Development of the cERL Vacuum System

Yasunori Tanimoto, Tohru Honda, Takashi Nogami, Ryota Takai
Takashi Obina, Seiji Asaoka, Takashi Uchiyama, Norio Nakamura

Accelerator Division VII
Accelerator Laboratory
KEK - High Energy Accelerator Research Organization

cERL mini-workshop, January 19, 2015

Outline

1. Design of the cERL vacuum system

2. Major development points
   - Low impedance vacuum components
   - NEG coating
   - Main beam dump

3. Operational problems

4. Summary

Design of the cERL Vacuum System

Low impedance vacuum components

- need to be developed to accommodate high charge (7.7 – 77 pC/bunch), short bunch (0.03 – 0.3 mm) and low emittance (< 1 mm·mrad) electron beams
- adopt **gapless and stepless structures** in flanges, monitors, etc. to reduce wake (RF) field excitation, and consequently to mitigate beam breakup (BBU) and chamber heating

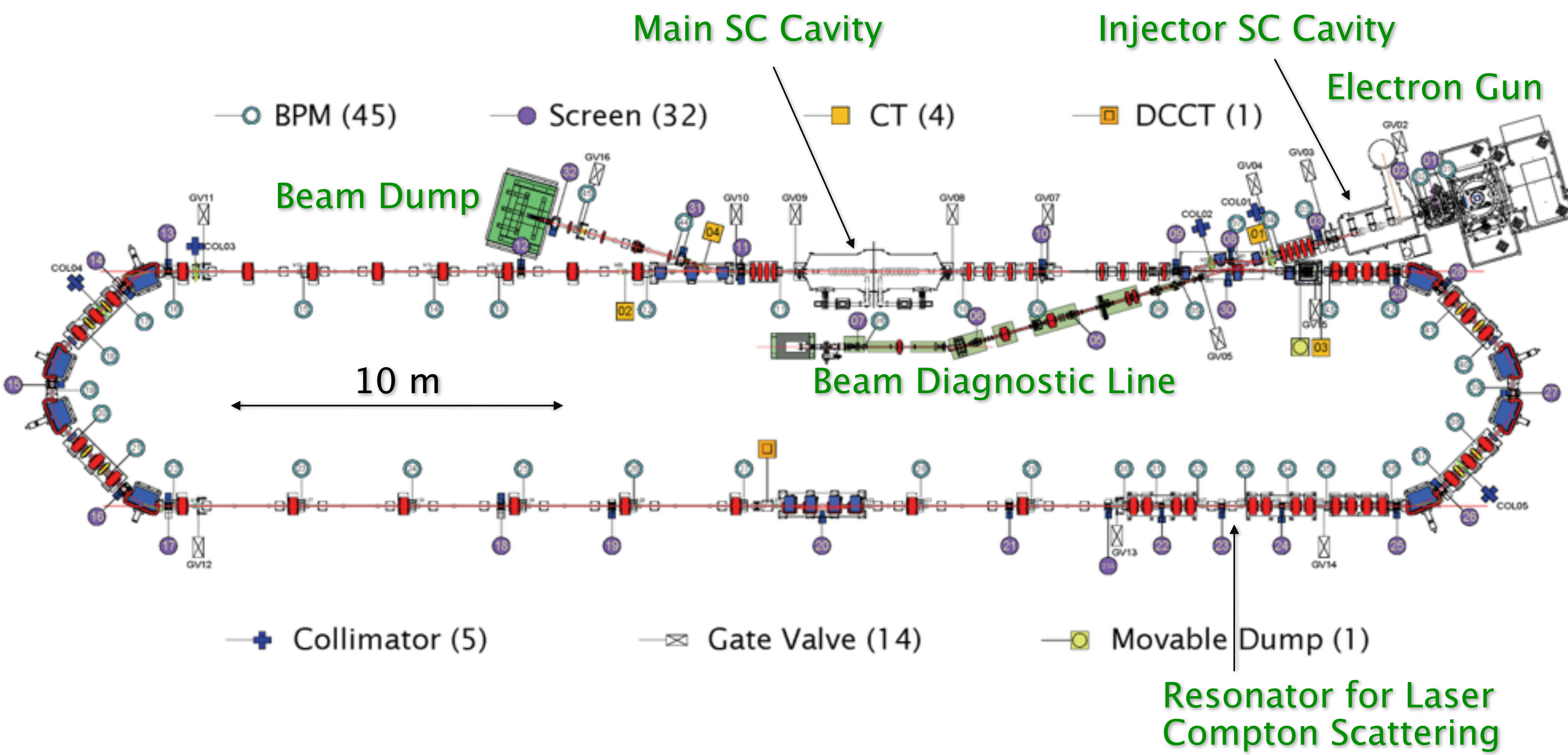
Required pressures

- basically **1×10^{-7} Pa** to mitigate beam-gas interactions (ion trapping and beam loss)
  lumped NEG pumps (LNPs) and sputter ion pumps (SIPs)
- around SC cavities: **1×10^{-8} Pa** to minimize gas condensation on cryo surfaces
  NEG-coated tubes, LNPs and SIPs

Ready for in-situ bakeout

- no SR scrubbing effect expected
  total incoherent SR (ISR) power **2.2 W** (125 MeV, 100 mA)
  total coherent SR (CSR) power **77 W** (125 MeV, 10 mA, σ_z= 0.3 mm)
- no measures needed against the SR heat load
  stainless steel 316L tubes wrapped with **Kapton film heaters**

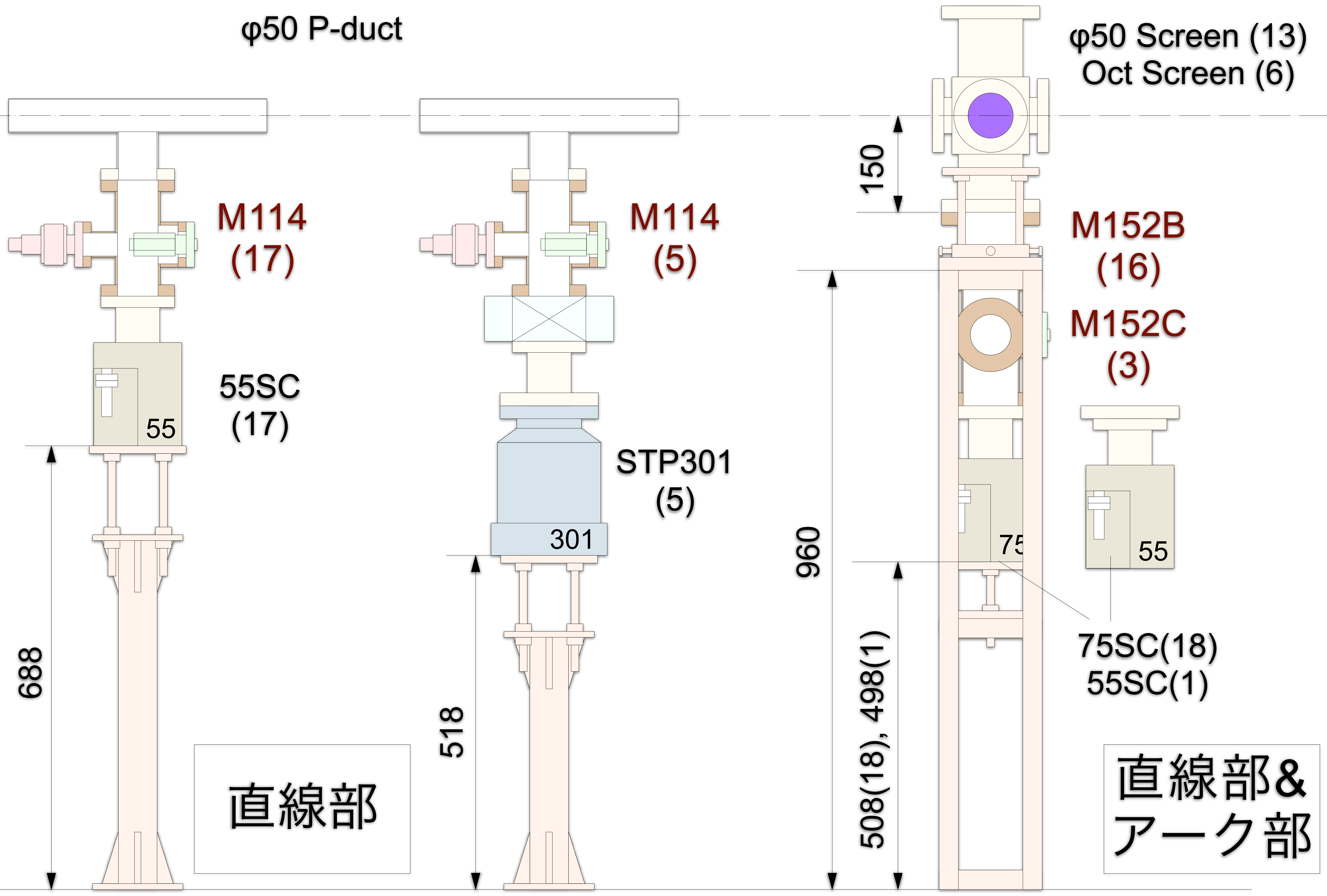
Schematic Layout of cERL



List of Vacuum Components

Sputter Ion Pump (SIP)	1 (300SC) 32 (75SC) 18 (55SC)
Non-Evaporable Getter (NEG) pump	52 (D200) 12 (WP38/950) 3 (coating)
Rough pump	9 (fixed) 6 (removal)
Cold Cathode Gauge (CCG)	38 (IKR070) 18 (IKR060)
Residual Gas Analyzer (RGA)	3
RF-shielded Gate Valve (GV)	8 (φ50) 1 (φ100) 2 (φ60, main cav)
RF-shielded bellows	36 (φ50) 3 (φ100)

RF-shielded Screen Monitor (MS)	16 (φ50) 6 (octagon) 2 (φ100) 2 (in chicane)
Beam Position Monitor (BPM)	27 (φ50) 2 (φ50, button) 10 (octagon) 2 (φ85)
Beam collimator	5
Current Transformer (CT)	4
DC Current Transformer (DCCT)	1
Movable Faraday cup	1
Main beam dump	1



φ50 P-duct
M114
(17)
55SC
(17)
55
688
直線部
M114
(5)
STP301
(5)
301
518
φ50 Screen (13)
Oct Screen (6)
150
M152B
(16)
M152C
(3)
960
508(18), 498(1)
55
75SC(18)
55SC(1)
直線部&
アーク部

List of Vacuum Components

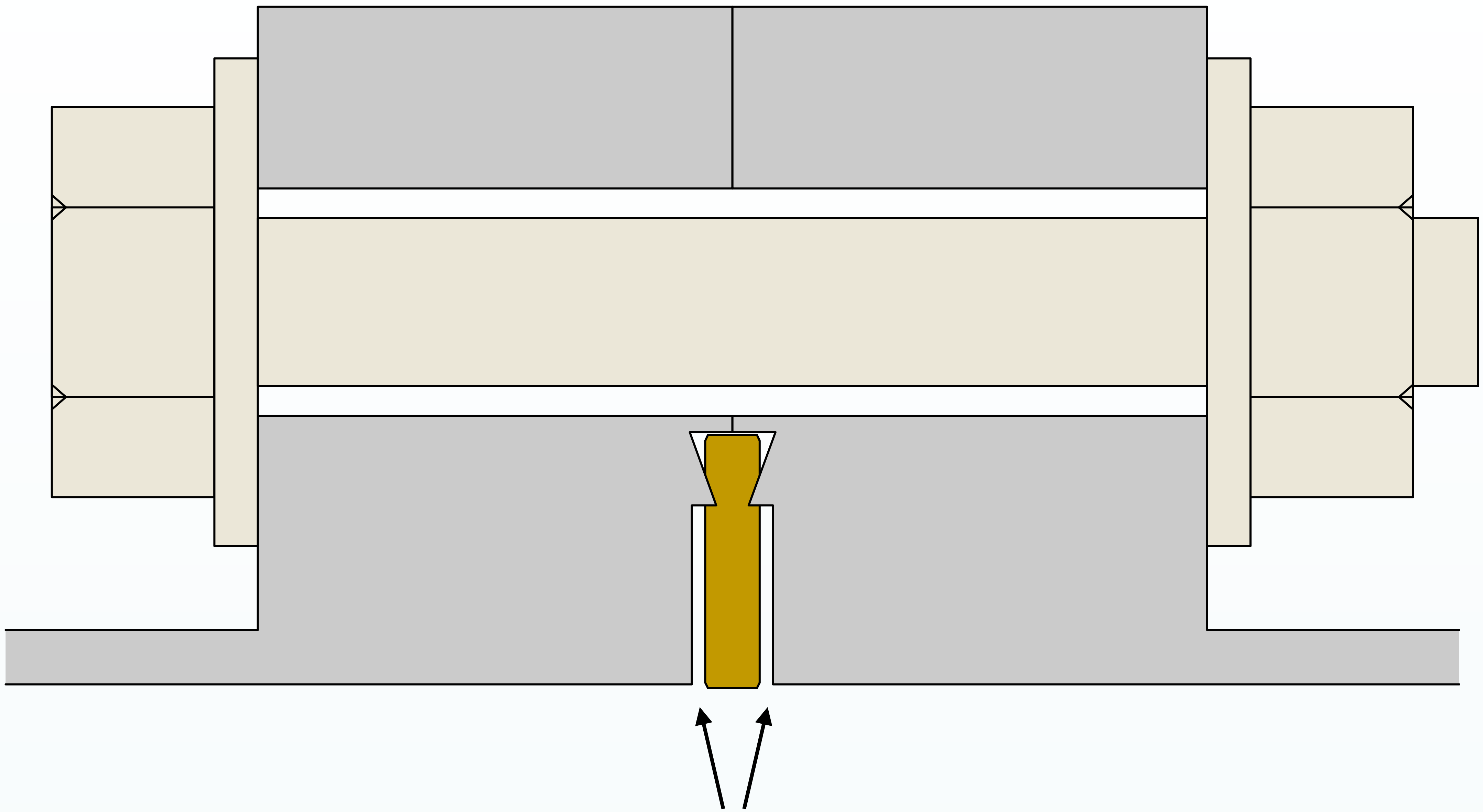
Sputter Ion Pump (SIP)	1 (300SC) 32 (75SC) 18 (55SC)
Non-Evaporable Getter (NEG) pump	52 (D200) 12 (WP38/950) 3 (coating)
Rough pump	9 (fixed) 6 (removal)
Cold Cathode Gauge (CCG)	38 (IKR070) 18 (IKR060)
Residual Gas Analyzer (RGA)	3
RF-shielded Gate Valve (GV)	8 (φ50) 1 (φ100) 2 (φ60, main cav)
RF-shielded bellows	36 (φ50) 3 (φ100)

RF-shielded Screen Monitor (MS)	16 (φ50) 6 (octagon) 2 (φ100) 2 (in chicane)
Beam Position Monitor (BPM)	27 (φ50) 2 (φ50, button) 10 (octagon) 2 (φ85)
Beam collimator	5
Current Transformer (CT)	4
DC Current Transformer (DCCT)	1
Movable Faraday cup	1
Main beam dump	1

