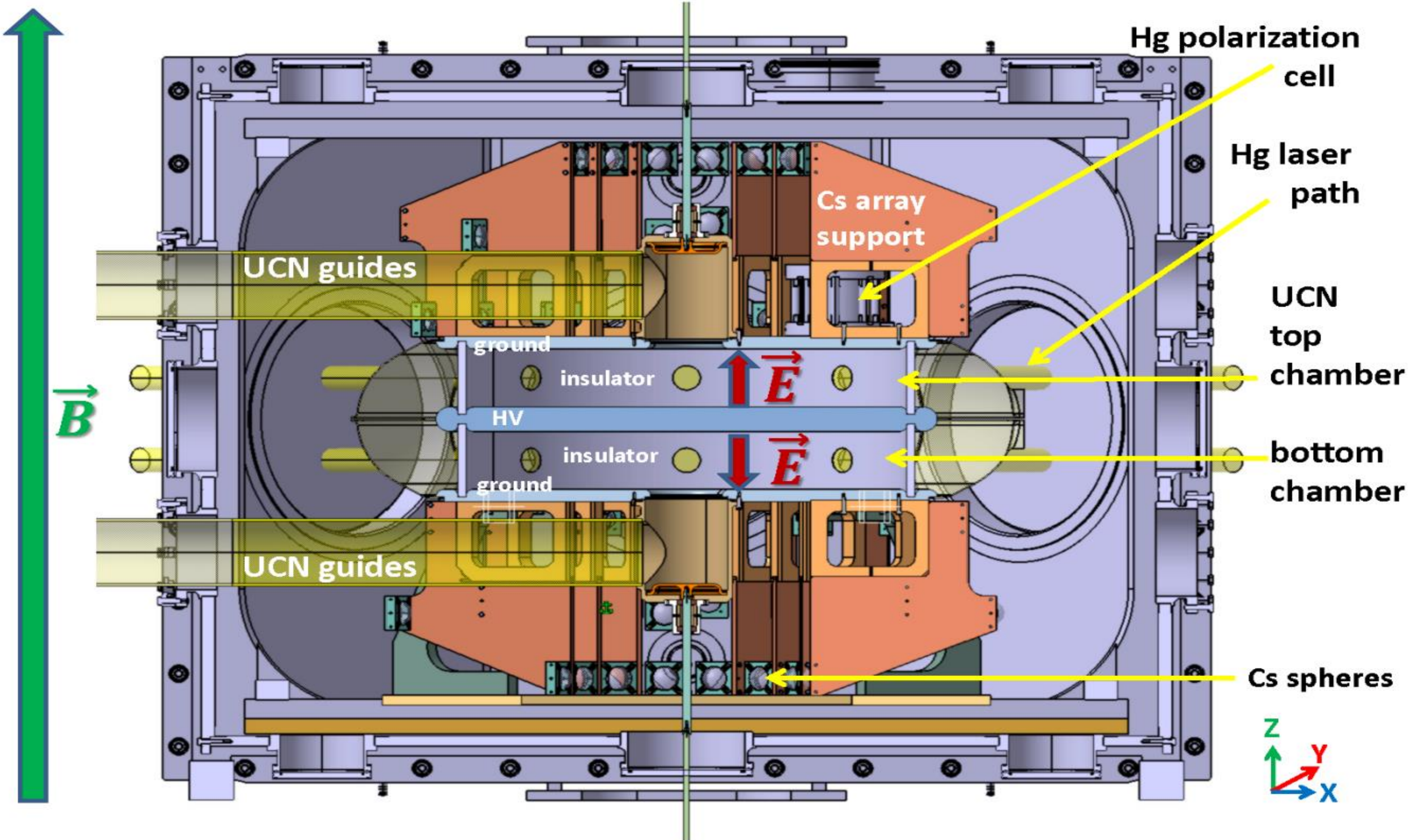
n2EDM HV

JACOB THORNE

Design goal

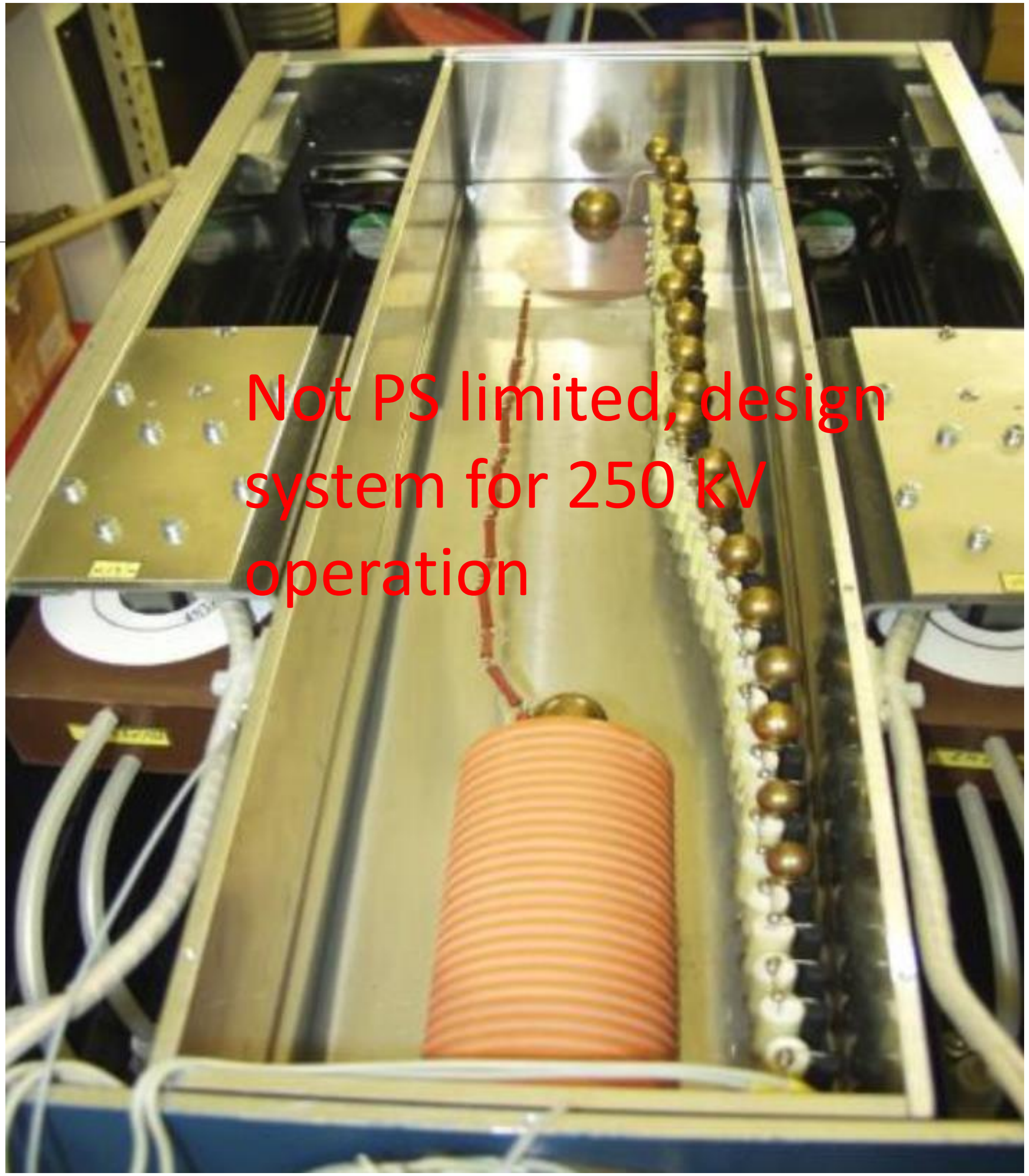
180kV
operation

	nEDM 2016	n2EDM baseline	n2EDM future
chamber	DLC & dPS	DLC & dPS	DLC & dPE
diameter D	47 cm	80 cm	100 cm
N (per cycle)	15'000	121'000	400'000
T	180 s	180 s	180 s
E	11 kV/cm	15 kV/cm	15 kV/cm
α	0.75	0.8	0.8
$\sigma(f_n)$ per cycle	9.6 µHz	4.5 µHz	2.5 µHz
$\sigma(d_n)$ per day	11×10^{-26} $e\cdot$cm	2.6×10^{-26} $e\cdot$cm	1.4×10^{-26} $e\cdot$cm
$\sigma(d_n)$ (final)	9.5×10^{-27} $e\cdot$cm	1.1×10^{-27} $e\cdot$cm	0.6×10^{-27} $e\cdot$cm


Hg polarization cell
Hg laser path
UCN top chamber
bottom chamber
Cs spheres
Cs array support
UCN guides
UCN guides
ground
insulator
HV
insulator
ground
$\vec{E}$
$\vec{E}$
$\vec{B}$
Z
Y
X

