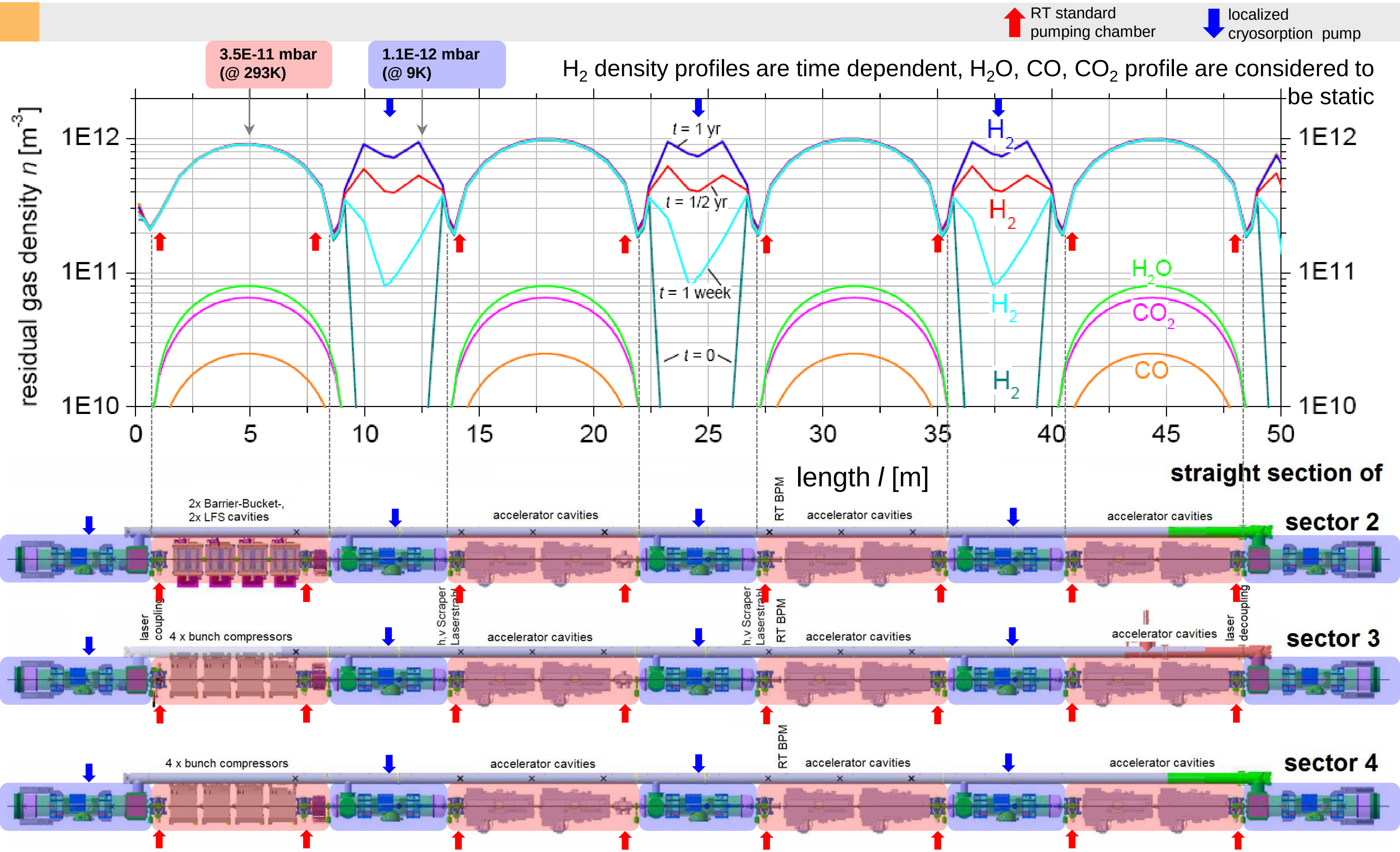


Gas specific pumping speeds of the pumps to be installed to the standard pumping chambers in the 10^{-11} mbar range (data taken by pump manufacturer). The pumping speed of NEG pump is reduced once it is mounted into a nipple.

	H_2	H_2O	CO	CH_4	Ar
NEG pump CapaciTorr D-3500	2200 ℓ/s	1650 ℓ/s	1000 ℓ/s	--	--
Ion getter pump Nobel diode type	800 ℓ/s	?	250 ℓ/s	150 ℓ/s	100 ℓ/s