Low impedance vacuum components

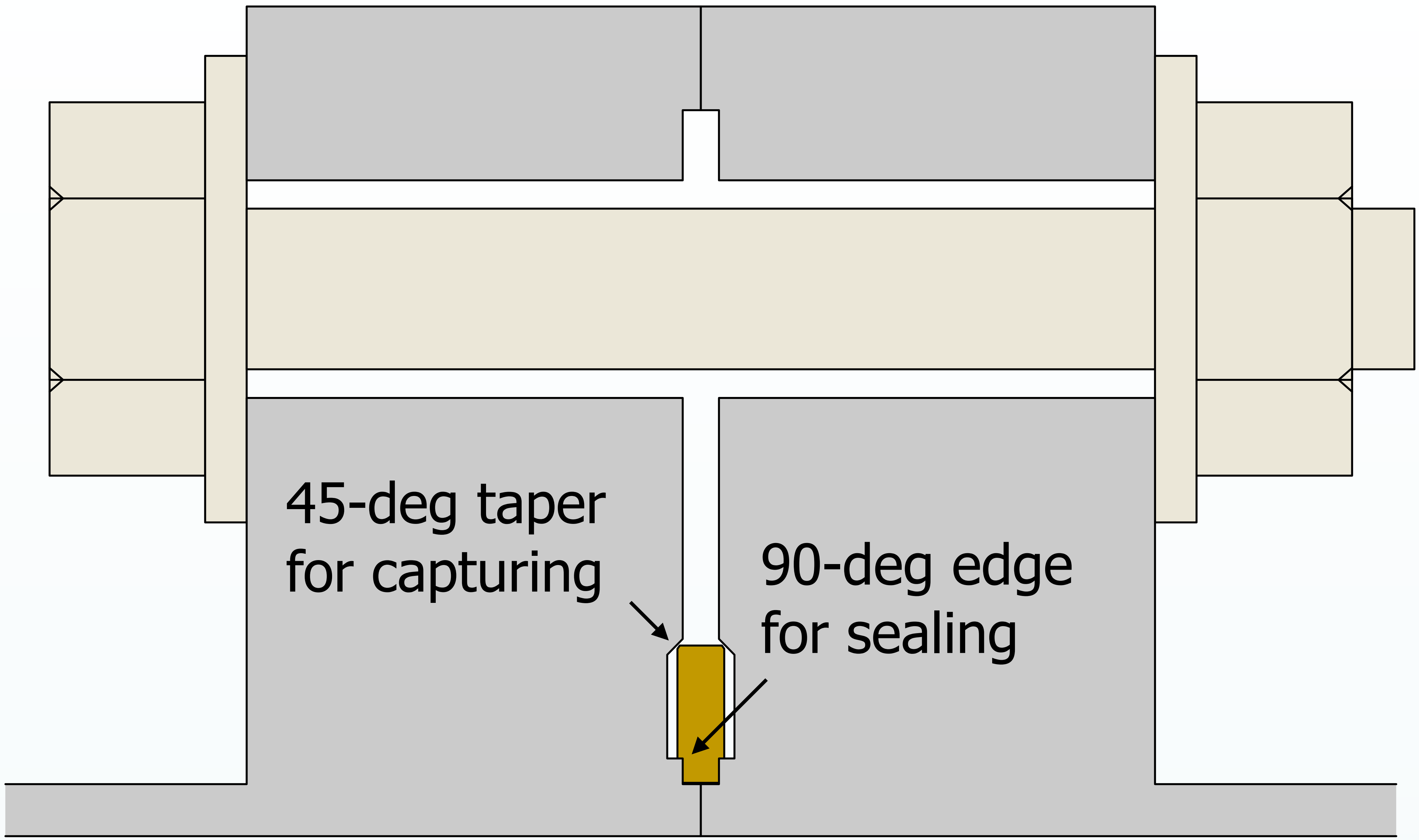
Standard CF Flange

(copper gasket)

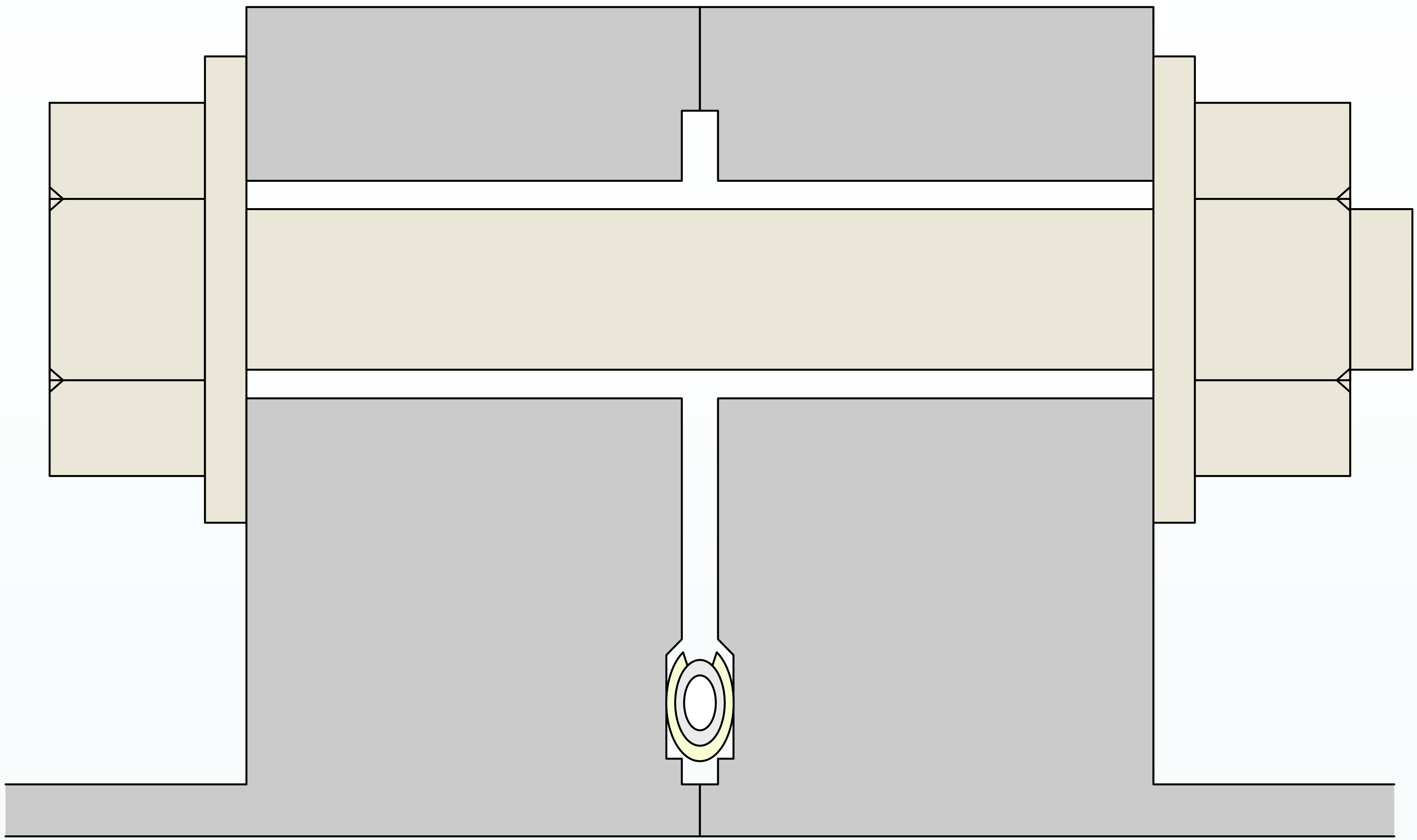


Gaps (> 0.5 mm) can be seen from the beam

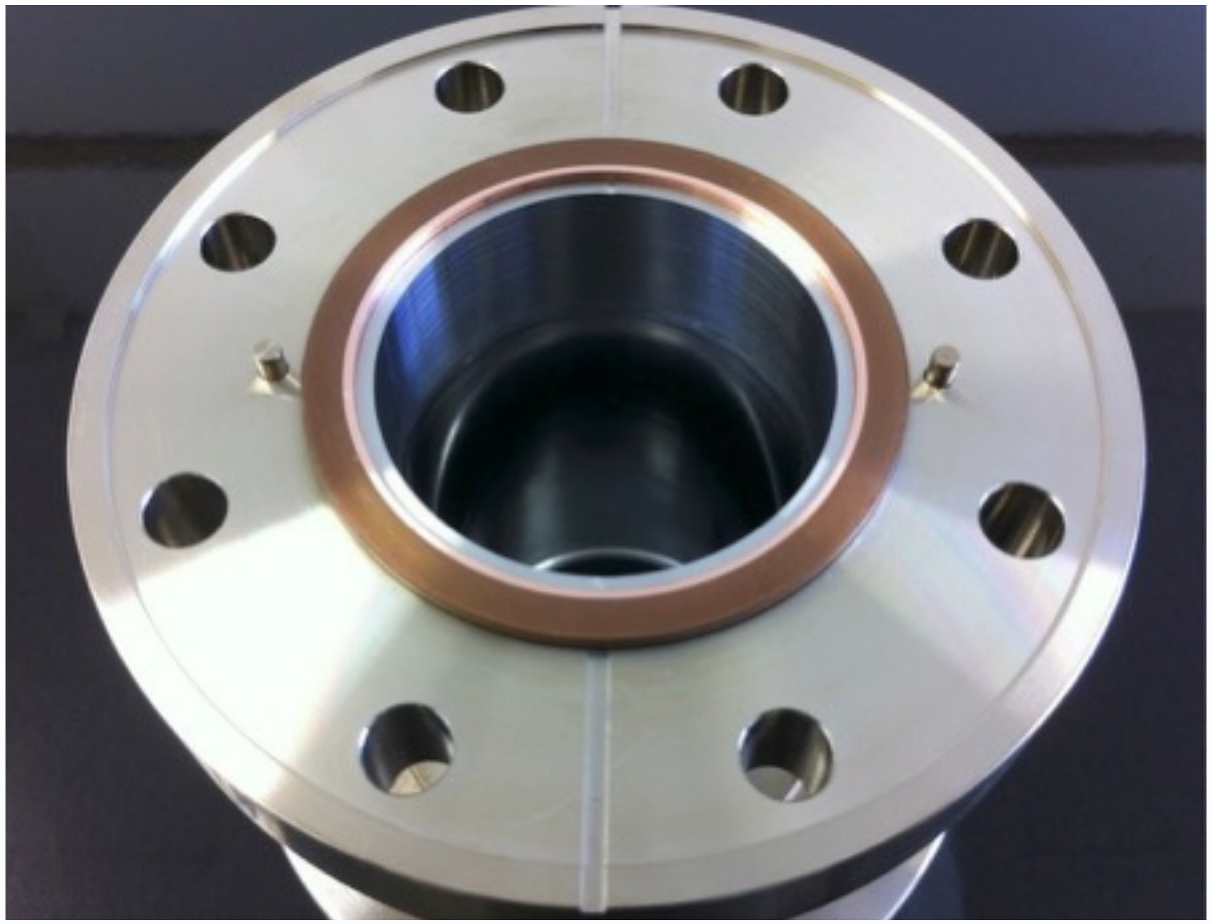
Impedance-free Flange (copper gasket)



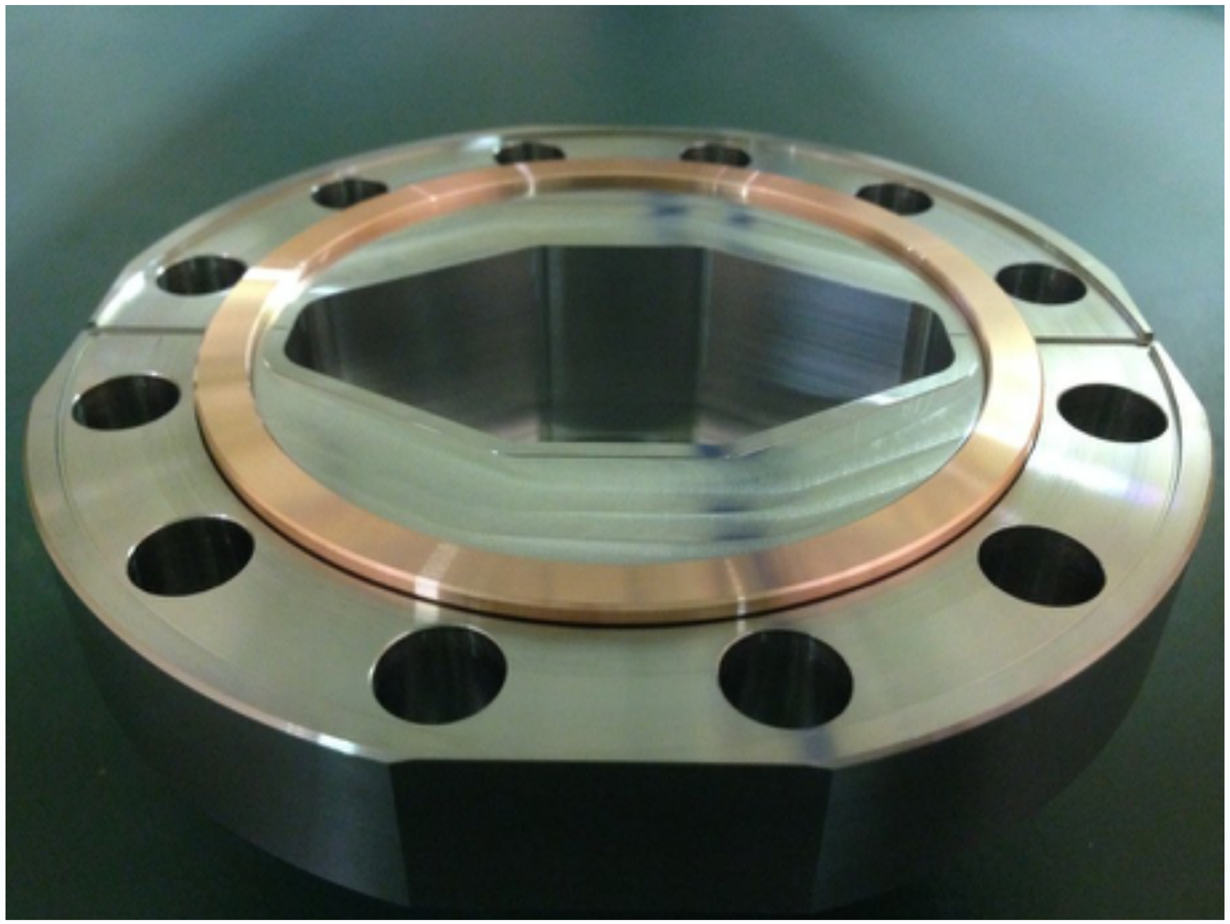
Impedance-free Flange
(U-tightseal or Helicoflex)



Impedance-free Flanges



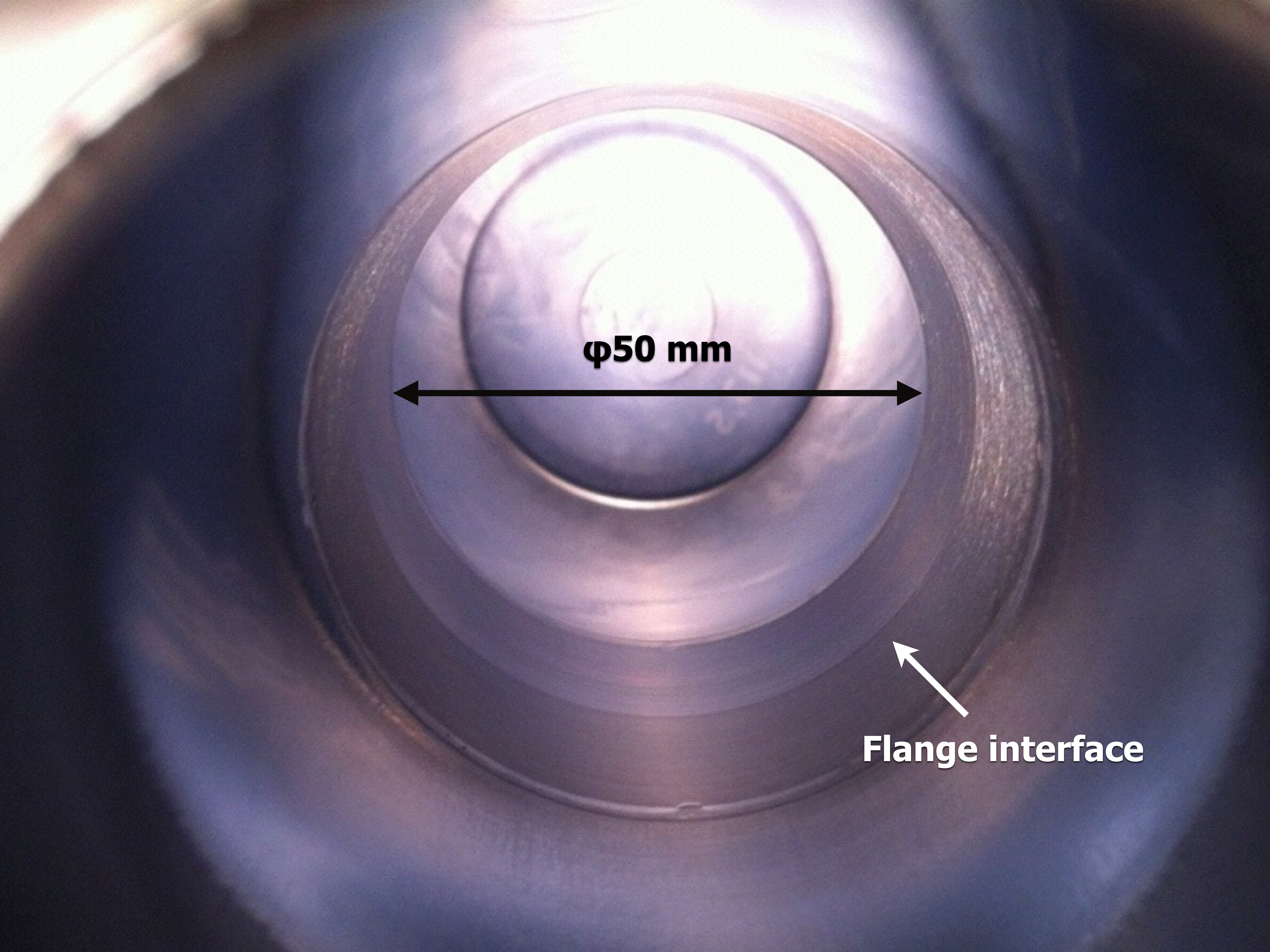
for straight sections
(ID φ50)