Power supply

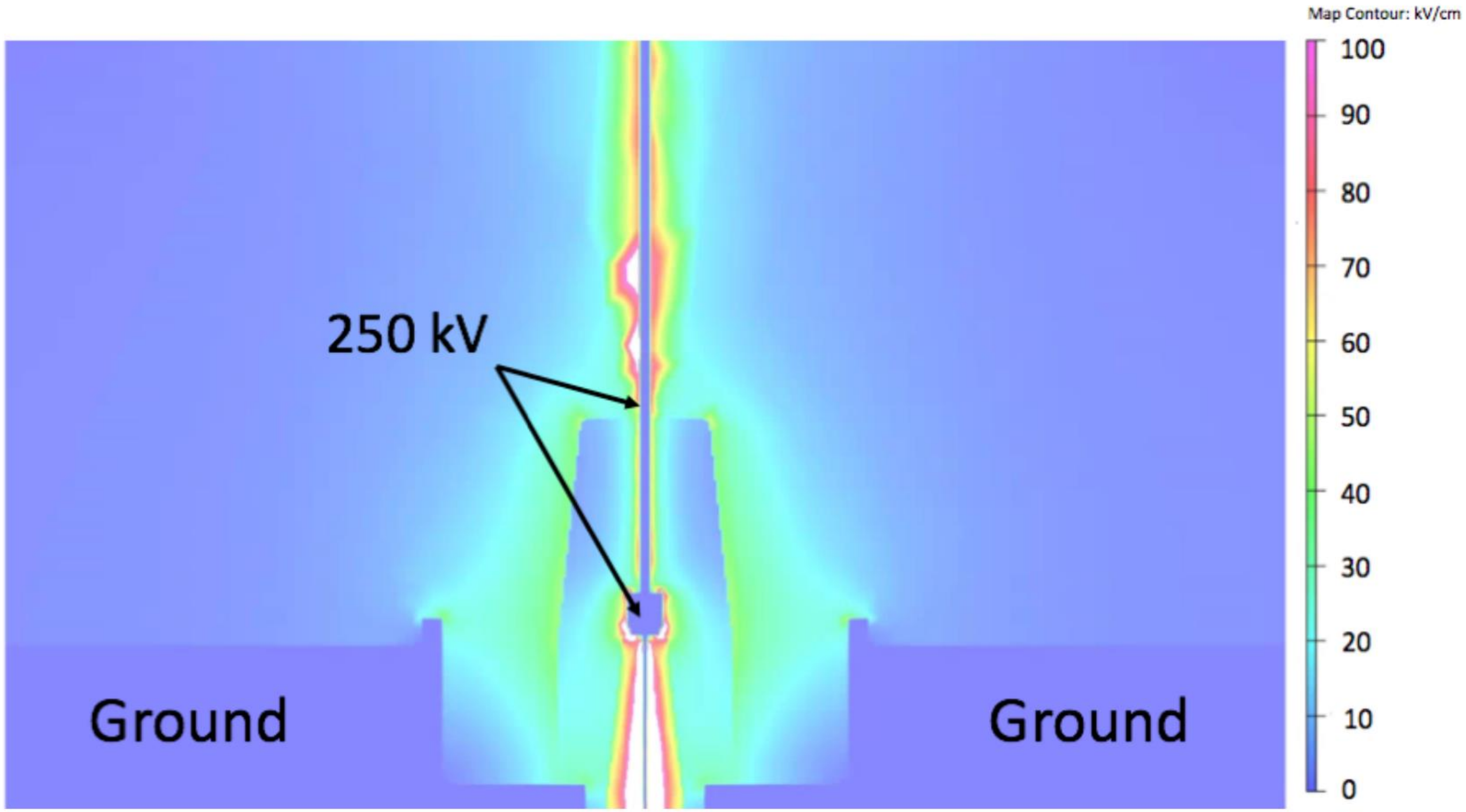
Max voltage:	$\pm 250\,\mathrm{kV}$
Current ranges:	$\pm 200\,\mu\mathrm{A}$
Voltage stability	$\leq \pm 1 \times 10^{-4}$ in 8h and $\leq \pm 1 \times 10^{-4}\mathrm{K}^{-1}$
Voltage ripples	$< 1\,V_{\mathrm{pp}}$
Max Ramp speed	$5\,\mathrm{kV/s}$
$\lvert E_{\max} \rvert - \lvert E_{rmmin} \rvert$	$\leq 100\,\mathrm{V}$
Oil free connection	
Switch for current range $200\,\mu\mathrm{A}/200\,\mu\mathrm{A}$	
Optical RS232 interface	
Remote control of interlock	
Current mode	

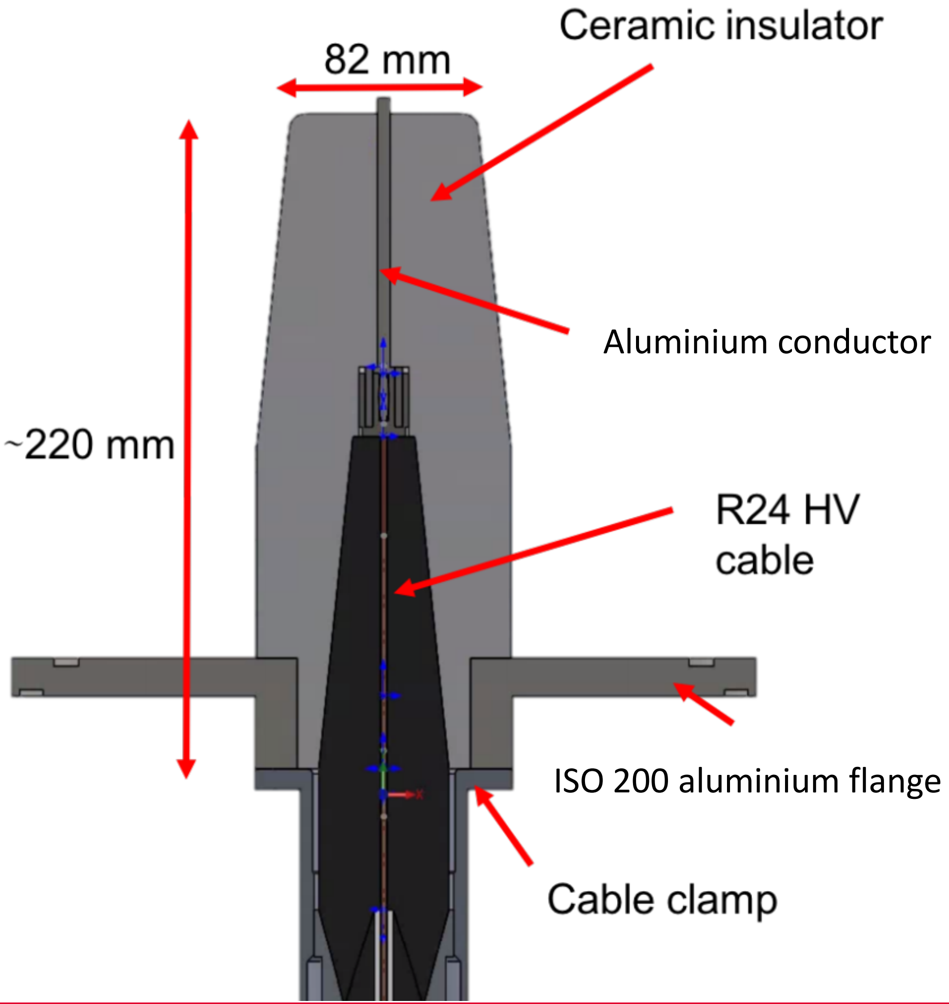


R24 HV cable

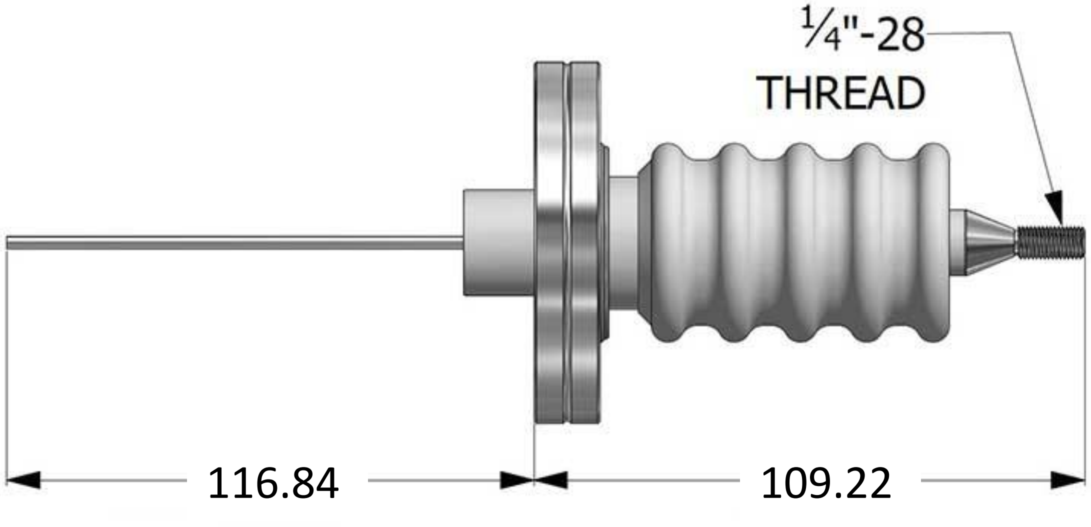
	P3/250
Rated voltage	250 kVDC
Nominal outside diameter	36 mm +/– 1.5
Coverage shielding braid	>80%
Conductor resistance Bare Conductor @ 20°C	6.6 mΩ/m
Conductor resistance Red & White Cond. @ 20°C	11.4 mΩ/m
Minimum bending radius (dynamic / stationary)	144 mm / 72 mm
Insulation resistance (wires to shield)	$\geq 1 \times 10^{12}$ Ω·m
Capacitance (wires to shield)	107 pF/m
Max. operating temperature	+70° C
Bending radius (stationary)	2 x D
Bending radius (dynamic)	4 x D