The room temperature SIS100 beam vacuum system

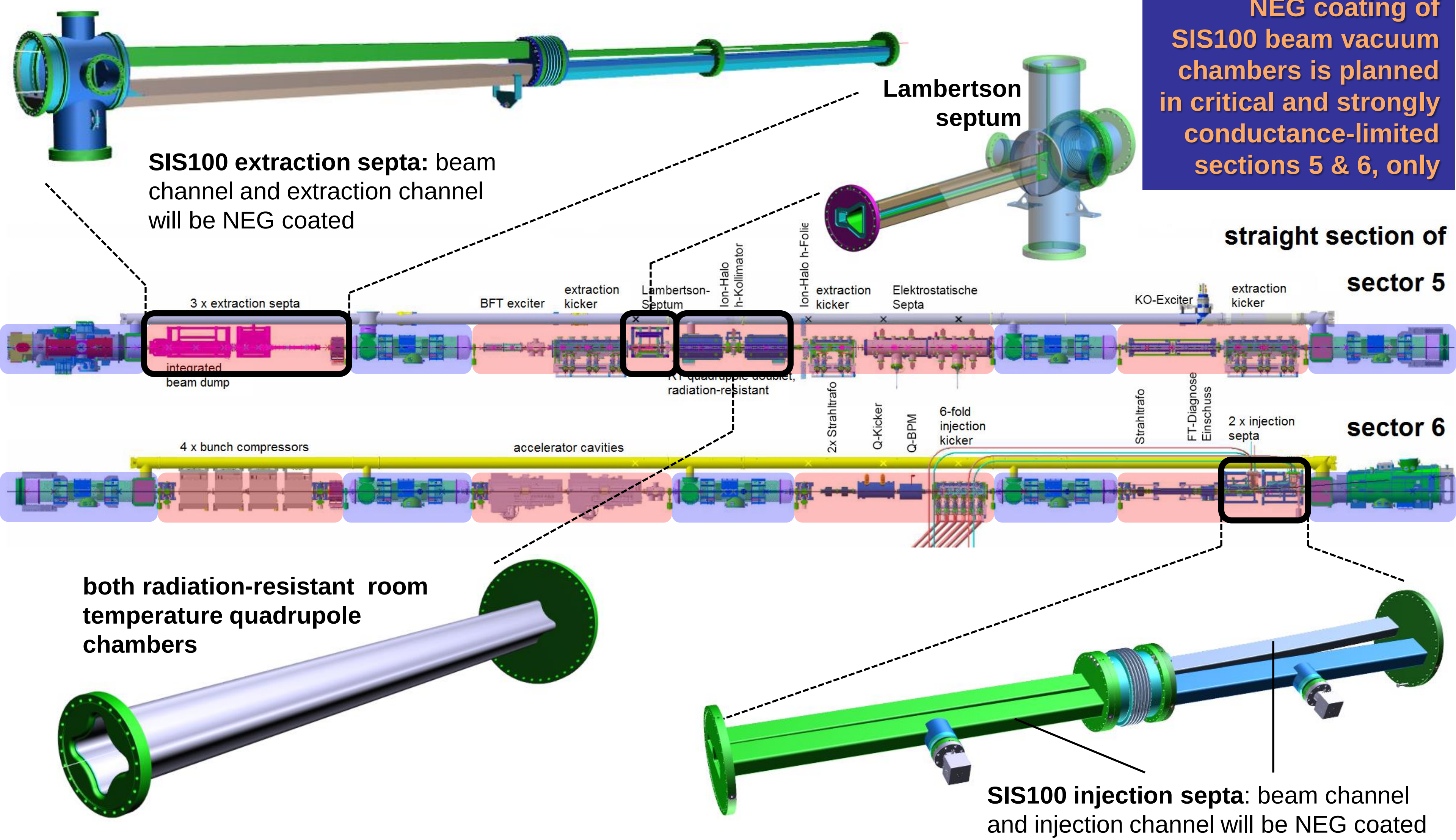
Residual gas density profile simulations of the straight vacuum sections in sectors 2 – 4



The room temperature SIS100 beam vacuum system

NEG coating in the straight vacuum sections

NEG coating of SIS100 beam vacuum chambers is planned in critical and strongly conductance-limited sections 5 & 6, only



Summary and Conclusions

Design of the vacuum system of SIS100 was challenging:

- design concept of the SIS100 beam vacuum is nearly completed
- **simulation results have confirmed that the expected dynamic vacuum instabilities should be under control, the vacuum system is safely designed and should work well !!!**

!

- Although, 80% of the cold surface in the cryogenic beam vacuum is held at “elevated” cryogenic temperatures between 9…15K, all requirements on beam vacuum quality are met, if
  - hydrogen flux from room temperature sections into cryogenic sections are kept very low (room temperature sections must thoroughly be baked out)
  - 14 additional localized cryosorption pumps are used in one cryogenic arc and one in each quadrupole module in the straight sections
- Eddy current heating of magnet chambers appears to be a major problem in fast-cycled sc accelerator machines → sophisticated chamber design is crucial → dipole and quadrupole chambers must be force-cooled in order to assure the efficiency of cryopumping
- Beam intensity limitations in ion accelerators due to ion stimulated desorption effects (ISD) can be effectively suppressed using a sophisticated ion catcher system

Thank you for your attention!

Special thanks to the colleagues,
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Ivan Pongrac,
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Seong Yeub Shim,
Carsten Omet,
Peter Spiller!