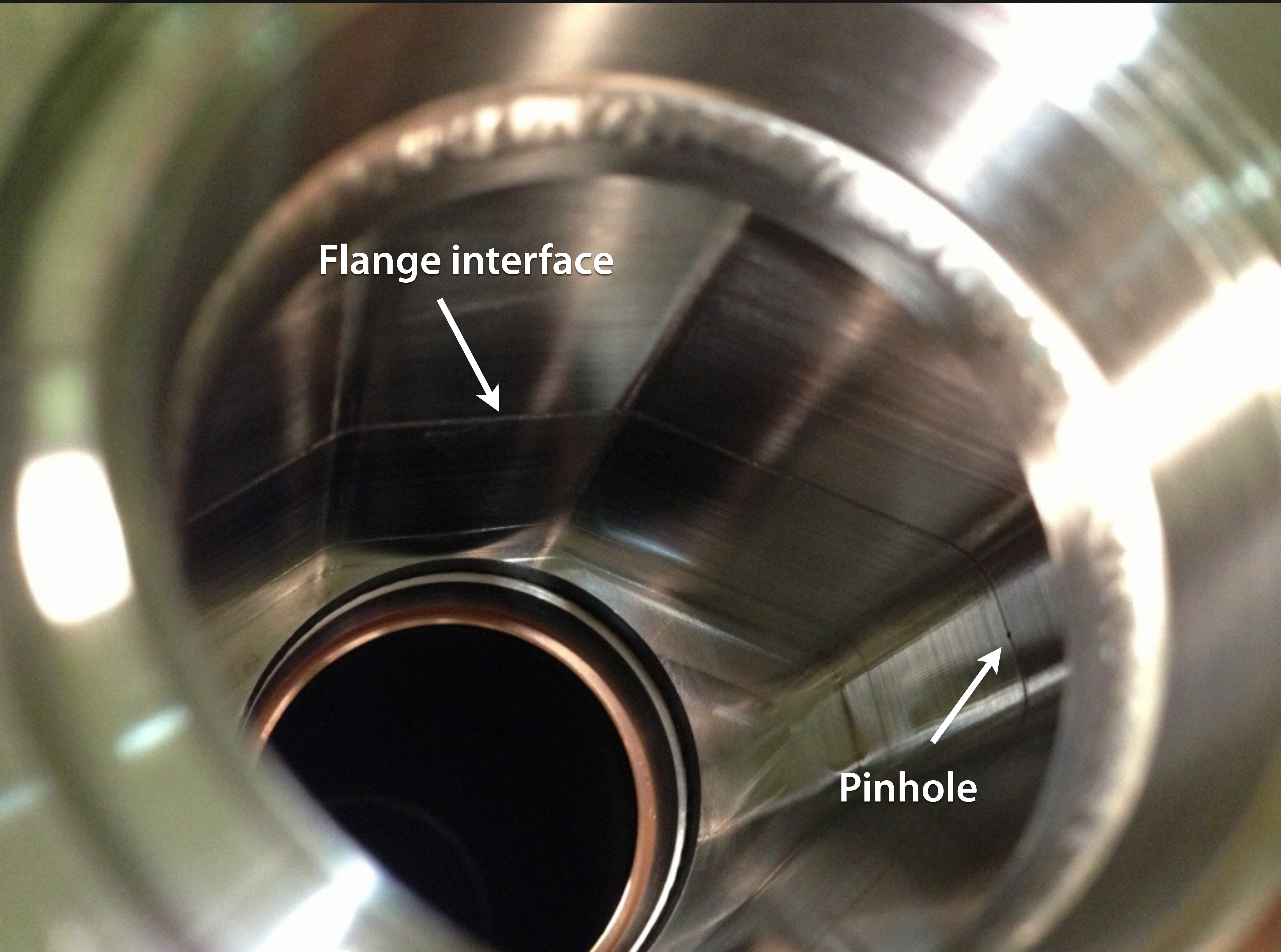


for arc sections
(70x40 oblong octagon)

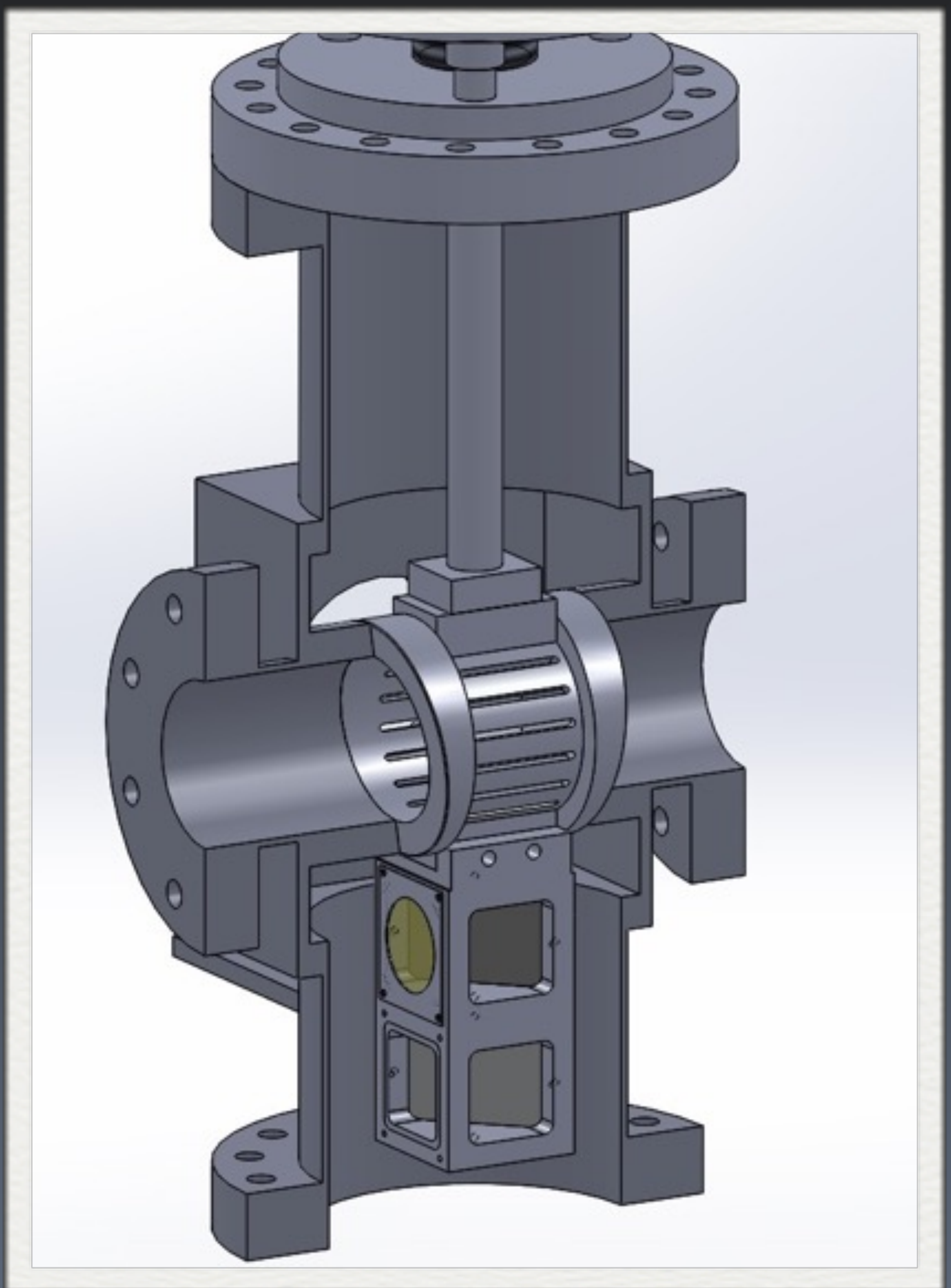
No vacuum leak was detected at over 160 flange joints.

Y. Tanimoto et al., “Design of the cERL Vacuum System,” Proc. IPAC’13, p.3315.


φ50 mm
Flange interface


Flange interface
Pinhole

RF-shielded Screen Monitor



Two kinds of screens (YAG and OTR) for transverse beam profile measurements

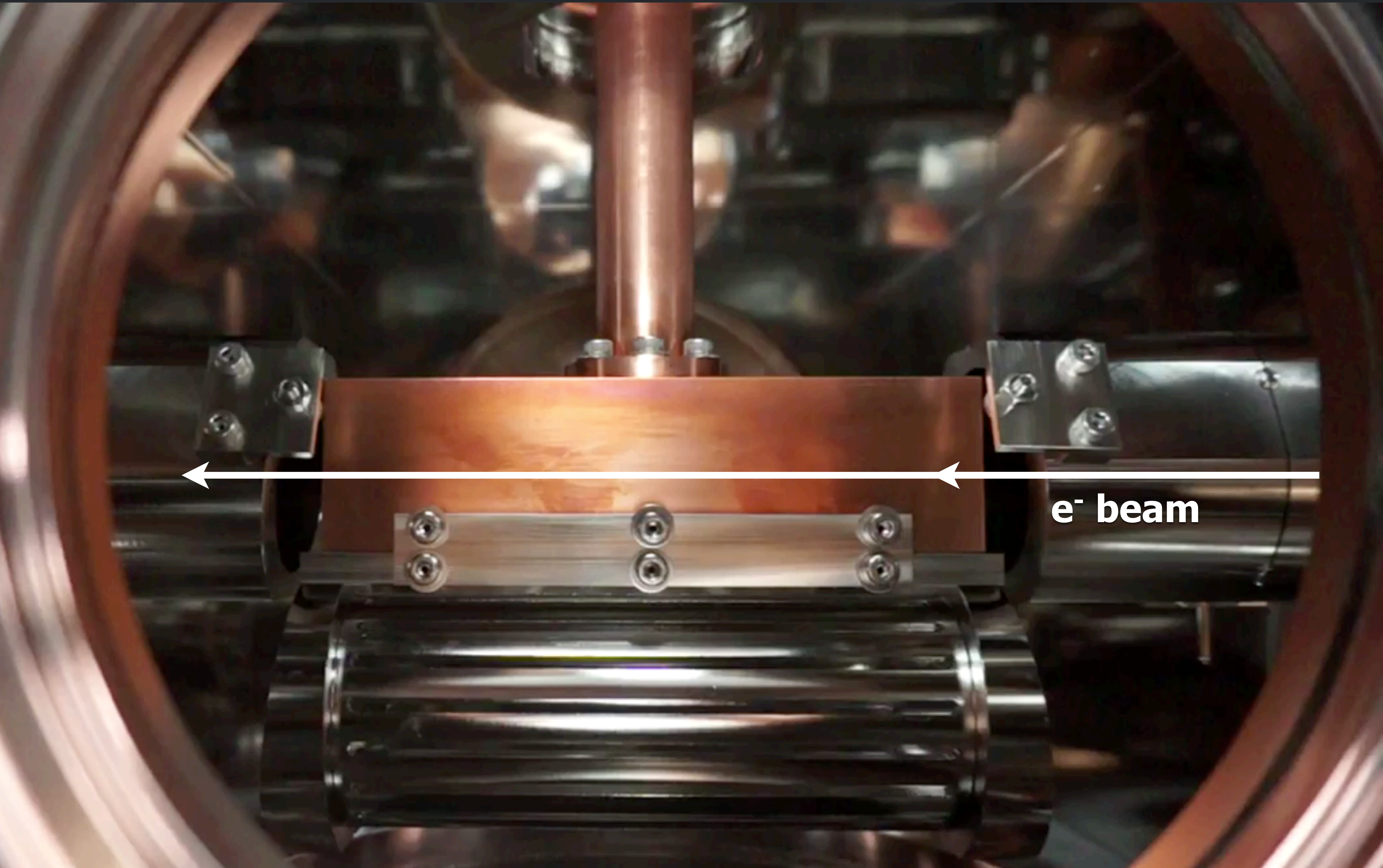
Screens are concealed behind an RF-shield tube while not in use

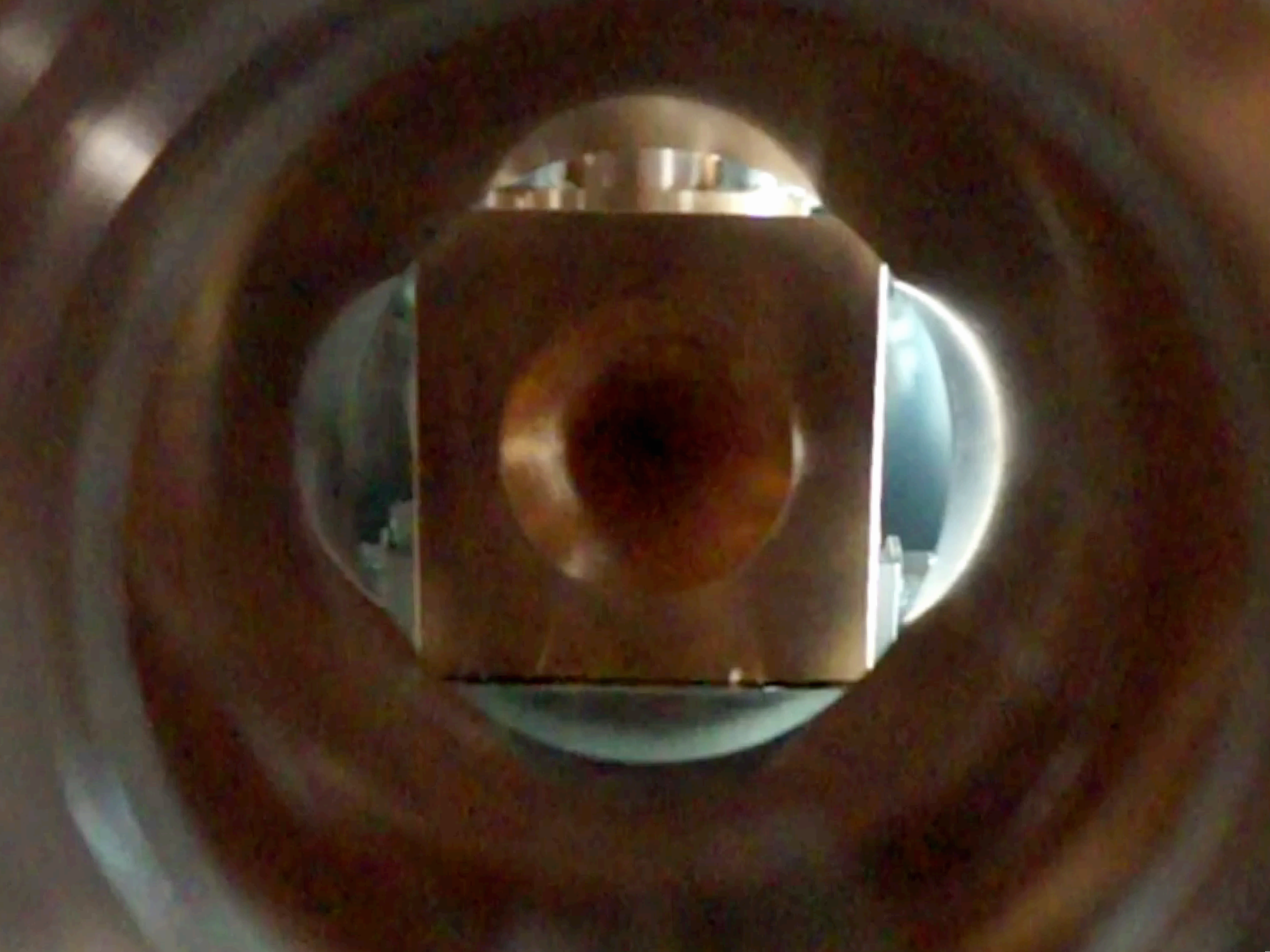
The RF shield reduces the longitudinal loss factor to below 1/100 (σ_z= 1 mm)