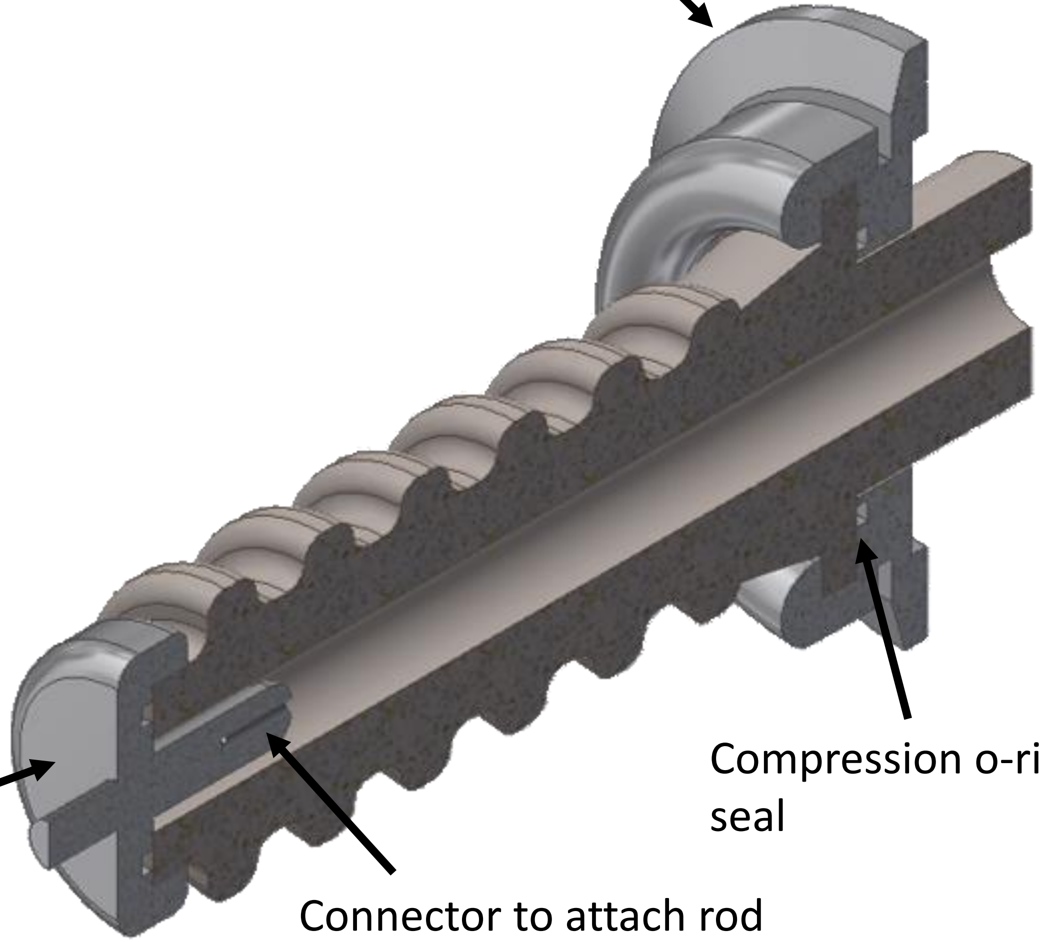
Custom HV feedthrough





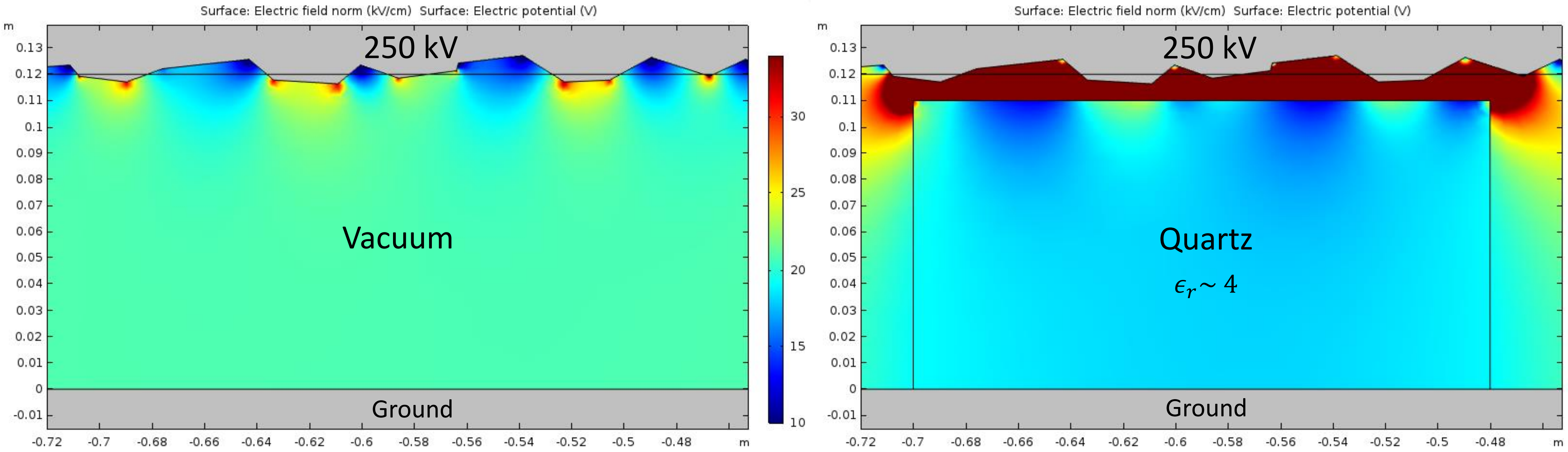
Prototype 50 kV feedthrough

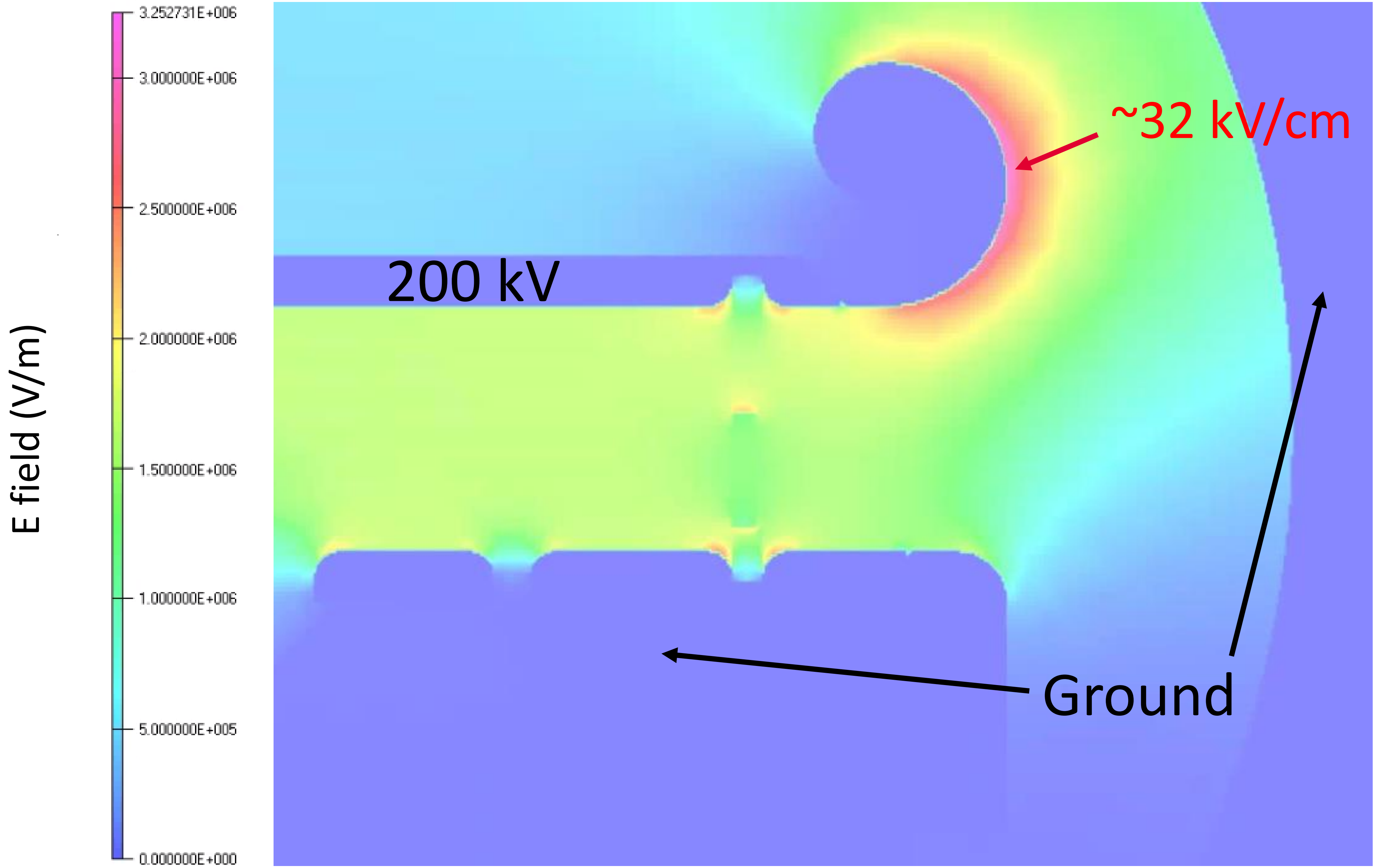




Possible ‘limitations’ in precession chamber E field

- nEDM capable of achieving ±200 kV without breakdown.
- Unknown how much higher we can achieve: possibly limited by CTJ, surface area effect, or from other unknown processes.
- Optimisation of precession chamber is required for 250 kV operation.




E field (V/m)
3.252731E+006
3.000000E+006
2.500000E+006
2.000000E+006
1.500000E+006
1.000000E+006
5.000000E+005
0.000000E+000
200 kV
~32 kV/cm
Ground