Based on the designs at JLab and BNL

R. Takai et al., "Design and Initial Commissioning of Beam Diagnostics for the KEK Compact ERL", Proc. IBIC14, MOCYB2.

Movable Faraday Cup





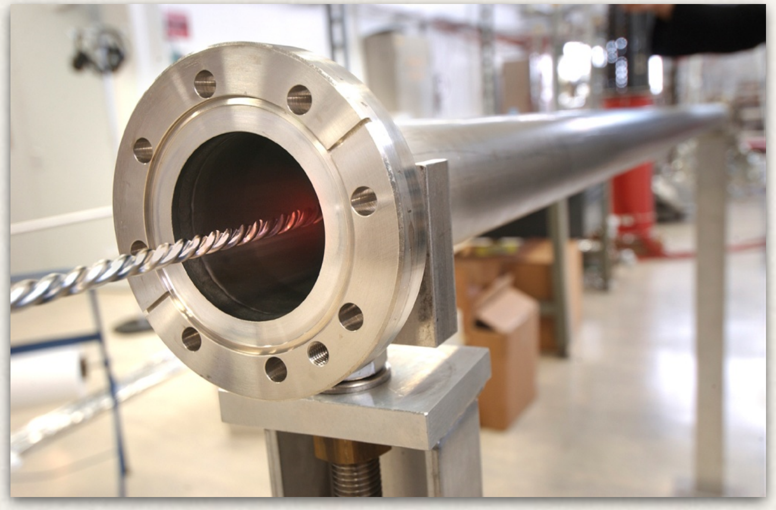
NEG coating

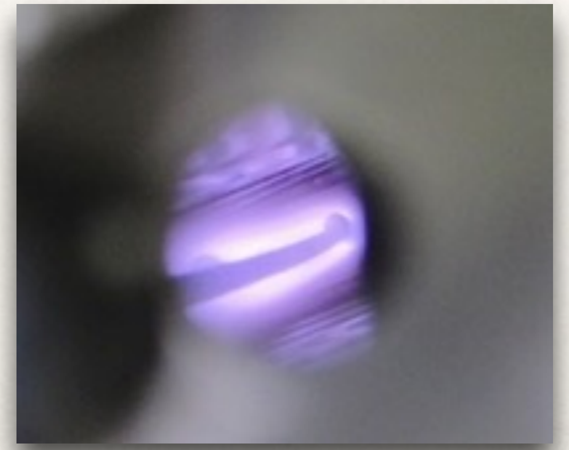
NEG coating

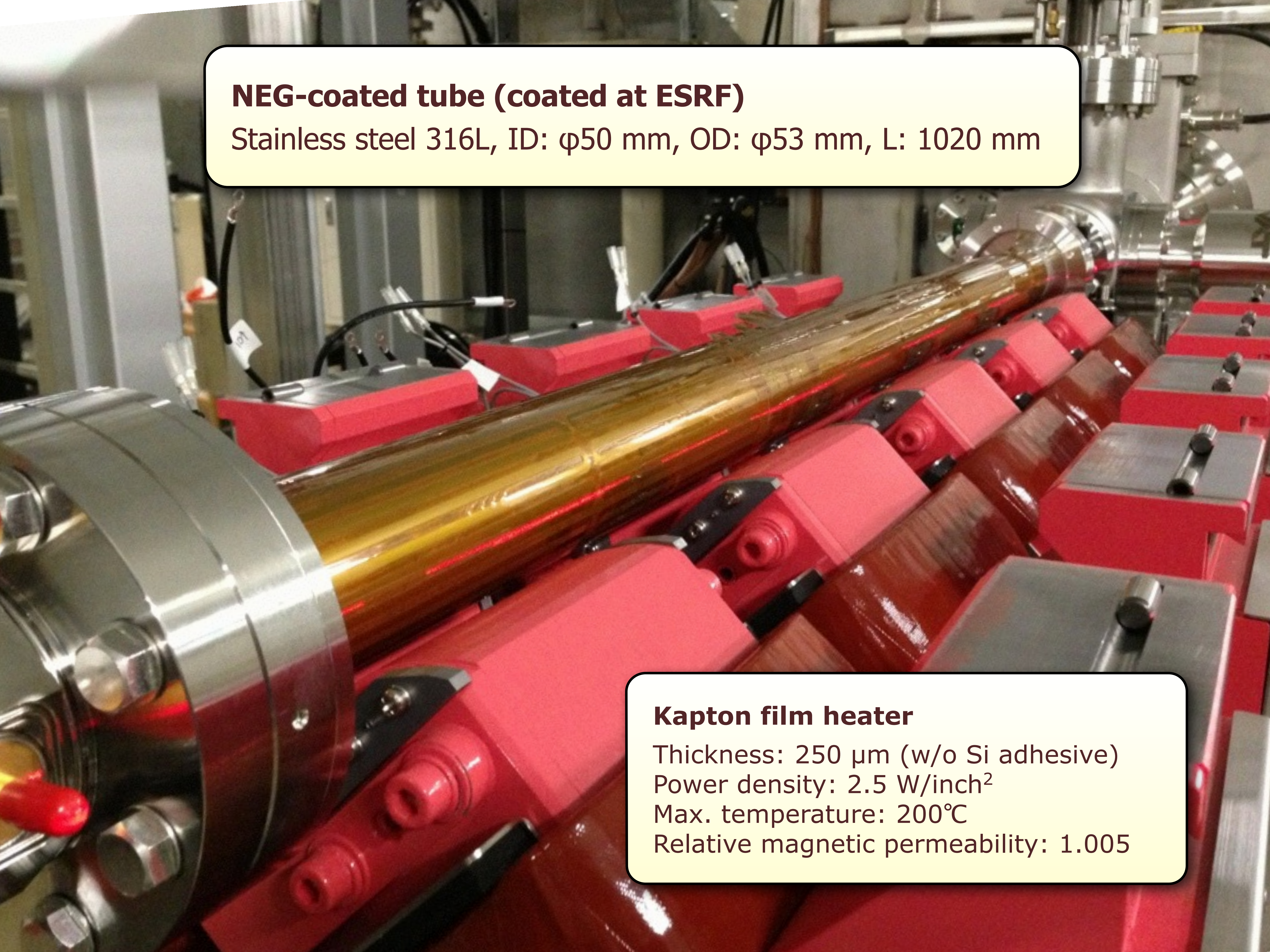
The technology of Non-Evaporable Getter (NEG) coating was established at CERN in late 1990s, and has been widely employed at various particle accelerators.

TiZrV thin films (0.5~1 μm) are deposited by magnetron sputtering, whereby the tube wall is changed into a vacuum pump with the following characteristics:

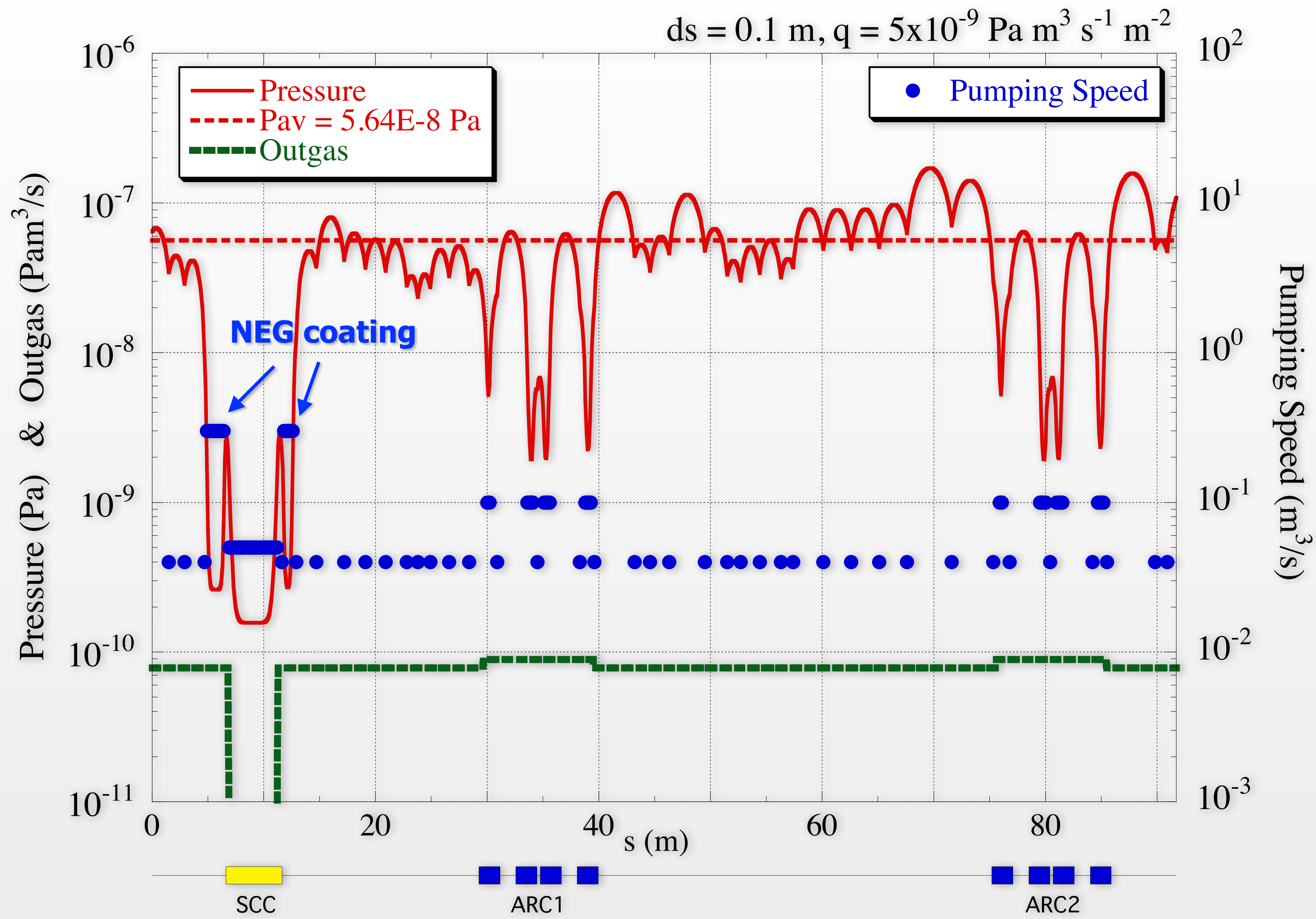
- Active gases are chemisorbed onto a activated surface.
- Noble gases are not pumped, and methane is hardly pumped at room temperature.
- Activation (e.g. 200°C for 24 h) can refresh a saturated surface by irreversible diffusion of oxygen and carbon into the film and by reversible desorption of hydrogen.