Precession chamber

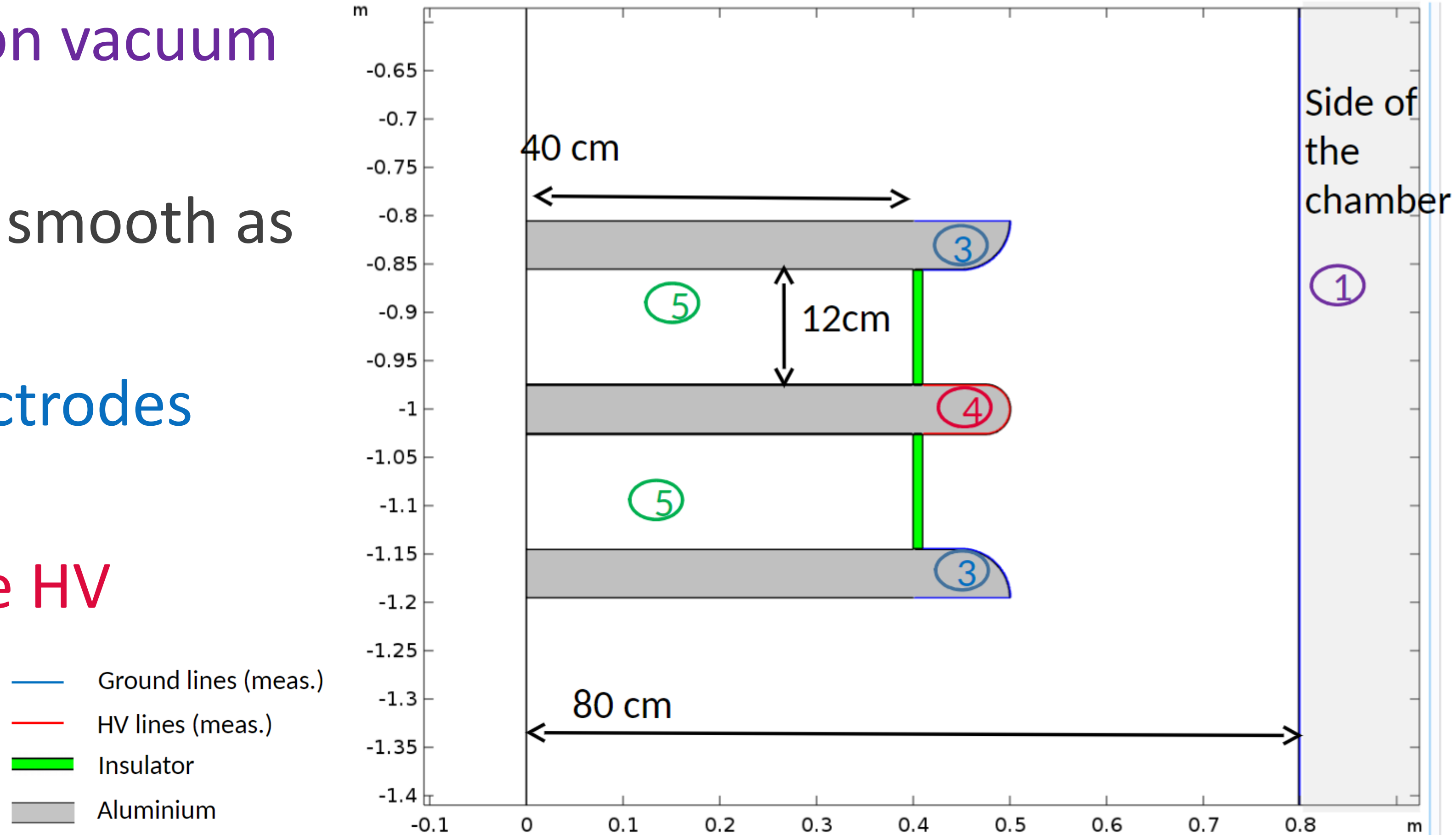
1. Avoid sharp edges on vacuum wall

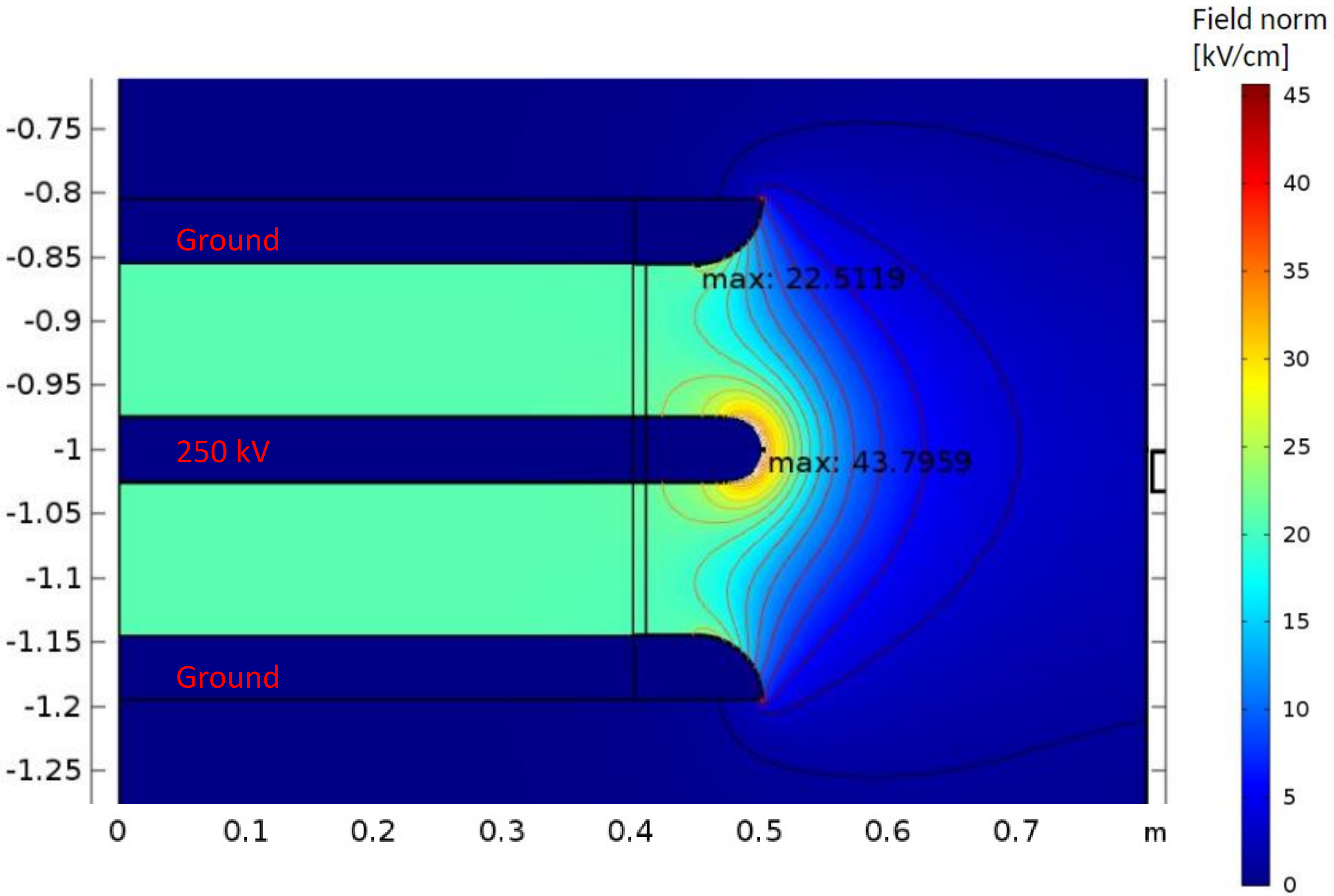
2. Electrode surface is smooth as possible

3. Field on ground electrodes minimal

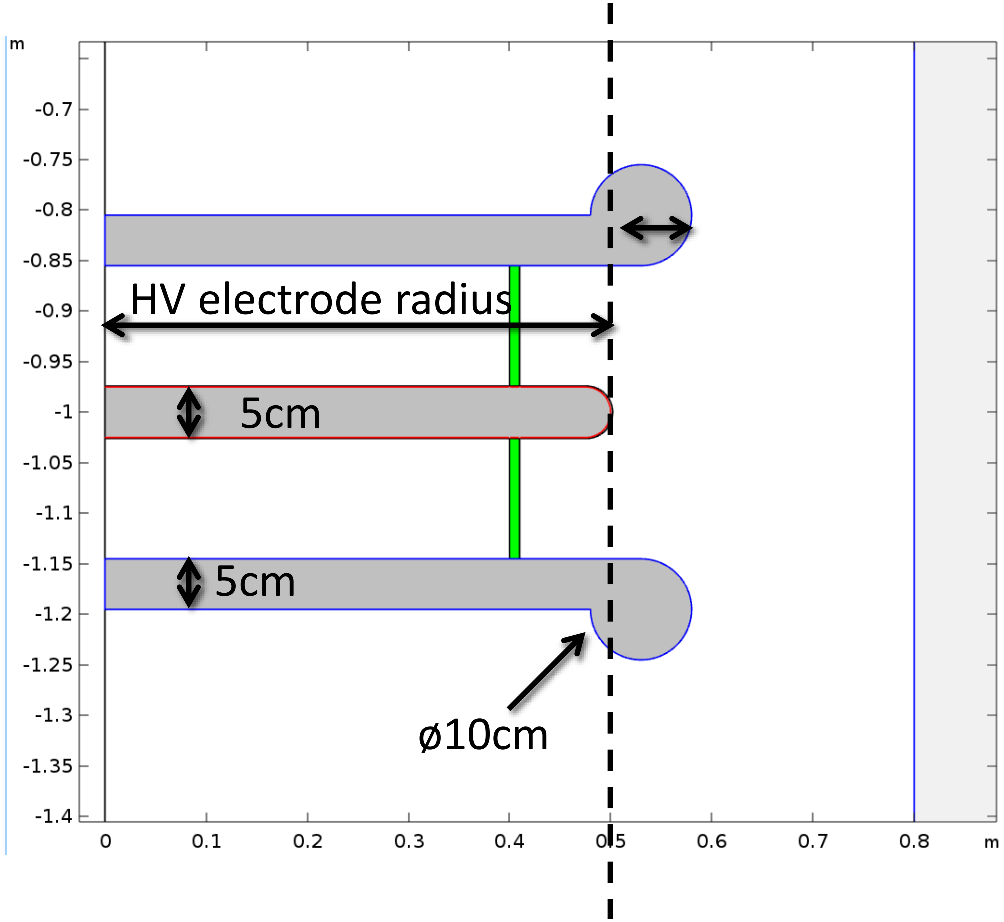
4. Minimal field on the HV electrode

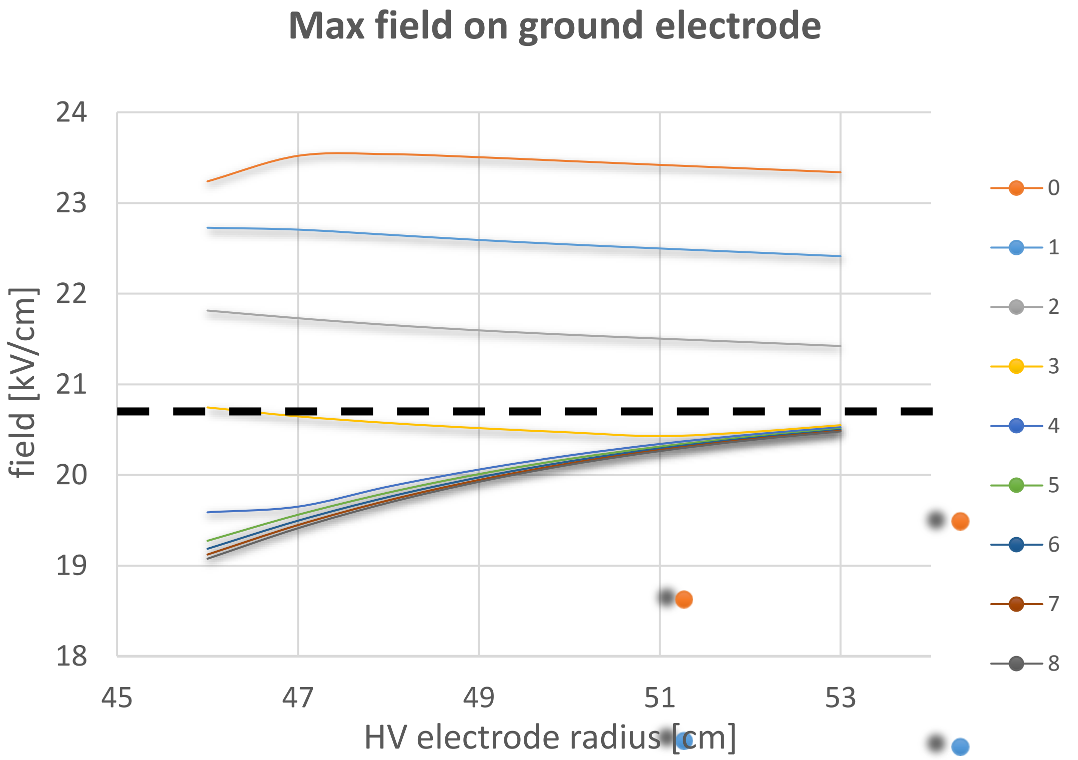
5. Homogeneity

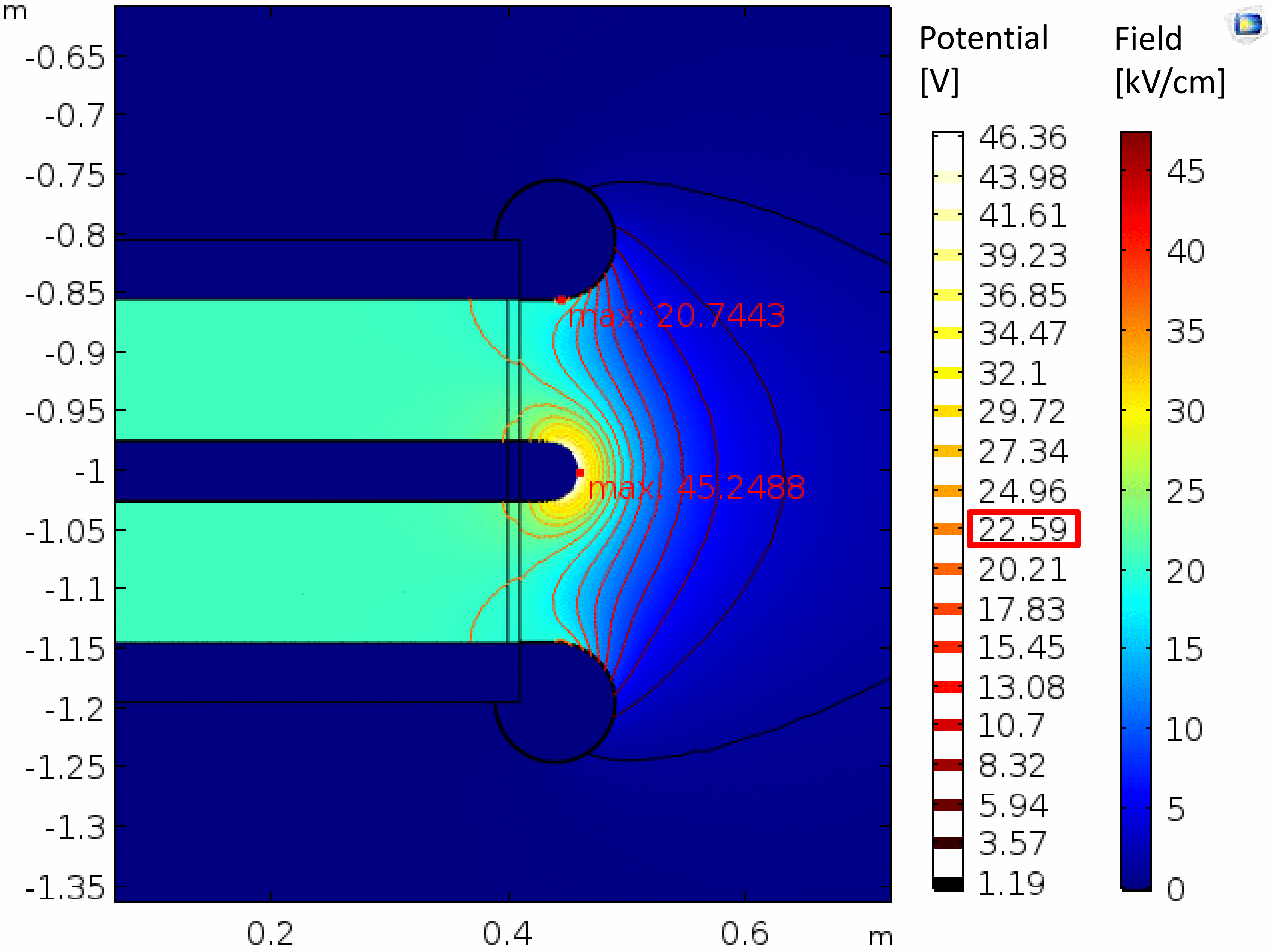



Field norm [kV/cm]
45
40
35
30
25
20
15
10
5
0
-0.75
-0.8
-0.85
-0.9
-0.95
-1
-1.05
-1.1
-1.15
-1.2
-1.25
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
m
Ground
250 kV
Ground
max: 22.5119
max: 43.7959