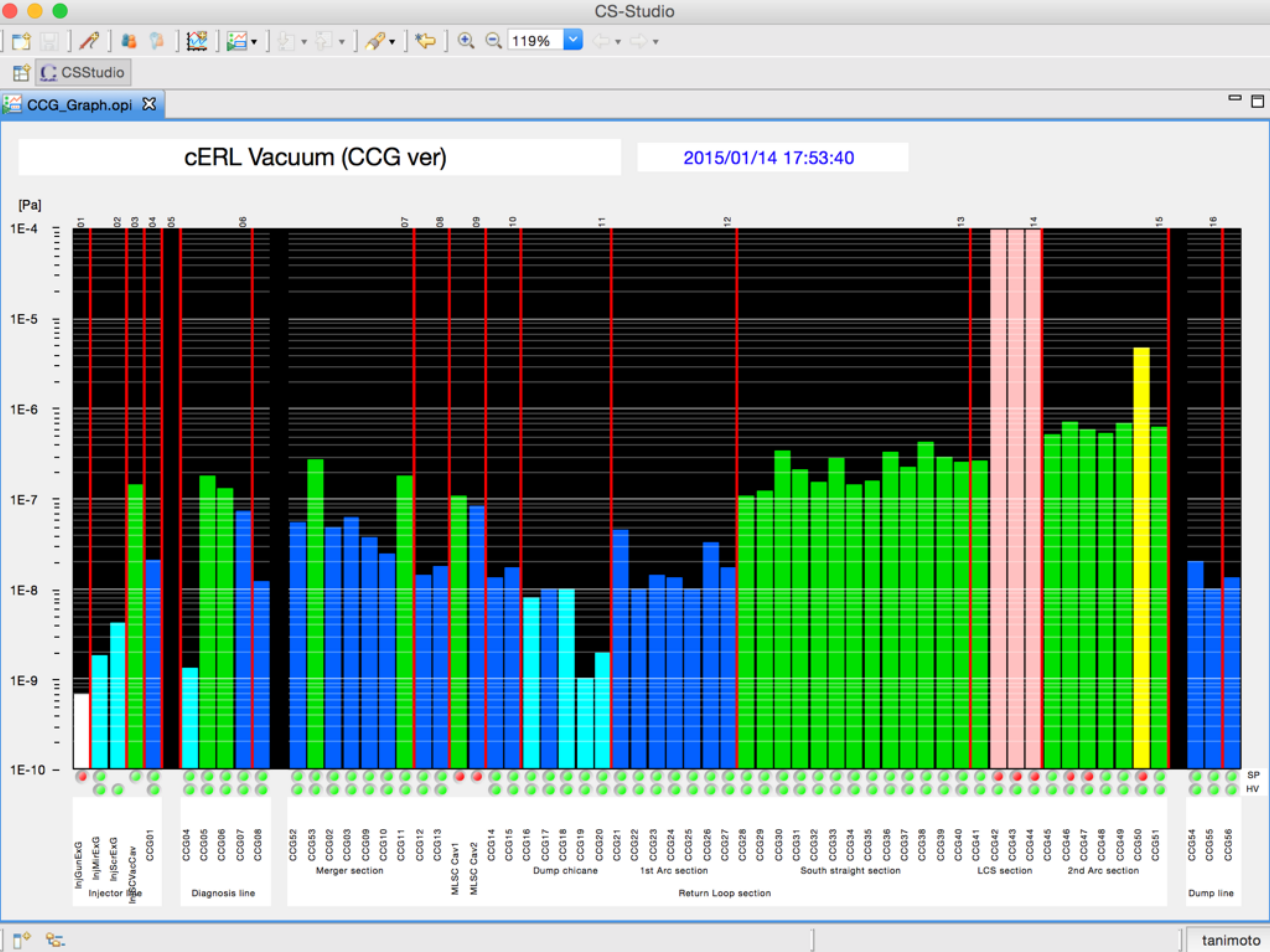




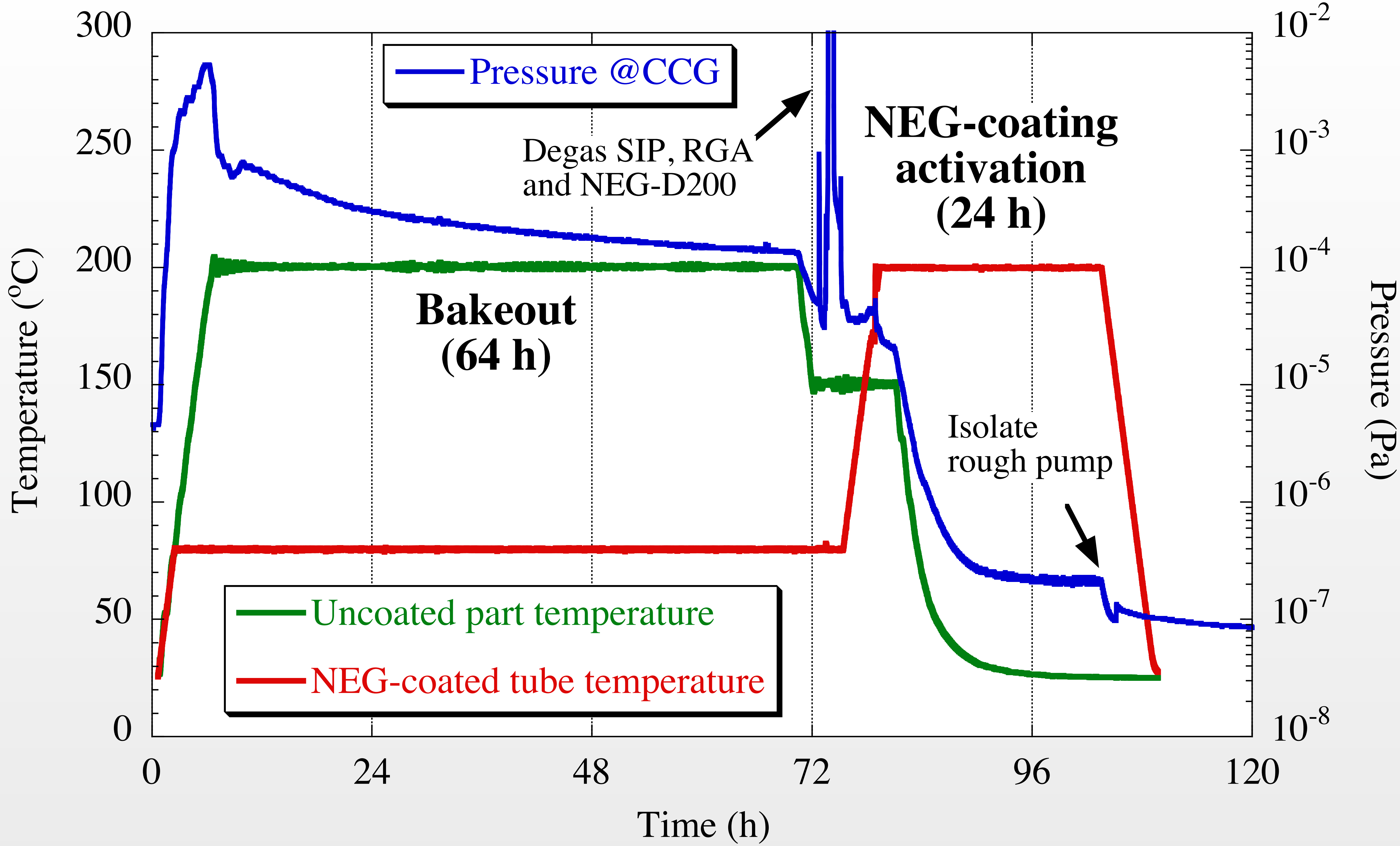


NEG-coated tube (coated at ESRF)
Stainless steel 316L, ID: φ50 mm, OD: φ53 mm, L: 1020 mm
Kapton film heater
Thickness: 250 μm (w/o Si adhesive)
Power density: 2.5 W/inch^2
Max. temperature: 200℃
Relative magnetic permeability: 1.005

Calculated Pressure Profile

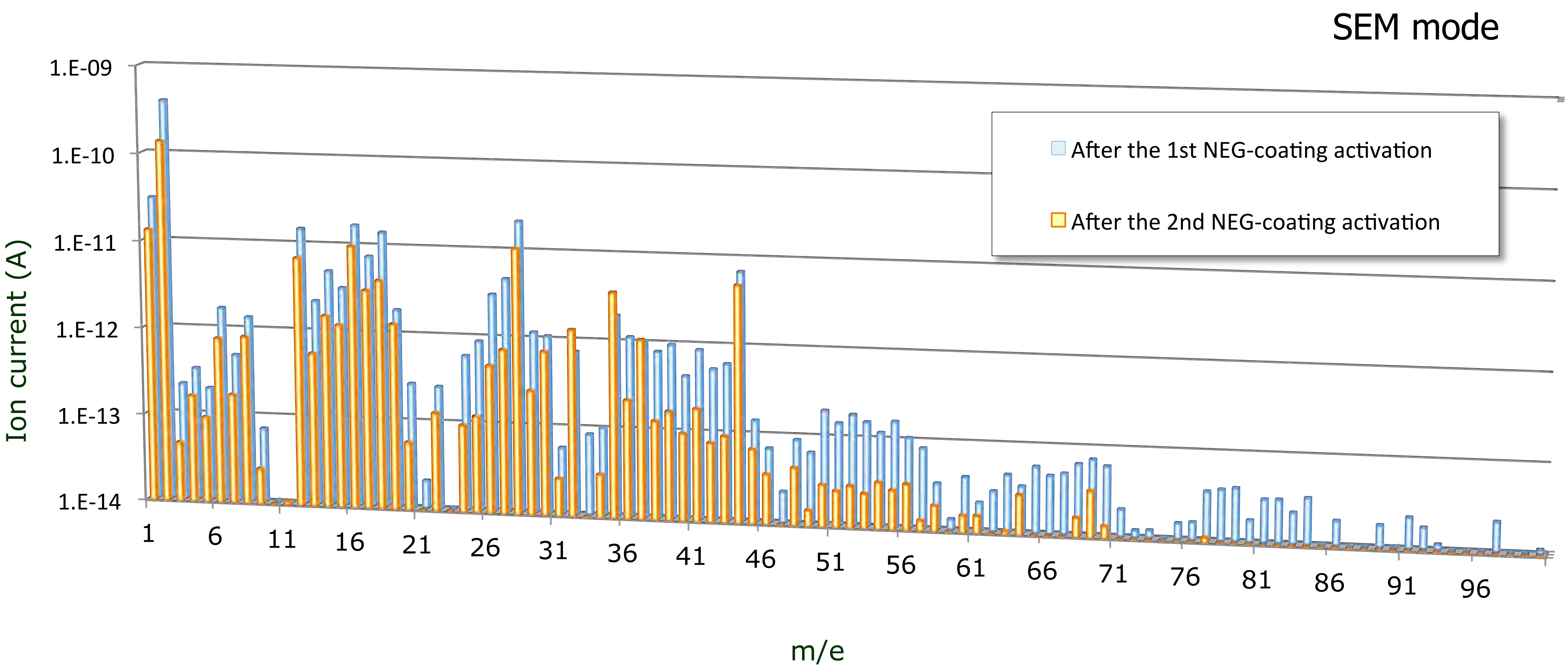



CS-Studio
119%
CSStudio
CCG_Graph.opi
cERL Vacuum (CCG ver)
2015/01/14 17:53:40
[Pa]
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
SP
HV
InjGunExG
InjMirExG
InjScrExG
CCG01
Injector line
CCG04
CCG05
CCG06
CCG07
CCG08
Diagnosis line
CCG52
CCG53
CCG02
CCG03
CCG09
CCG10
CCG11
CCG12
CCG13
MLSC Cav1
MLSC Cav2
CCG14
CCG15
CCG16
CCG17
CCG18
CCG19
CCG20
CCG21
CCG22
CCG23
CCG24
CCG25
CCG26
CCG27
CCG28
CCG29
CCG30
CCG31
CCG32
CCG33
CCG34
CCG35
CCG36
CCG37
CCG38
CCG39
CCG40
CCG41
CCG42
CCG43
CCG44
CCG45
CCG46
CCG47
CCG48
CCG49
CCG50
CCG51
Merger section
Dump chicane
1st Arc section
South straight section
LCS section
2nd Arc section
Return Loop section
CCG54
CCG55
CCG56
Dump line
tanimoto

NEG-coating Activation



Residual Gas Analysis



Hydrogen Equilibrium Pressure
- Sieverts' Law -

Hydrogen pumping by dissociative adsorption is reversible on NEG:

$$H_2(\text{gas}) \rightleftarrows 2H(\text{dissolved})$$

Sieverts' constant: $K_S = \frac{c_H}{\sqrt{p_{H_2}}}$

Changes in Gibbs energy under T = const.:

$$\Delta G = \Delta H - T\Delta S$$

$$\Delta G = -RT \ln K_S$$

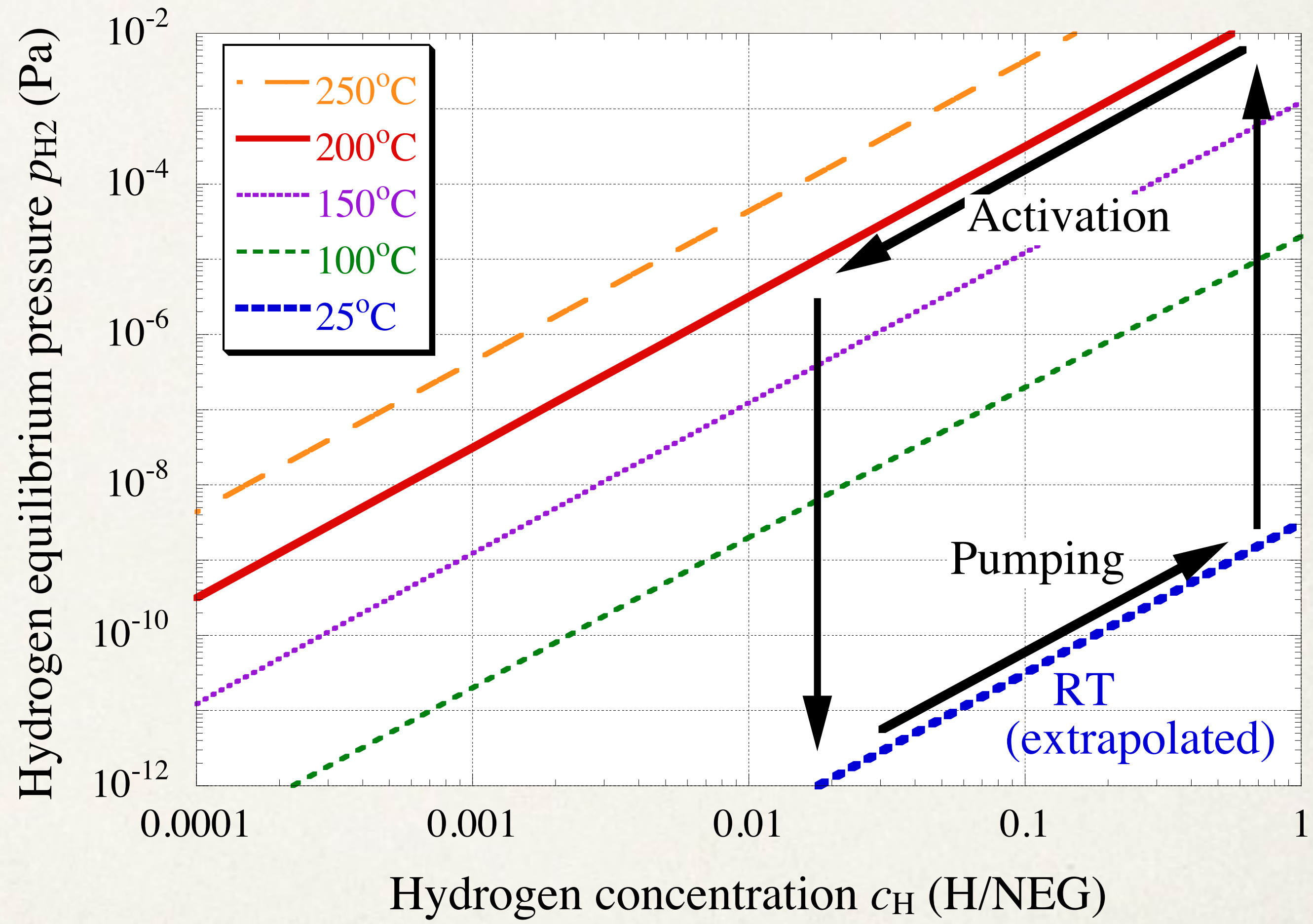
Sieverts' law gives the hydrogen adsorption isotherm:

$$\ln p_{H_2} = 2\left(\ln c_H - \frac{\Delta S}{R} + \frac{\Delta H}{RT}\right)$$

A. Rossi of CERN experimentally obtained ΔS and ΔH for NEG coating:

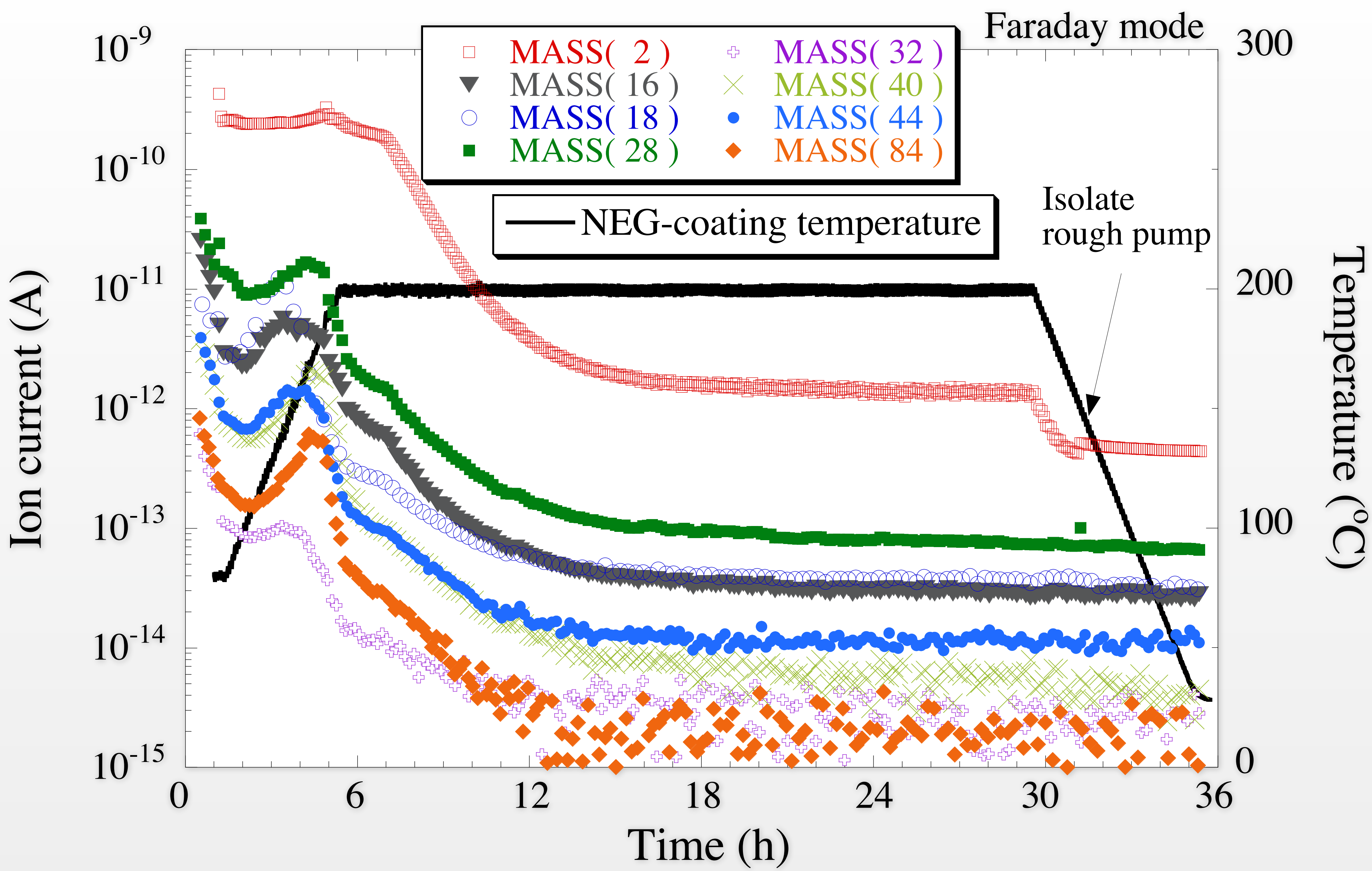
$$\Delta S = -100 \text{ J K}^{-1} \text{ mol}^{-1}$$

$$\Delta H = -54.0 \text{ kJ mol}^{-1}$$



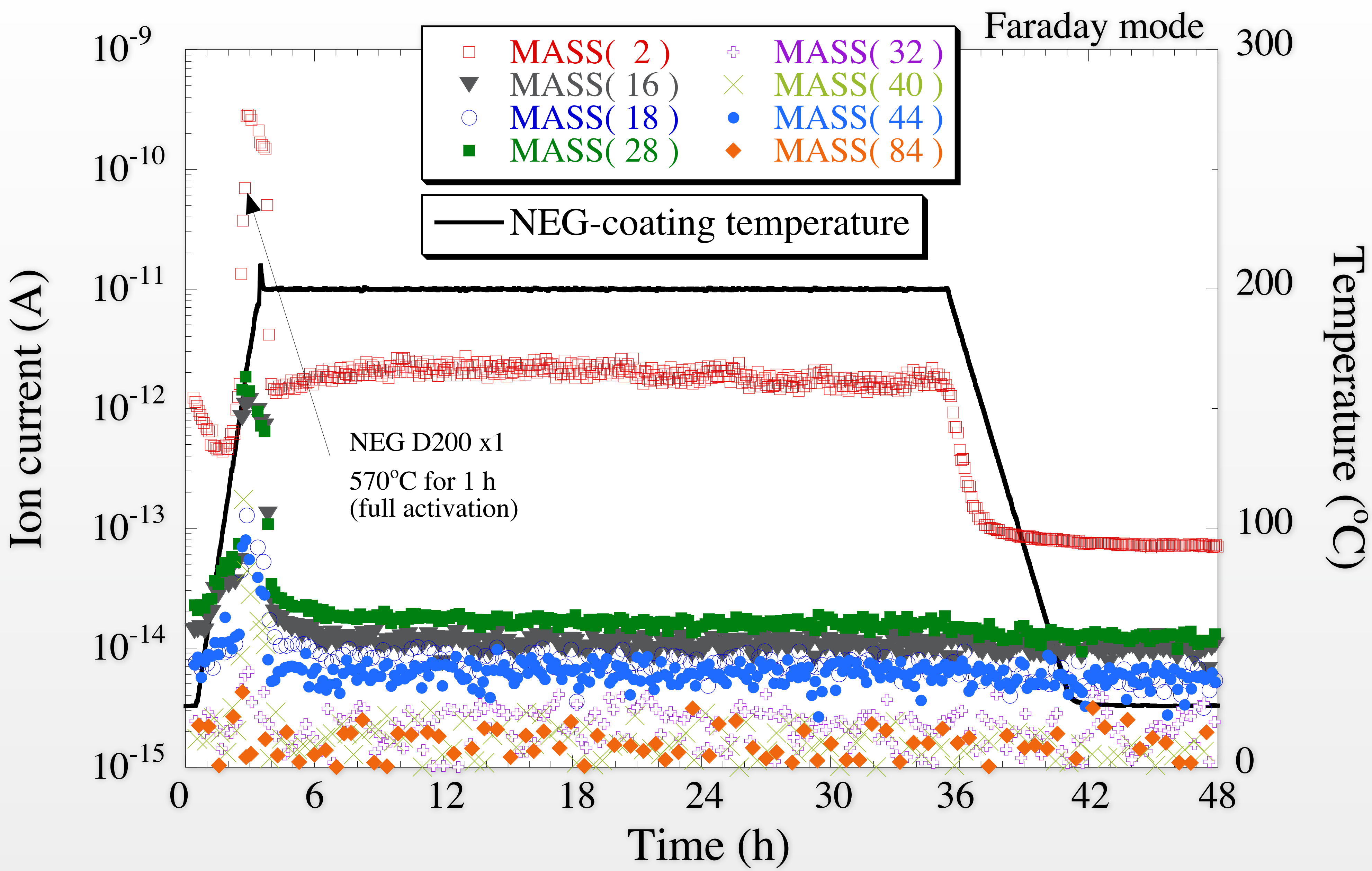
A. Rossi, "H_2 Equilibrium Pressure with a NEG-Coated Vacuum Chamber as a Function of Temperature and H_2 Concentration", Proc. EPAC06, p.1444.

Outgassing during NEG-coating Activation (first time)



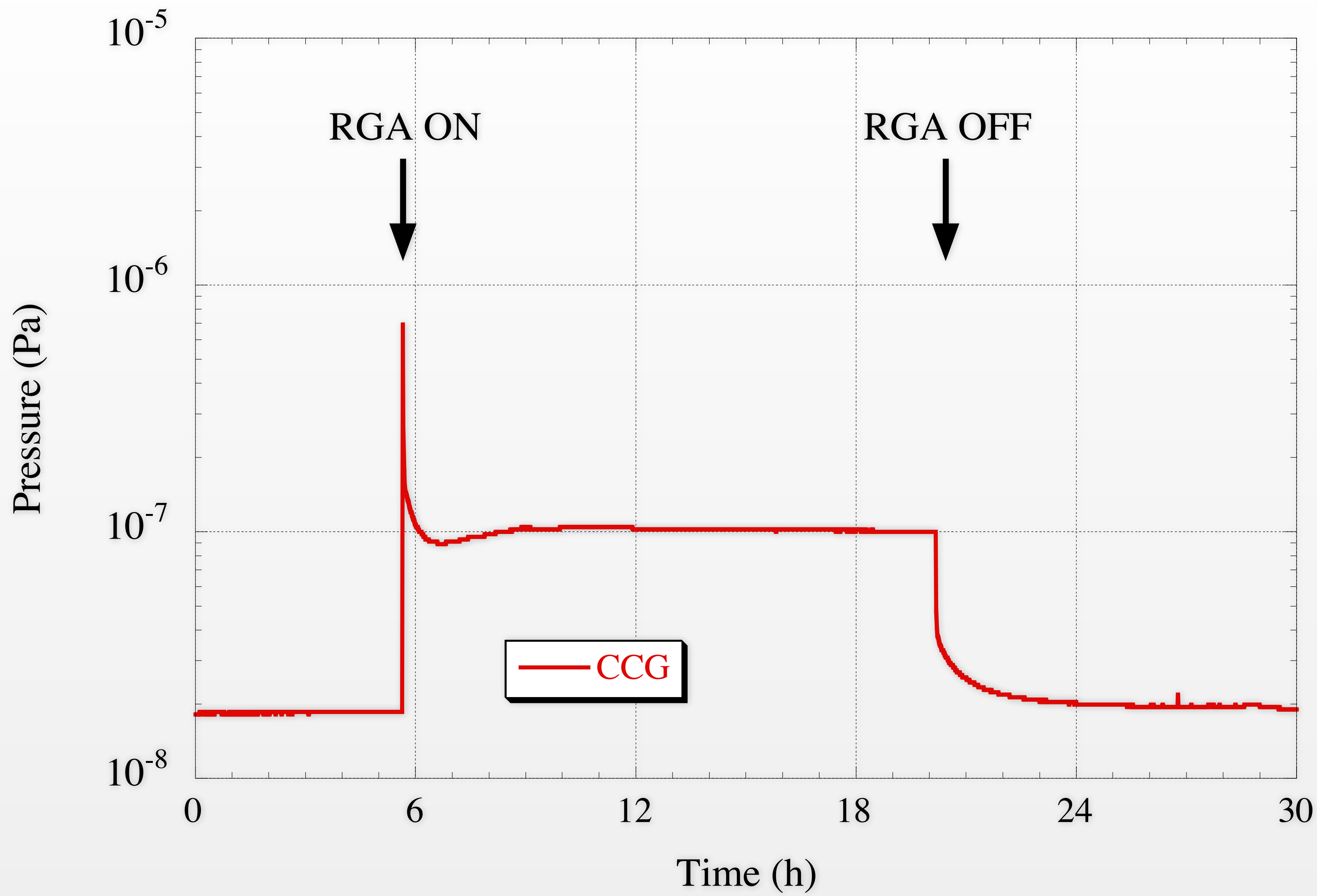
Two-order decrease in the hydrogen pressure

Outgassing during NEG-coating Activation (second time)



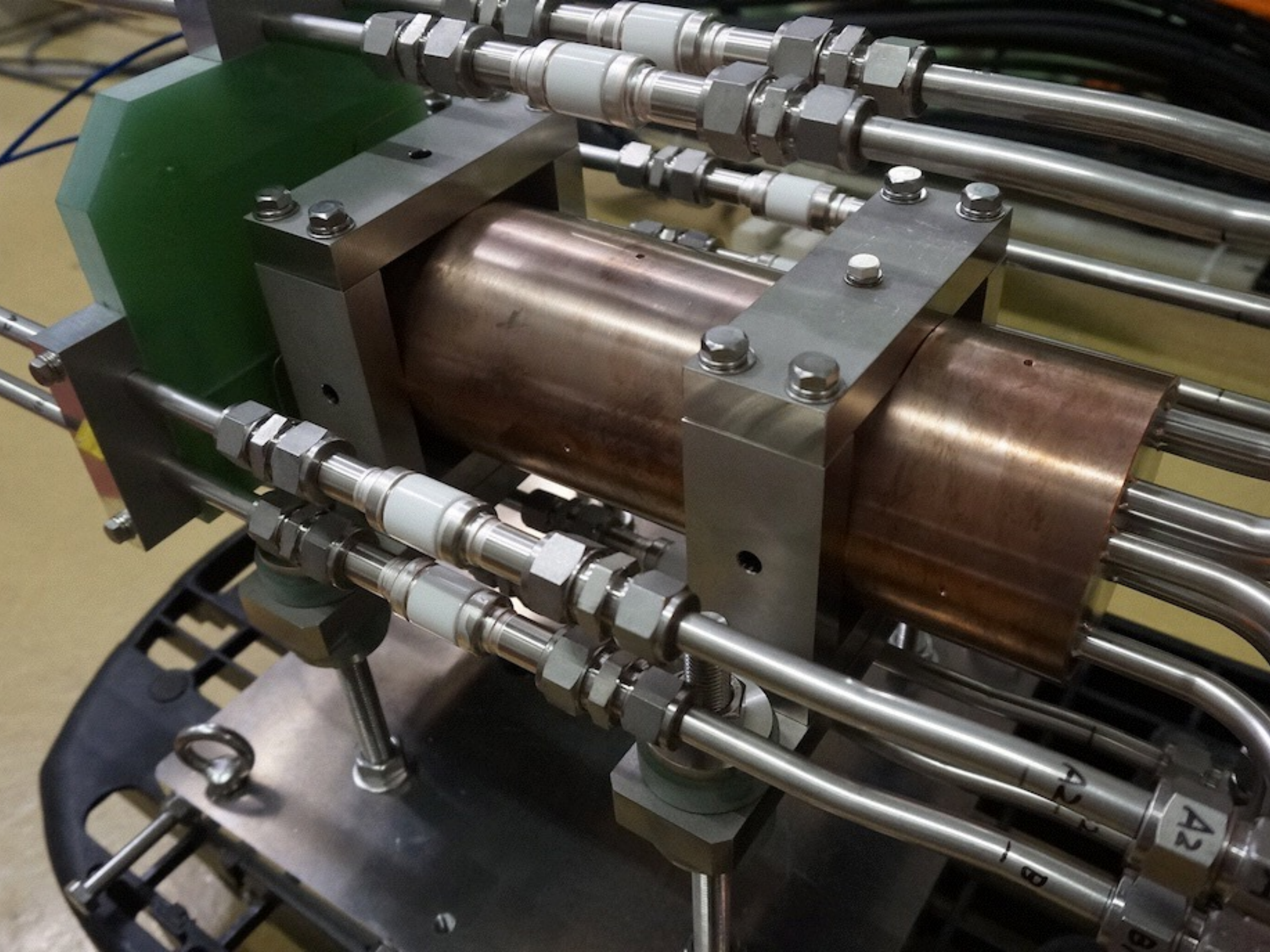
No decrease in the hydrogen pressure

Outgassing from the RGA



The RGA was identified as the main outgassing source.

Main beam dump


A2

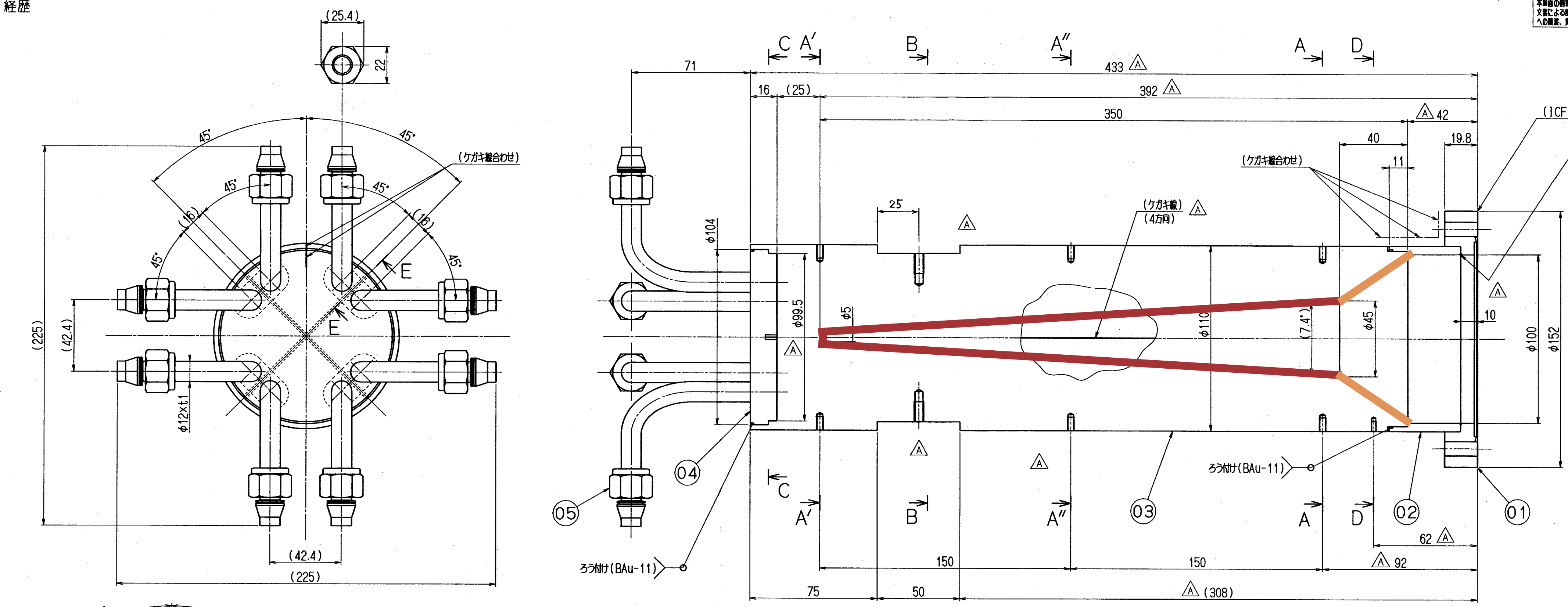

cERL-C17
14.7t
cERL-C18
14.7t
浅岡

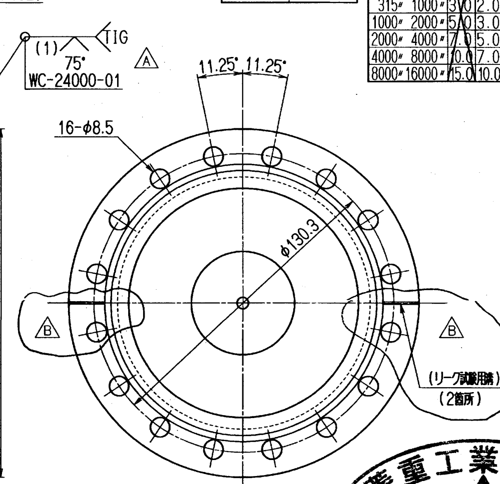
本図面の情報は三菱重工業(株)の財産であり、文書による許可なしには、いかなる複写、他人への譲渡、貸出しならびにその使用を禁ずる。	スペック番号	スペック名称	審査完了確認	2013.9.25 井上

表面粗さ	
記号	Ra
▽▽▽▽	0.2a以下
▽▽▽	1.6a以下
▽▽	6.3a以下
▽	12.5a以下

普通寸法許容差（溶接構造物）

呼び寸法の区分	寸法許容差 一般	寸法許容差 特殊
1以上 120以下	±1.5	±1.2
120をこえ315以下	2.0	1.5
315〃 1000〃	3.0	2.0
1000〃 2000〃	5.0	3.0
2000〃 4000〃	7.0	5.0
4000〃 8000〃	10.0	7.0
8000〃 16000〃	15.0	10.0