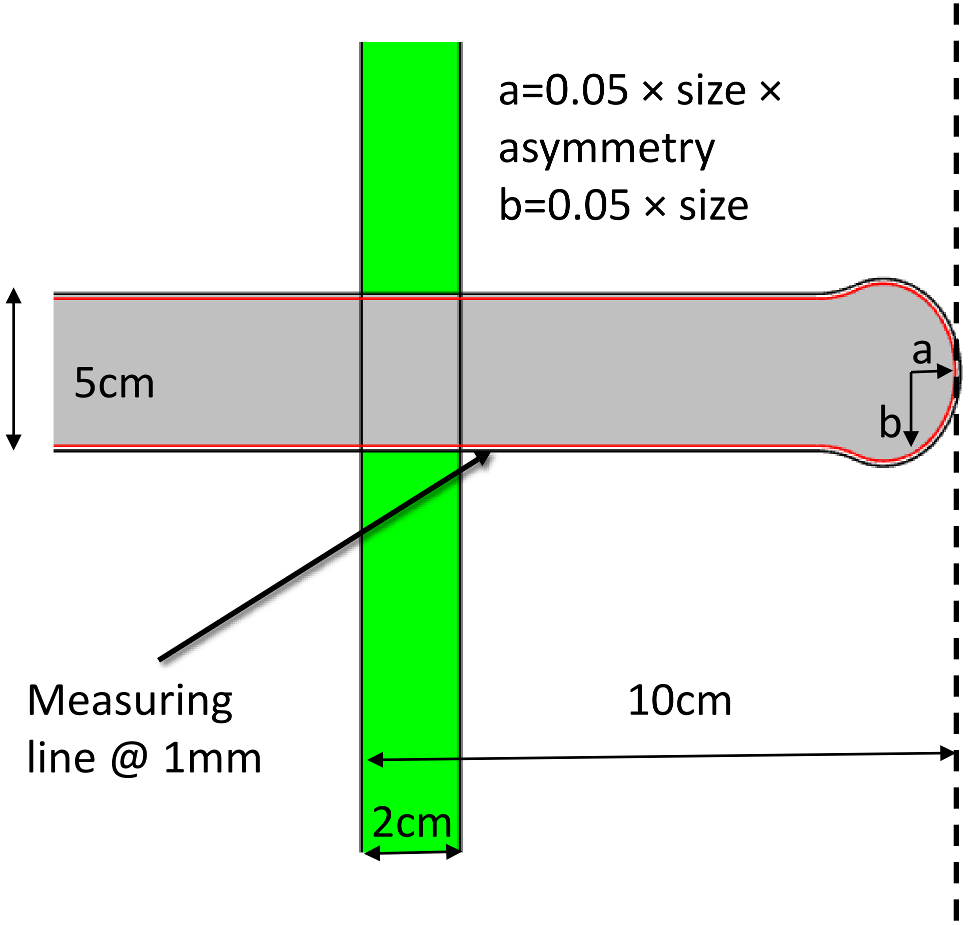
Optimising ground electrode

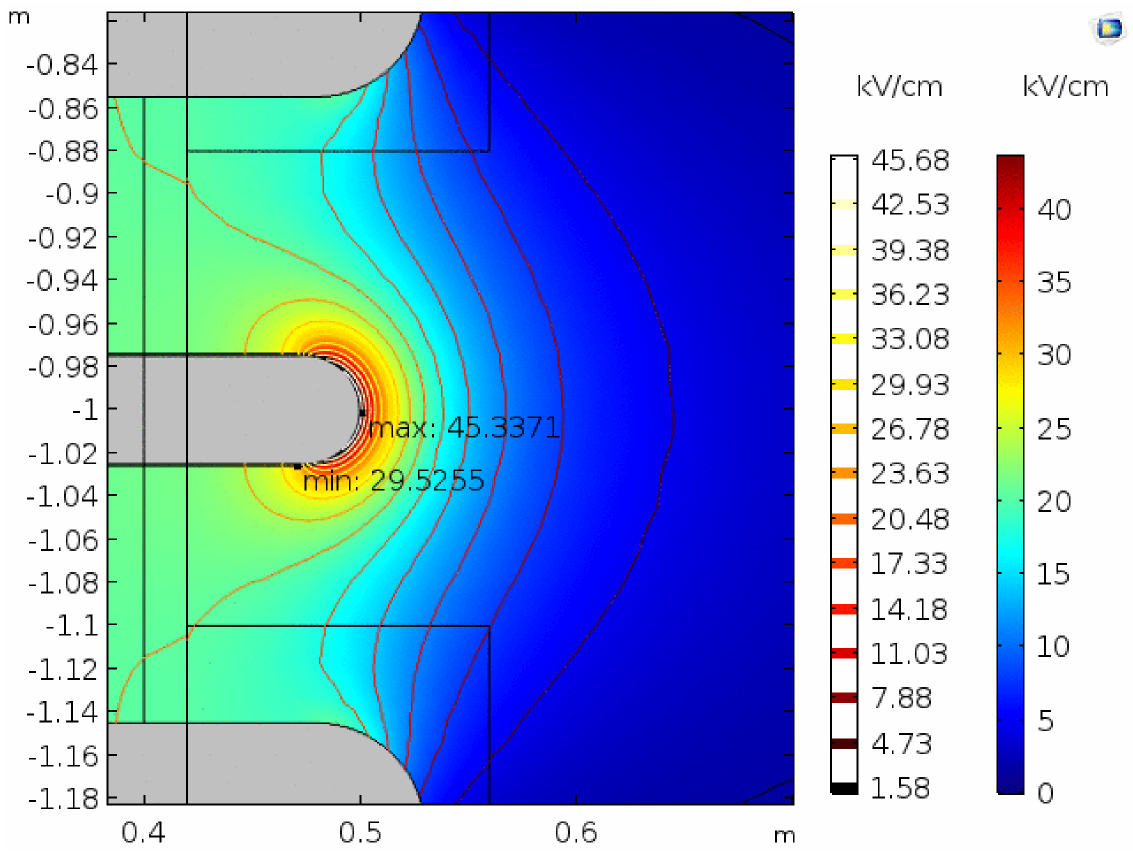


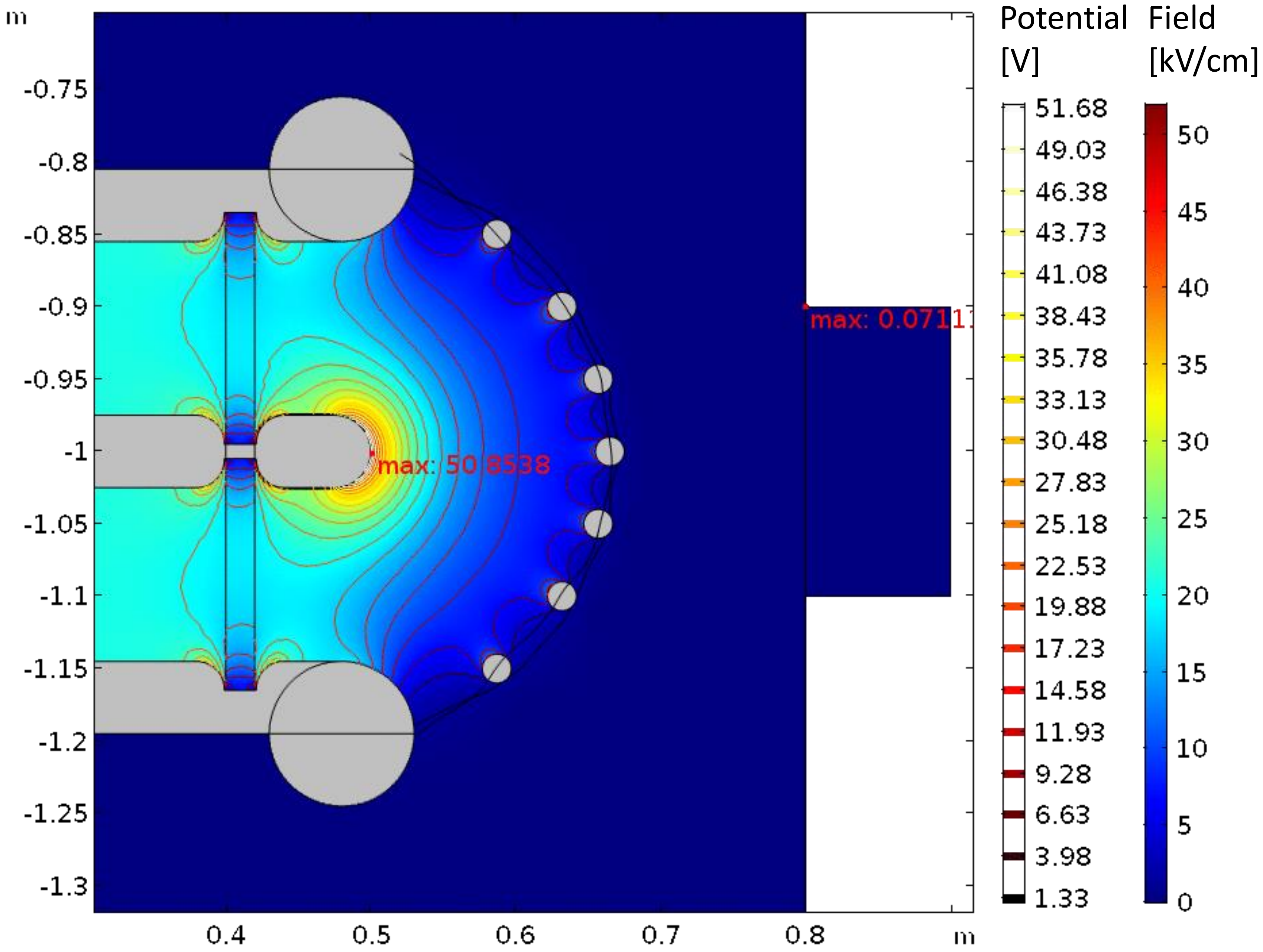



m
-0.65
-0.7
-0.75
-0.8
-0.85
-0.9
-0.95
-1
-1.05
-1.1
-1.15
-1.2
-1.25
-1.3
-1.35
0.2
0.4
0.6
m
max: 20.7443
max: 45.2488
Potential [V]
46.36
43.98
41.61
39.23
36.85
34.47
32.1
29.72
27.34
24.96
22.59
20.21
17.83
15.45
13.08
10.7
8.32
5.94
3.57
1.19
Field [kV/cm]
45
40
35
30
25
20
15
10
5
0

Corona of the HV electrode





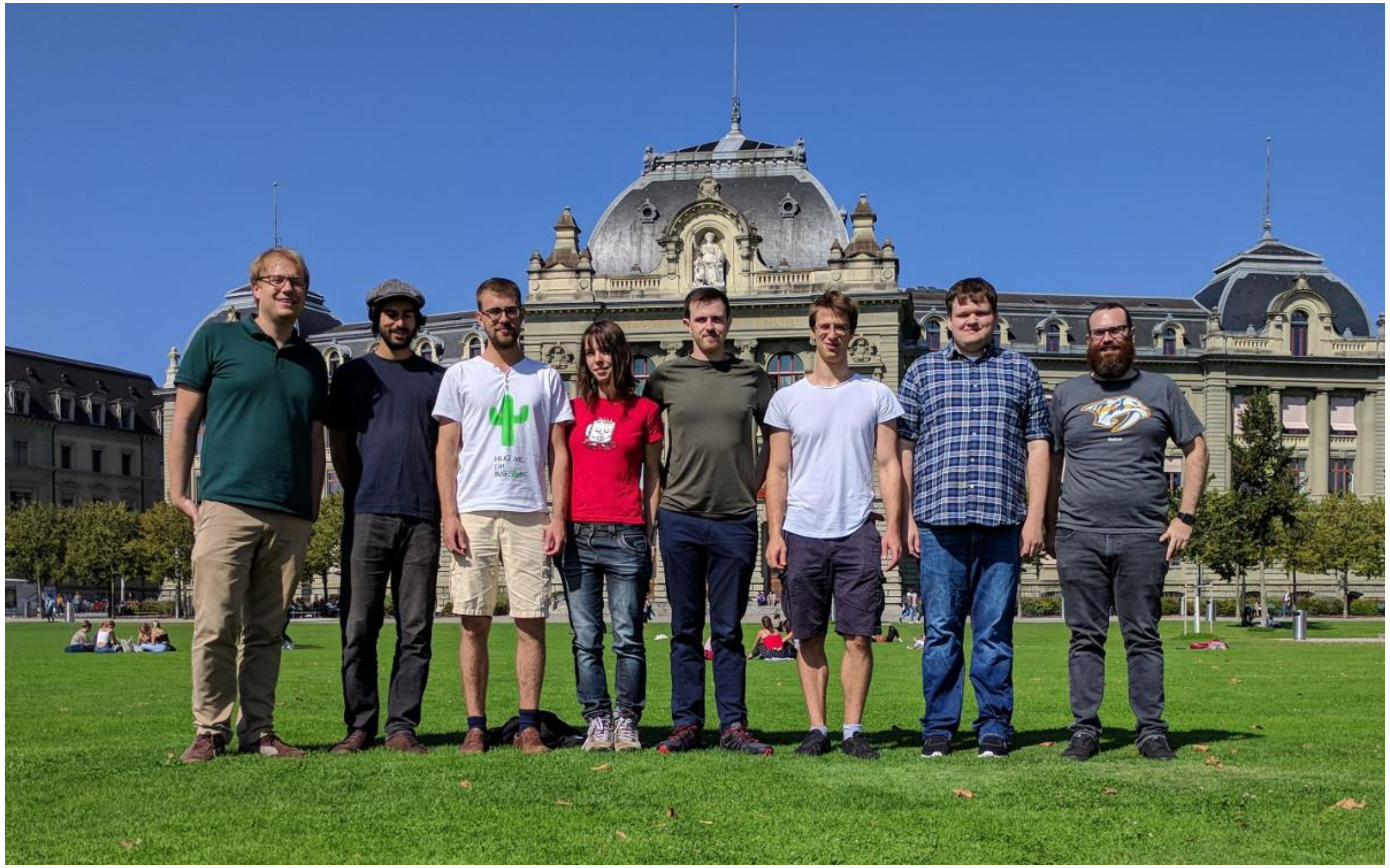

m
-0.75
-0.8
-0.85
-0.9
-0.95
-1
-1.05
-1.1
-1.15
-1.2
-1.25
-1.3
0.4
0.5
0.6
0.7
0.8
m
max: 50.8538
max: 0.0711
Potential [V]
51.68
49.03
46.38
43.73
41.08
38.43
35.78
33.13
30.48
27.83
25.18
22.53
19.88
17.23
14.58
11.93
9.28
6.63
3.98
1.33
Field [kV/cm]
50
45
40
35
30
25
20
15
10
5
0

Further optimisation/development

- Groove geometry of precession chamber, including vacuum seal.
- Quartz window geometry on the insulator.
- Experimental testing of prototype feedthrough, HV and magnetic.
- Construction and development of 250 kV feedthrough

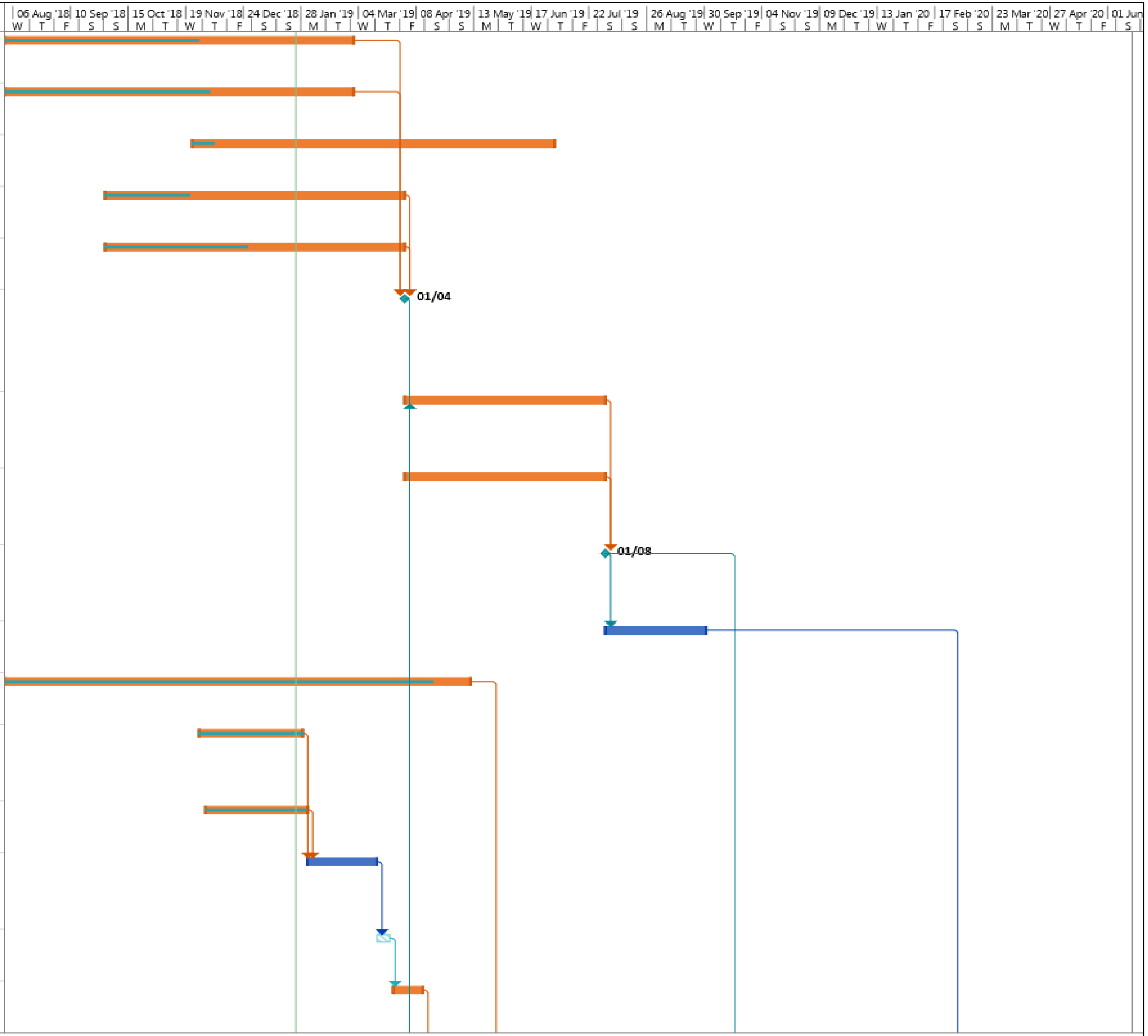
Acknowledgements

- Estelle Chanel
  (PhD student)
- Andrew Mullins
  (Fulbright student)

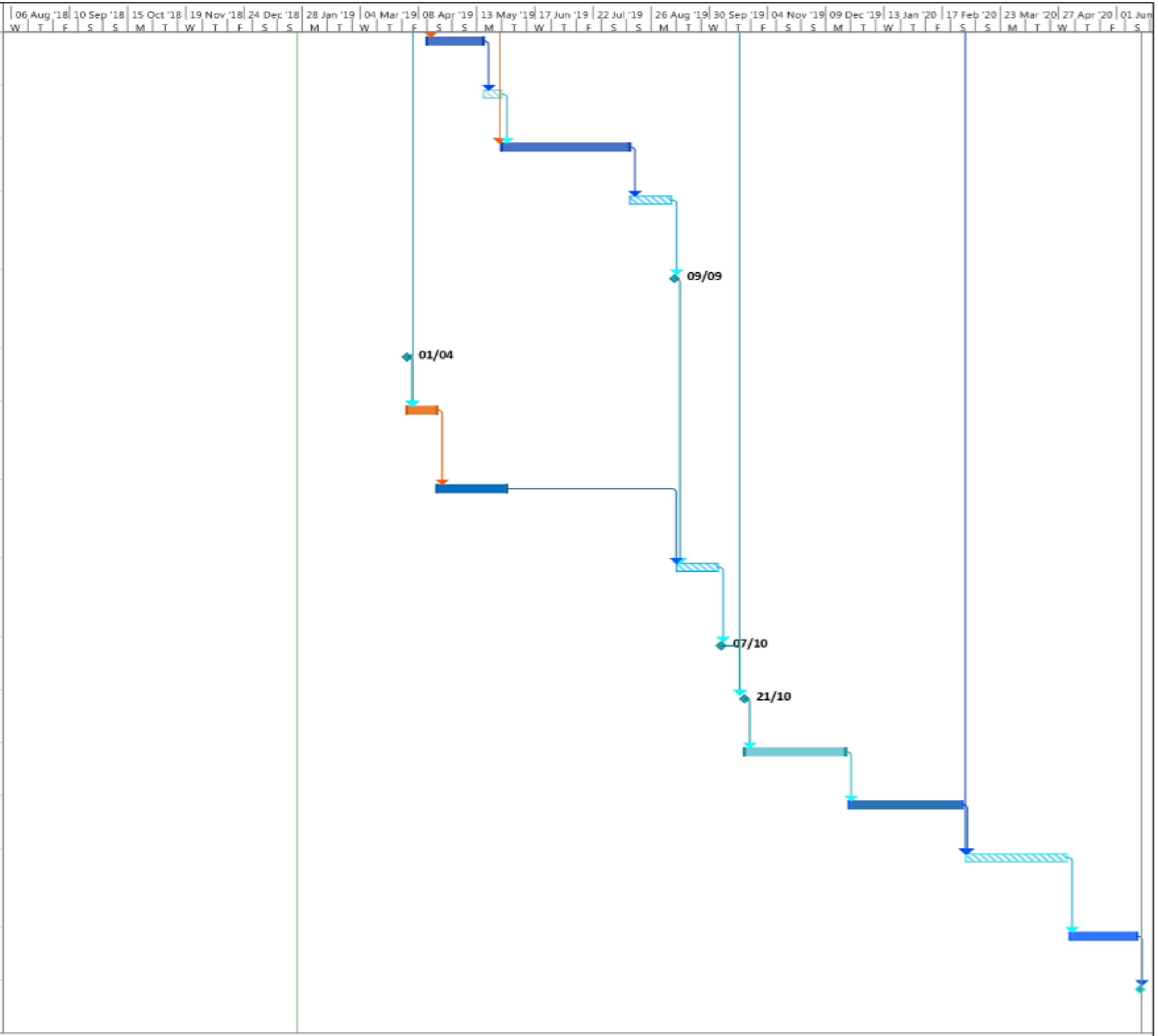


Backup slides

ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1			T26/27 Electrode general geometry	152 days	Wed 01/08/18	Thu 28/02/19		
2			T26/27/28 Insulator general geometry	152 days	Wed 01/08/18	Thu 28/02/19		
3			T28 Quartz window geometry	157 days	Fri 23/11/18	Sun 30/06/19		
4			T25 HV connection to electrode	131 days	Mon 01/10/18	Sun 31/03/19		
5			T25 Grounding rings geometry	131 days	Mon 01/10/18	Sun 31/03/19		
6			T25 Preliminary drawing of electrodes to company	0 days	Mon 01/04/19	Mon 01/04/19	5,4,2,1	
7			T20 Call for electrode requirements	88 days	Mon 01/04/19	Wed 31/07/19	22	
8			T20 Bottom electrode support determined	88 days	Mon 01/04/19	Wed 31/07/19		
9			T20 Electrode interface points determined	0 days	Thu 01/08/19	Thu 01/08/19	7,8	
10			T25 Ground shell machining	43 days	Thu 01/08/19	Mon 30/09/19	9	
11			T25 HV feedthrough 250 kV designed	203 days	Wed 01/08/18	Fri 10/05/19		
12	✓		T25 HV feedthrough, sample magnetic tests	45 days	Tue 27/11/18	Mon 28/01/19		
13	✓		T25 HV 50 kV prototype designed	45 days	Sat 01/12/18	Thu 31/01/19		
14			T25 HV 50 kV prototype machining	30 days	Fri 01/02/19	Thu 14/03/19	12,13	
15			T25 HV 50 kV prototype testing	6 days	Fri 15/03/19	Fri 22/03/19	14	
16			T25 HV 100 kV protype design	14 days	Mon 25/03/19	Thu 11/04/19	15	



ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
17			T25 HV 100 kV protype machining	25 days	Sat 13/04/19	Thu 16/05/19	16	
18			T25 HV 100 kV prototype testing	7 days	Fri 17/05/19	Mon 27/05/19	17	
19			T25 HV 250 kV machining	55 days	Tue 28/05/19	Mon 12/08/19	11,18	
20			T25 HV feedthrough performance and modifications	19 days	Tue 13/08/19	Fri 06/09/19	19	
21			T25 HV 250 kV feedthrough complete	0 days	Mon 09/09/19	Mon 09/09/19	20	
22			T20 ACL HV review	0 days	Mon 01/04/1	Mon 01/04/1		
23			T26/27 1/2 scale electrode prototype design	14 days	Mon 01/04/19	Thu 18/04/19	22,6	
24			T26/27 1/2 scale electrode production	30 days	Fri 19/04/19	Thu 30/05/19	23	
25			T26/27 1/2 scale electrode testing + modifications	19 days	Tue 10/09/19	Fri 04/10/19	24,21	
26			ACL HV review 2	0 days	Mon 07/10/1	Mon 07/10/1	25	
27			T26/27 Electrodes ordered	0 days	Mon 21/10/19	Mon 21/10/19	26,9	
28			T26/27 Electrodes machining	45 days	Mon 21/10/19	Fri 20/12/19	27	
29			T26/27 Electrodes delivery	50 days	Mon 23/12/19	Fri 28/02/20	28	
30			T26/27 Electrodes + ground rings magnetic testing	45 days	Mon 02/03/20	Fri 01/05/20	29,10	
31			T26/27 Electrodes coating	30 days	Mon 04/05/20	Fri 12/06/20	30	
32			T26/27 Electrodes delivered	0 days	Mon 15/06/20	Mon 15/06/20	31	