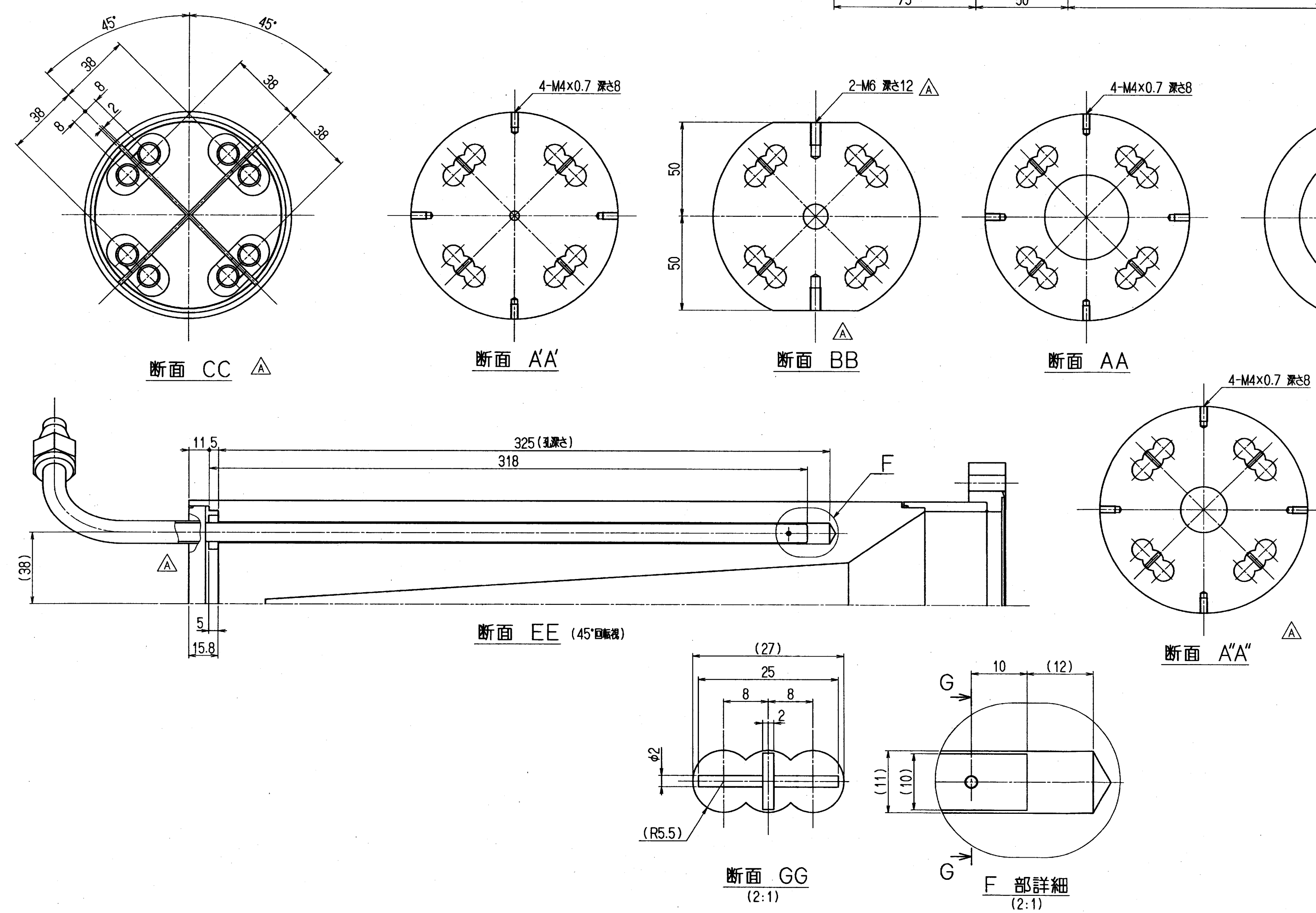
溶接線明細表

溶接線番号	溶接施工法	検査手順
WC-24000-01	TIG	VT

KEK殿御承認欄

承認申請図

設計外注品



注意事項

1. 本部品は酸化しやすい為、取り扱いには十分注意し、素手でさわらないこと。
2. 本部品は非常に変形しやすいので、加工・組立ての際大きな力を加えぬこと。
3. フランジのシール面は、傷つかぬように十分注意すること。
4. 本製品は、超高真空部品(到達真空度：1×10^{-7}Pa以下)であるので取り扱いには十分注意し、ビームダンプ内面には油分、塵、埃等の異物が付着せぬよう清浄な環境で組立を行い、素手で触れないよう注意すること。
5. 冷却水路の耐圧強度は、1.0MPa以上とする。
6. 本部品の許容リーク量は1.0×10^{-10}Pa・m^3/s以下とする。
7. ⑫⑬をろう付け後、⑪をTIG溶接のこと。
8. 必要に応じ蓋ろう付面にはNiメッキ(5~7μm)を施工すること。

番号	名称	数	予備数	材質	符号	寸法	図面番号	重量	記事
05	ナット&フェルール・セット(φ12)	8		SUS316				0.030×8=0.24	Swagelok SS-12M0-NFSET
04	ビームダンプ蓋部分組立品	1		SUS304 △A			E3-24001	1.44	△A
03	胴部(2)	1		アルミナ分散強化銅(GLIDCOP AL-15)			E3-24002-03	25.7	
02	胴部(1)	1		SUS316L			E3-24002-02	0.50	
01	フランジ(ICF152)	1		SUS316L			E3-24002-01	1.10	
—	ビームダンプ組立品	1		—				29.0	△A

符号	理由	アイテム確認	処置	年月日	点検	工事番号
B2	⑪リーク溝追加	未着		H25. 9.20	井上 原	496420
A21	部品図修正の反映 ケガキ線追加 断面BB見直し	未着		H25. 9.12	仙入 原	496420

名称：ビームダンプ 組立図

認可	検図	製図	尺度	第三角法	形式またはM/C NO.	図番
仙入	原	MMS 伏野	1:1.5		次世代光源用ビームダンプ	E3-24000

訂正 型 B 1

作成日 2013. 9. 9 加速器設計課

廃却日

三菱重工業株式会社

三菱重工業株式会社 '25. 9. 25 加速器設計課 先端機器事業推進

加速器設計(客先) ② ③ 加速器設計(メーカ) ① ①

合計 3+6+3

工事番号 496420

注主 KEK殿

製作台数 1

1台分個数 —

親図面番号 —

図面表番号 J496420

出図 25.9.25

L-E3-24000-2

【許容応力】

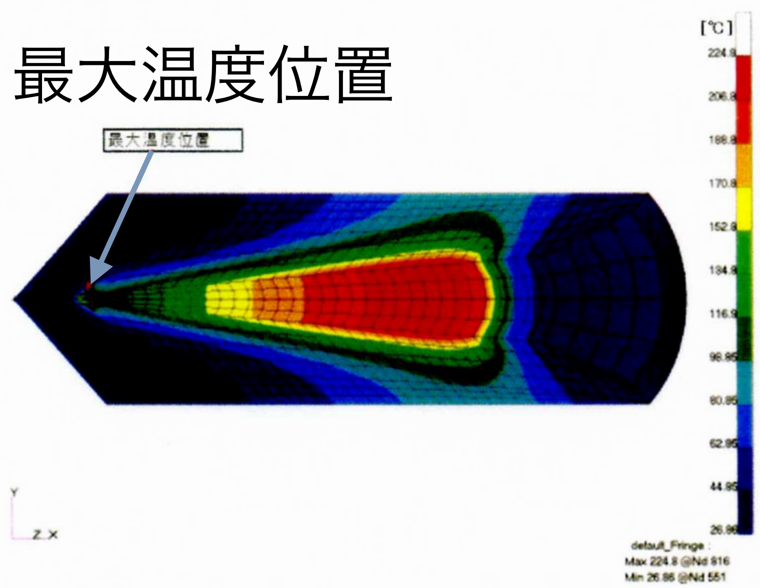
- JIS B 8266:2003（圧力容器の構造－特定規格）を参考に，基本許容応力 Sm は「常温及び設計温度における材料の引張強さの 1/4，又は 0.2%耐力の 1/1.5 のうちの最小値」と設定します。
- また，温度荷重による応力を評価する為，応力許容限界は 3Sm と設定します。

	GlidCop AL-15			
温度	引張強さ※ [N/mm^2]	0.2%耐力※ [N/mm^2]	基本許容応力 Sm [N/mm^2]	応力許容限界 3sm [N/mm^2]
25	414	352	103.5	310.5
100	364	330	91	273
200	330	300	82.5	247.5
300	292	278	73	219
400	264	250	66	198
500	257	232	64.3	192.9
600	230	220	57.5	172.5

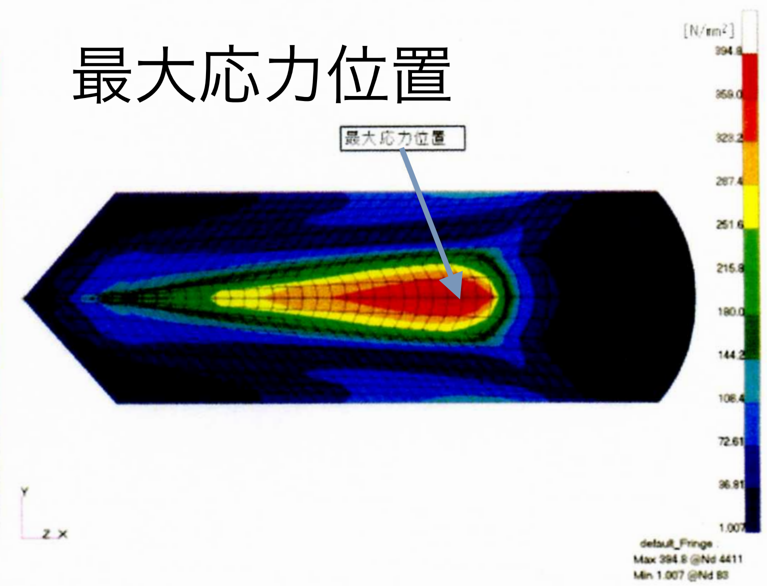
※出典：メーカカタログ

3.3 ビームサイズφ40mm

(1) 代表として，60kW 入熱の場合の発生温度，発生応力コンター図を以下に示します。

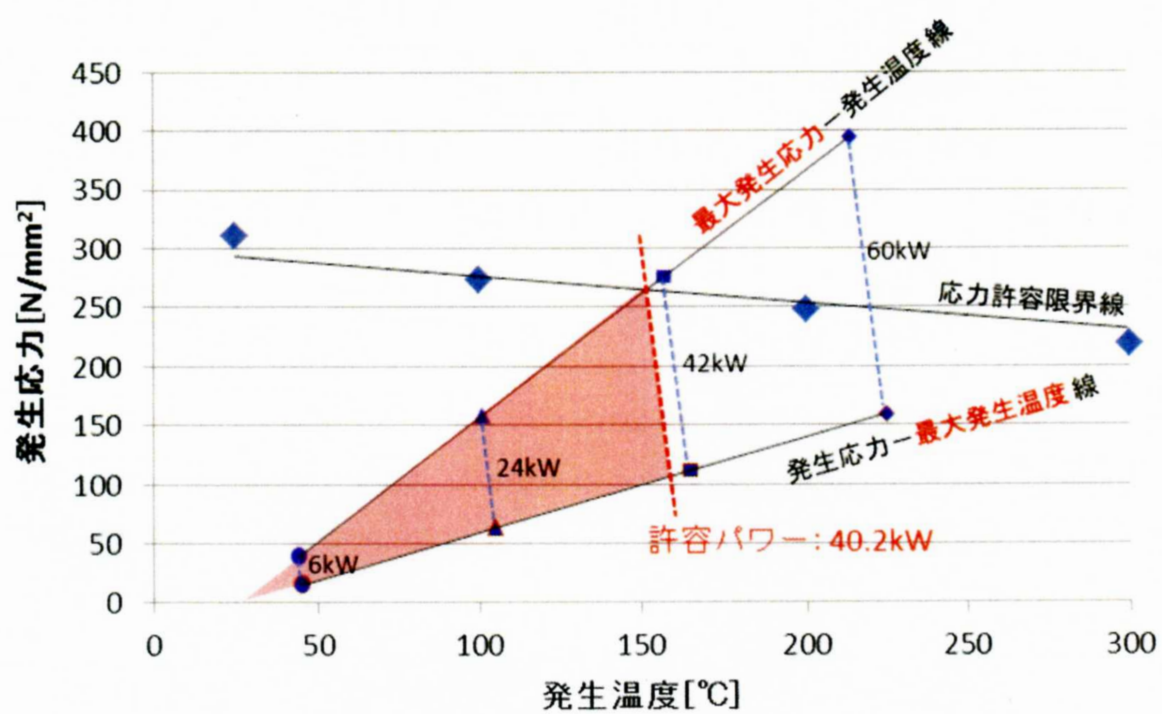


発生温度コンター図
（最大発生温度 224.8℃）



発生応力コンター図
（最大発生応力 394.8N/mm²）

(2) ビームパワーを 6～24～42～60kW と変えて解析を行った結果，発生温度，発生応力の関係は下図の通り，比例関係にあることを確認しました。
同関係図に 2 項「許容応力」にて設定した応力許容限界をプロットした結果，現計画形状及びビームサイズφ40mm において，許容ビームパワーは 40.2kW と確認できました。



発生応力ー発生温度　線図

260 N/mm²
@150℃

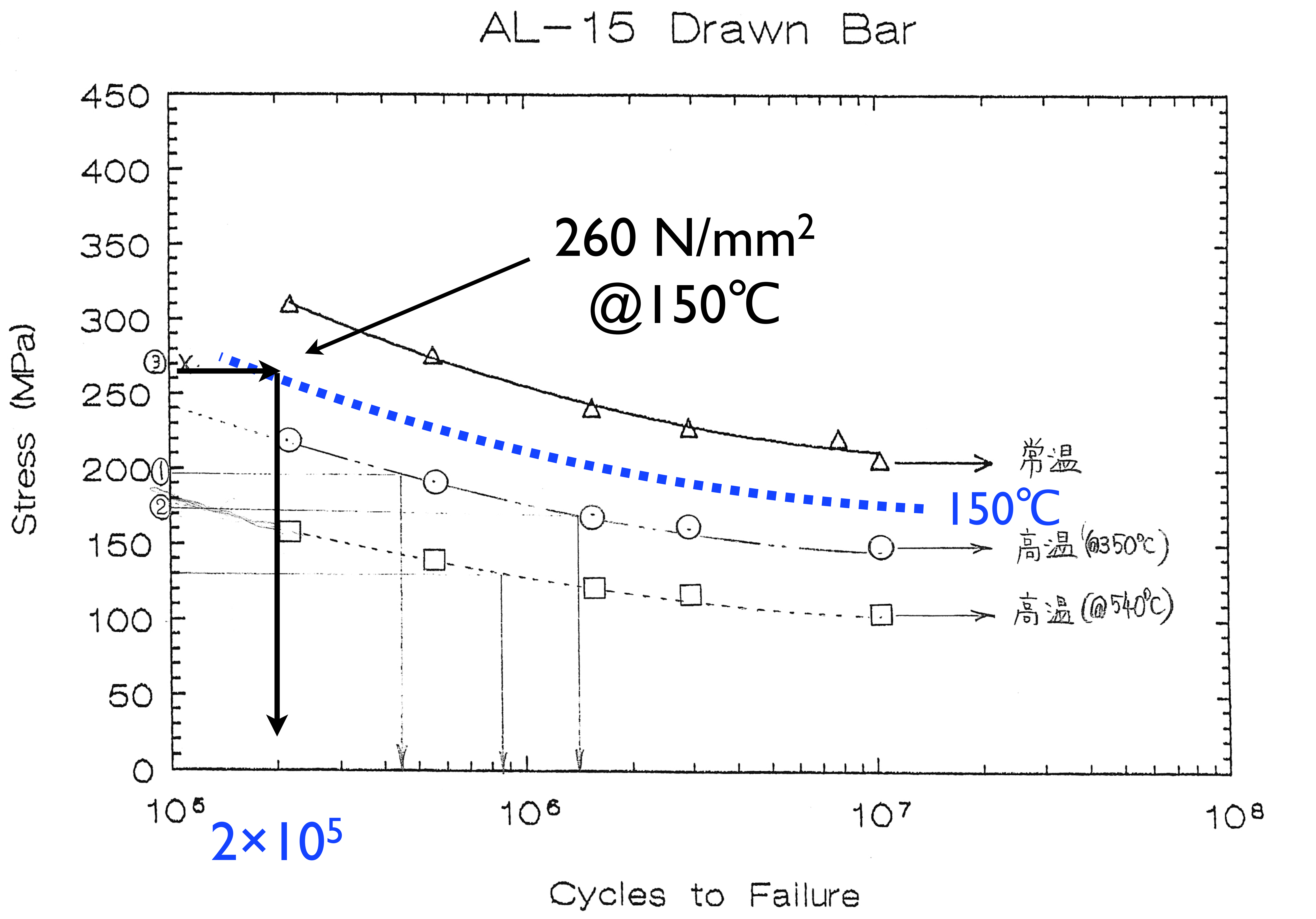


図 12. アルミナ分散強化銅（AL-１５）の疲労曲線

C.05.01.E

1. ビーム径と許容ビームパワー

ビーム径 (mm)	許容ビームパワー (kW)	許容ビーム電流@5MeV (mA)	最大発生応力 (N/mm^2)	最大応力点温度 (℃)	パワー密度 (W/mm^2)
φ20	14	2.8	260	150	3.2
φ30	25	5.0	260	150	2.5
φ40	40	8.0	260	150	2.3
φ45	(50)	10.0	(260)	(150)	2.2

2. 熱サイクルによる寿命

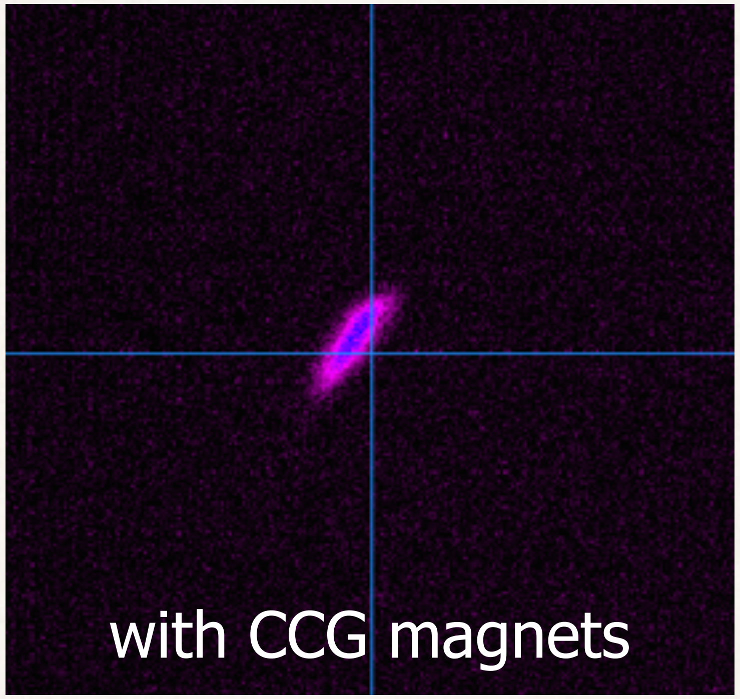
発生応力260N/mm^2、発生温度150℃の場合、約20万回と推測される

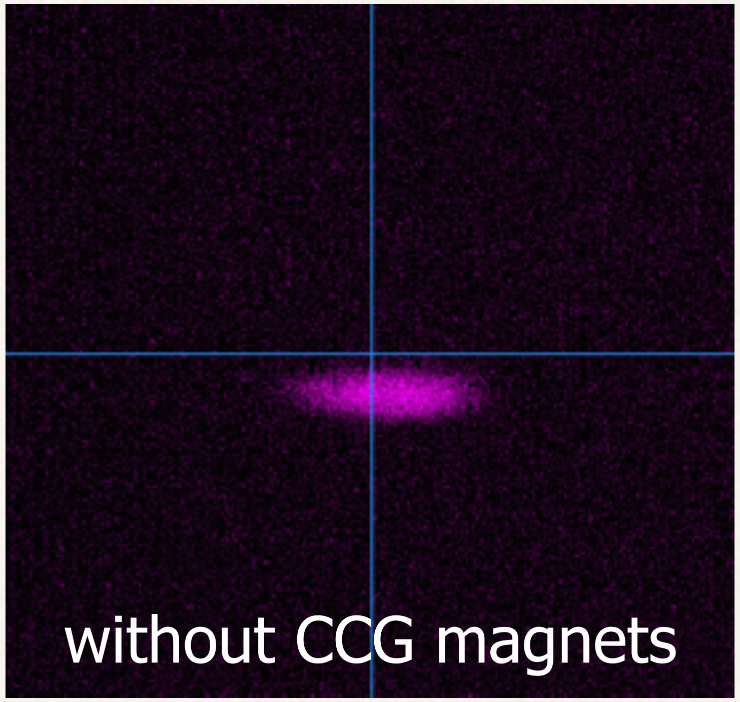
3. 今後の予定

600kW (6MeV-100mA) に対応したビームダンプの設計

Operational Problems

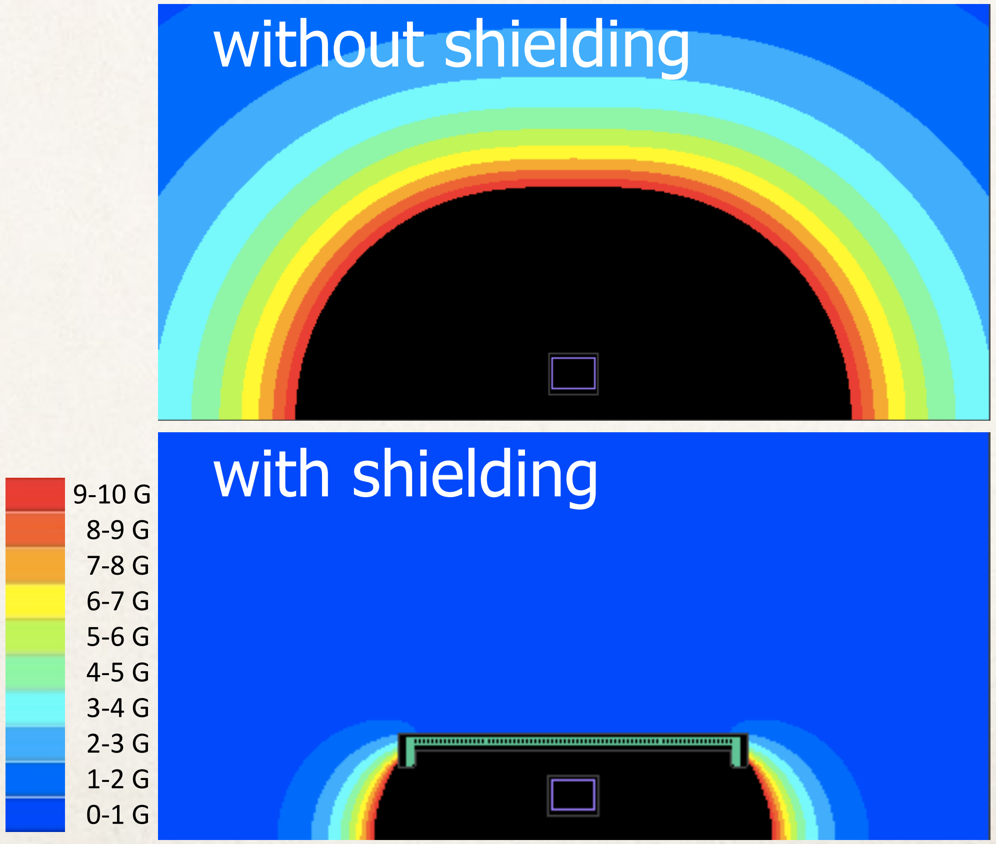
Influence of CCG Magnets on Low Energy Beams



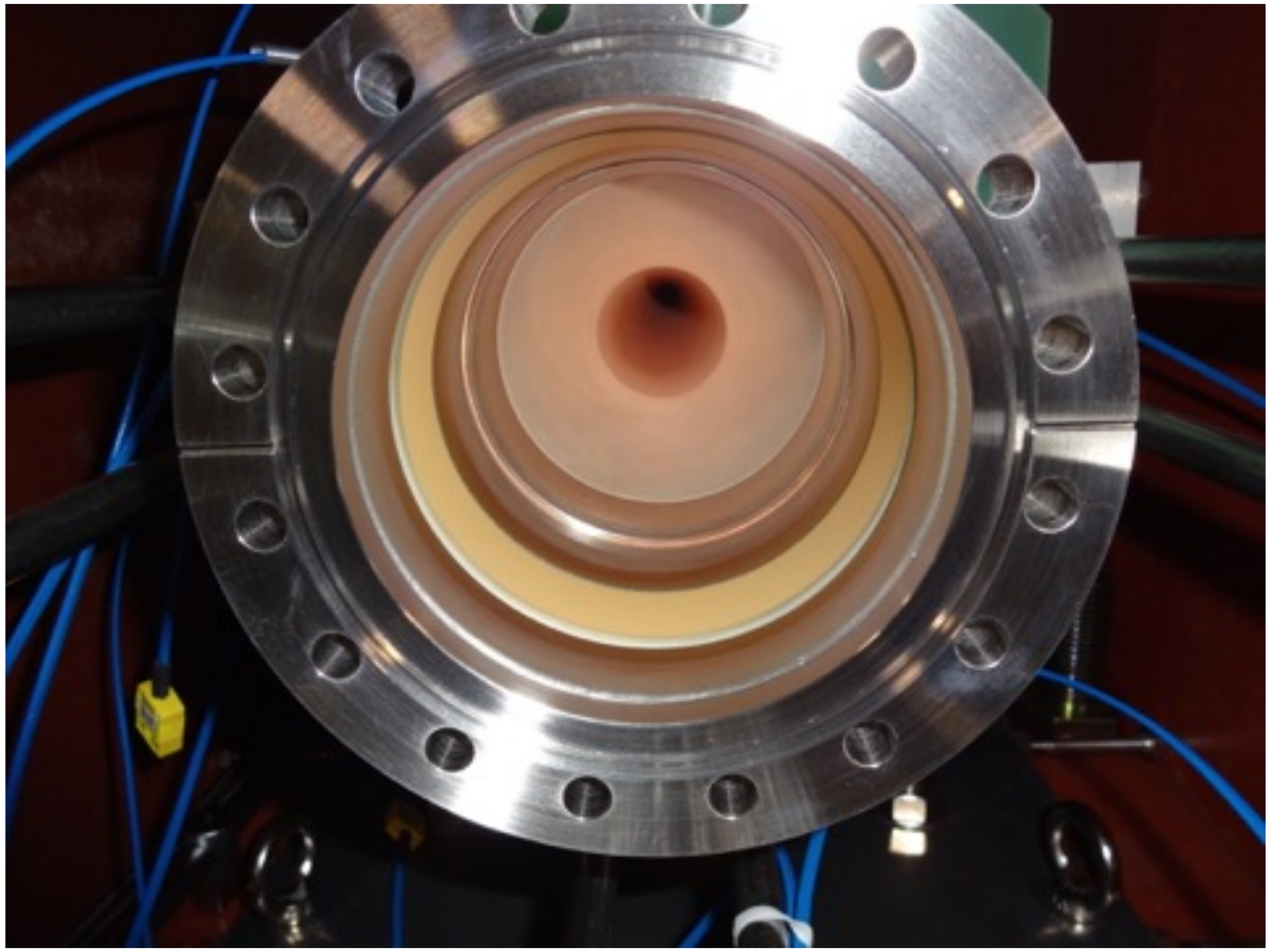


Magnetic shielding:

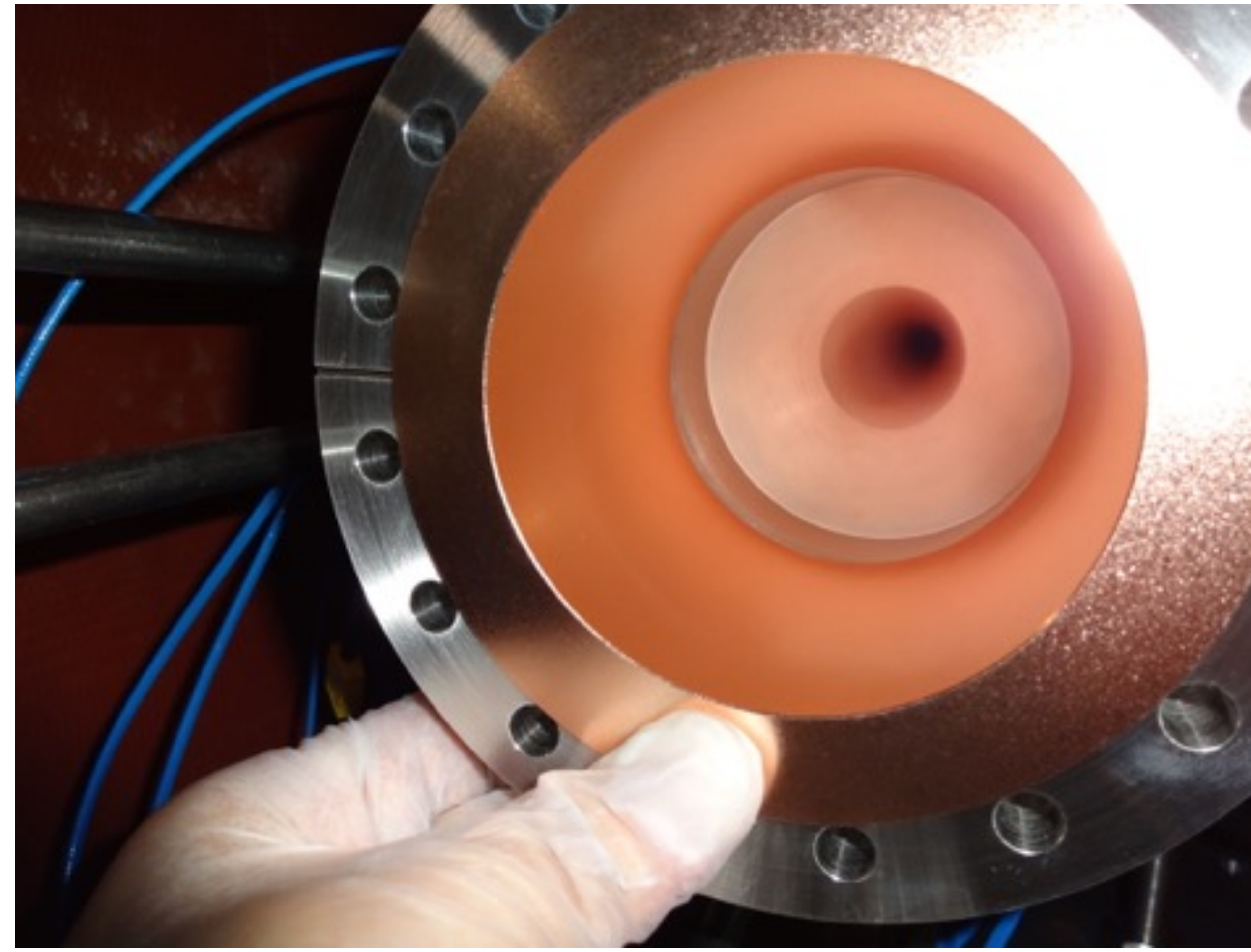
- permalloy PC
- 3 mm thick
- B@beam < 1/10
- pressure reading drop < 10%



主ビームダンプ部の突発的な圧力上昇



主ダンプ前セラミックダクト
内径φ100, 長さ100
（セラミック長30）
TiNコーティング 10nm



セラミックガード取り付け
無酸素銅
内径φ88, 外径φ96, 長さ90

Summary

- The cERL vacuum system was designed to circulate high charge and short bunch electron beams without degrading the low beam emittance.

- Several low impedance vacuum components, namely, impedance-free flanges and movable monitors with RF-shielding, were specially developed for the cERL.

- NEG-coated tubes were installed to pump the sections adjacent to the SC cavities down to 1×10^{-8} Pa. Their performances were evaluated by outgassing measurements during activation.

- The main beam dump was manufactured based on thermal-structural analysis. It can absorb 40 kW (e.g. 8 mA at 5 MeV) electron beams with a diameter of 40 mm up to about 2×10^{5} cycles.

- CCG's permanent magnets were found out to influence the low energy beams, and specially designed magnetic shields were applied to 50 CCGs.

- The cERL vacuum system has contributed to the successful commencement of machine commissioning. Performance of the vacuum components will be examined further in the future upgraded operations.

Thank you for your attention.