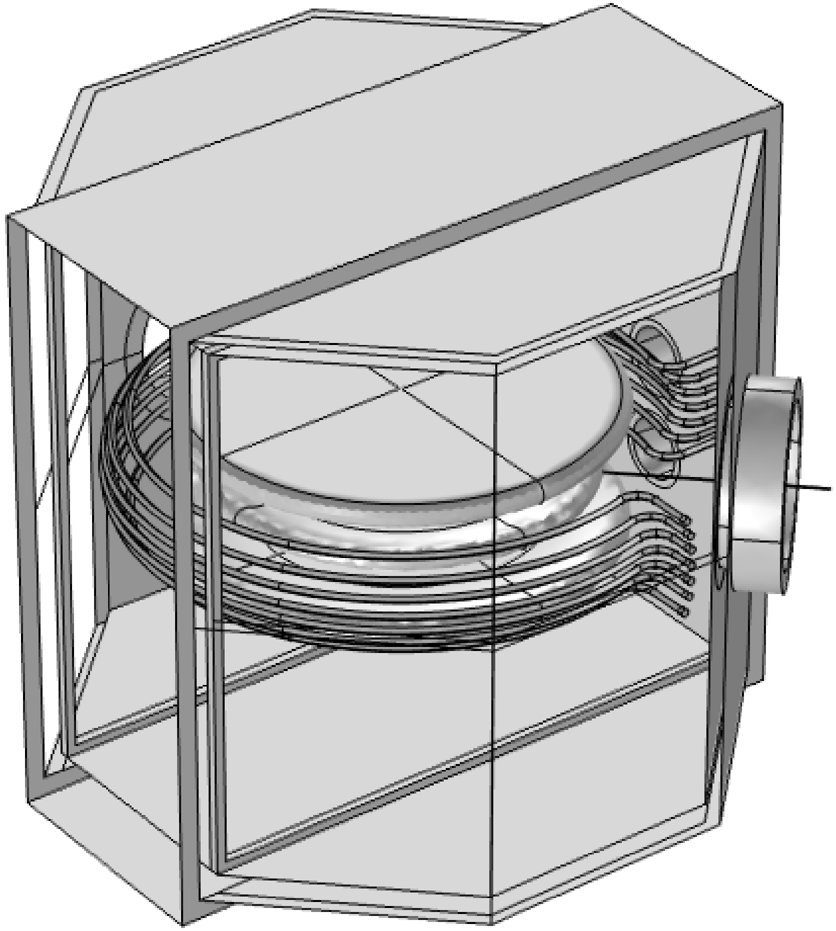
Budget

n2EDM	Task Definition	Task	SubTask	Status	Responsible	Responsible	Manpower	Manpower	Manpower	Estimate	Funded	Spent	Remark
updated Version	Main coordinator	ID	number	Marker	institution	person	estimate	available	spent	kCHF	kCHF	kCHF	
12/11/2018							pers.month	PM	PM				
Florian Piegsa							2019/20	2019/20	up to 2018	2019/20	2019/20	up to 2018	
Precession chamber Coordination	**Coordination: UB - Florian Piegsa**												
	Interface Management to UCN Guides (Task 21)	T20	1	ONG	UB / PSI	F. Piegsa / B. Lauss	1	0	0				
	Interface Management to Vacuum Vessel (Task 23)	T20	2	ONG	UB / LPC	F. Piegsa / T. Lefort	1	0	0				
	Interface Management to High Voltage (Task 25)	T20	3	ONG	UB	F. Piegsa	1	0	0				
	Interface Management to High Voltage Electrode (Task 26)	T20	5	ONG	UB	F. Piegsa	1	0	0				
	Interface Management to High Voltage Electrode (Task 27)	T20	6	ONG	UB	F. Piegsa	1	0	0				
	Interface Management to Isolator Rings (Task 28)	T20	7	ONG	UB / GUM	F. Piegsa / D. Ries	1	0	0				
	Interface Management to Corona Ring (Task 29)	T20	8	ONG	UB	F. Piegsa	1	0	0				
	Interface Management to UCN Shutters (Task 30)	T20	9	ONG	UB / PSI	F. Piegsa / B. Lauss	1	0	0				
	Interface Management to Leakage Currents (Task 32)	T20	10	ONG	UB / Sussex	F. Piegsa / Sussex	1	0	0				
	Interface Management to Hg System (Task 33)	T20	11	ONG	UB / LPSC	F. Piegsa / LPSC	1	0	0				
	Interface Management to 3He System (Task 34)	T20	12	ONG	UB / Sussex	F. Piegsa / Sussex	1	0	0				
	Interface Management to Cs System (Task 35)	T20	13	ONG	UB / PSI	F. Piegsa / PSI	1	0	0				
	Interface Management to MSR and coil system	T25	14	ONG	UB / PSI	F. Piegsa / B. Lauss	1	0	0				
	Interface Management to precession chamber /electrode + corona	T25	15	ONG	UB	F. Piegsa	1	0	0				
	Interface Management to DAQ	T25	16	ONG	UB / Mainz	F. Piegsa / D. Ries	1	0	0				
Total							15	0		0	0	0	
High Voltage	**Coordination: UB - Florian Piegsa**												
	Specifications	T25	1	ONG	UB	F. Piegsa	6	3	1				
	HV Concept, FE Simulations and Interfaces	T25	2	ONG	UB	F. Piegsa	6	3	1				
	HV Powersupply	T25	3	RTM	PSI	P Schmidt-Wellenburg	2	0		230	115	0	incl. Prototype
	HV Feedthrough - design / prototype	T25	4	ONG	UB	F. Piegsa	3	2	1	5	5	0	estimate / SNF 200021_181996 Bern
	HV Feedthrough - construction	T25	5	WPD	UB	F. Piegsa	3	2	0	20	20	0	estimate / SNF 200021_181996 Bern
	HV Cable	T25	6	ONG	PSI	P. Schmidt-Wellenburg	2	0					
Total							22	10		255	140	0	

Budget

n2EDM	Task Definition	Task	SubTask	Status	Responsible	Responsible	Manpower	Manpower	Manpower	Estimate	Funded	Spent	Remark
updated Version	Main coordinator	ID	number	Marker	institution	person	estimate	available	spent	kCHF	kCHF	kCHF	
12/11/2018							pers.month	PM	PM				
Ground electrodes	**Coordination: UB - Florian Piegsa**												
	Ground electrodes - simulation	T26	1	ONG	UB	F. Piegsa	4	1	1	0	0	0	
	Ground electrodes - design	T26	2	ONG	UB	F. Piegsa	4	0	1	10	10	0	Protoyping / SNF 200021_181996 Bern
	Ground electrodes - construction	T26	3	WPD	UB	F. Piegsa	6	0	0	100	0	0	estimate
	Ground electrodes - coating	T26	4	WPD	PSI / UB	B. Lauss / F. Piegsa	4	0					B. Lauss ?
	Magnetic testing	T26	5	ONG	PTB / PSI / UB	A. Schnabel / B. Lauss / F. P	2	0	0	2	0	0	Transport costs ?
Total							20	1		112	10	0	
HV electrodes	**Coordination: UB - Florian Piegsa**												
	HV electrode - simulation	T27	1	ONG	UB	F. Piegsa	4	1	1	0	0	0	
	HV electrode - design	T27	2	ONG	UB	F. Piegsa	4	0	1	10	10	0	Protoyping / SNF 200021_181996 Bern
	HV electrode - construction	T27	3	WPD	UB	F. Piegsa	6	0	0	50	0	0	estimate
	HV electrode - coating	T27	4	WPD	PSI / UB	B. Lauss / F. Piegsa	4	0					B. Lauss ?
	Magnetic testing	T27	5	ONG	PTB / PSI / UB	A. Schnabel / B. Lauss / F. P	2	0	0	2	0	0	Transport costs ?
Total							20	1		62	10	0	
Corona and ground rings	**Coordination: UB - Florian Piegsa**												
	Corona ring - simulation	T29	1	ONG	UB	F. Piegsa	2		1	0	0	0	
	Corona ring - design	T29	2	ONG	UB	F. Piegsa	2		1	5	0	0	
	Corona ring - construction	T29	3	WPD	UB	F. Piegsa	4		0	5	0	0	
	Magnetic testing	T29	4	WPD	UB	F. Piegsa	2		0	2	0	0	Transport costs ?
Total							10	0		12	0	0	
TOTAL							**805**	**585**		**5348**	**4437**	**1480**	

Overview

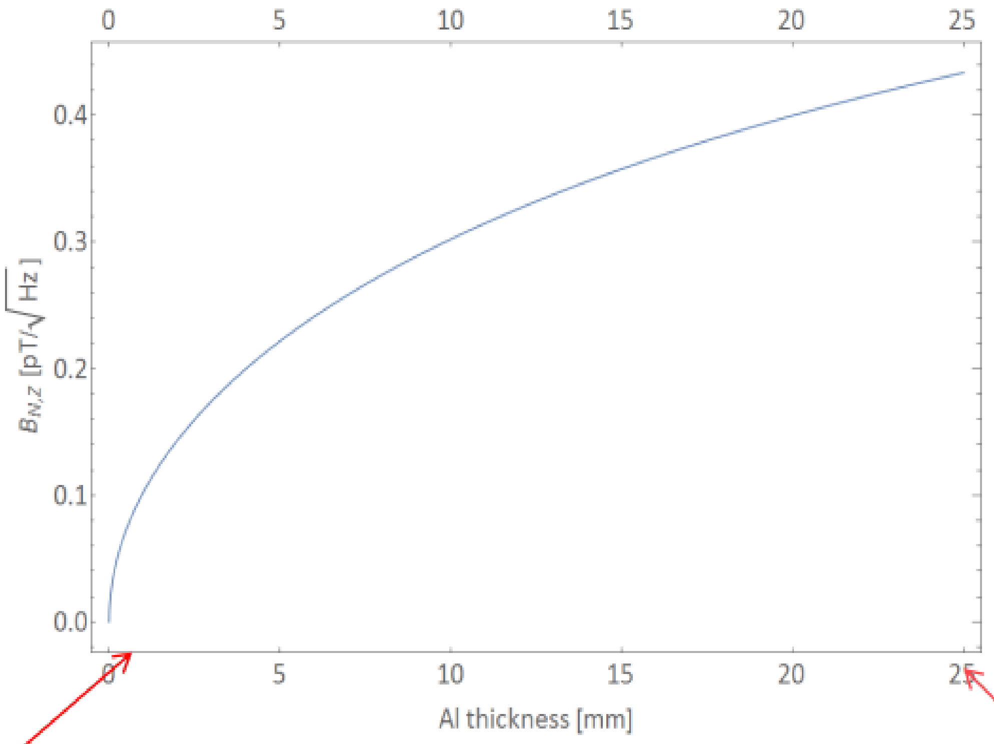


Comsol design from Andrew Mullins

Parameters	Values and comments
Radius of HV/Gr	HV ≥ 47 cm Gr ~ HV + 3 or 4 cm
Thickness HV/Gr	HV>4cm Gr~ 3cm with sphere
Thickness of the insulator	>2cm
Corona HV	Asymmetry 1 Size [1,1.2]
Protection cage	Yes ~ 3 rings ?
Feedthrough	On going
Groove	deep outside fillet Square shape
Quartz window	Insulator thickness

Johnson noise

- Simulation performed by Pin-Jung Chiu
- Precession period of 200s
- Linear spectral density of the JNN created by 2 electrodes, $B_{N,z}$, at the center of the chamber, z = 0, with f = 2.5×10^{-3} Hz.

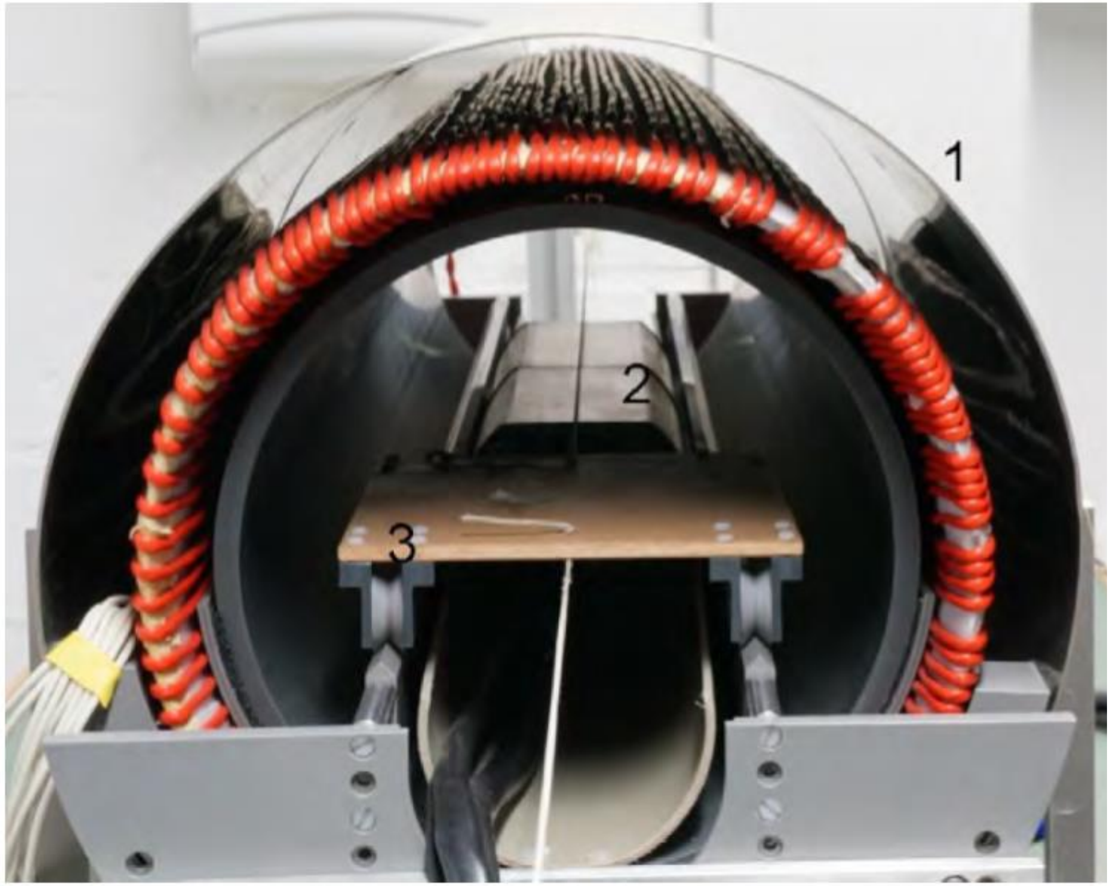


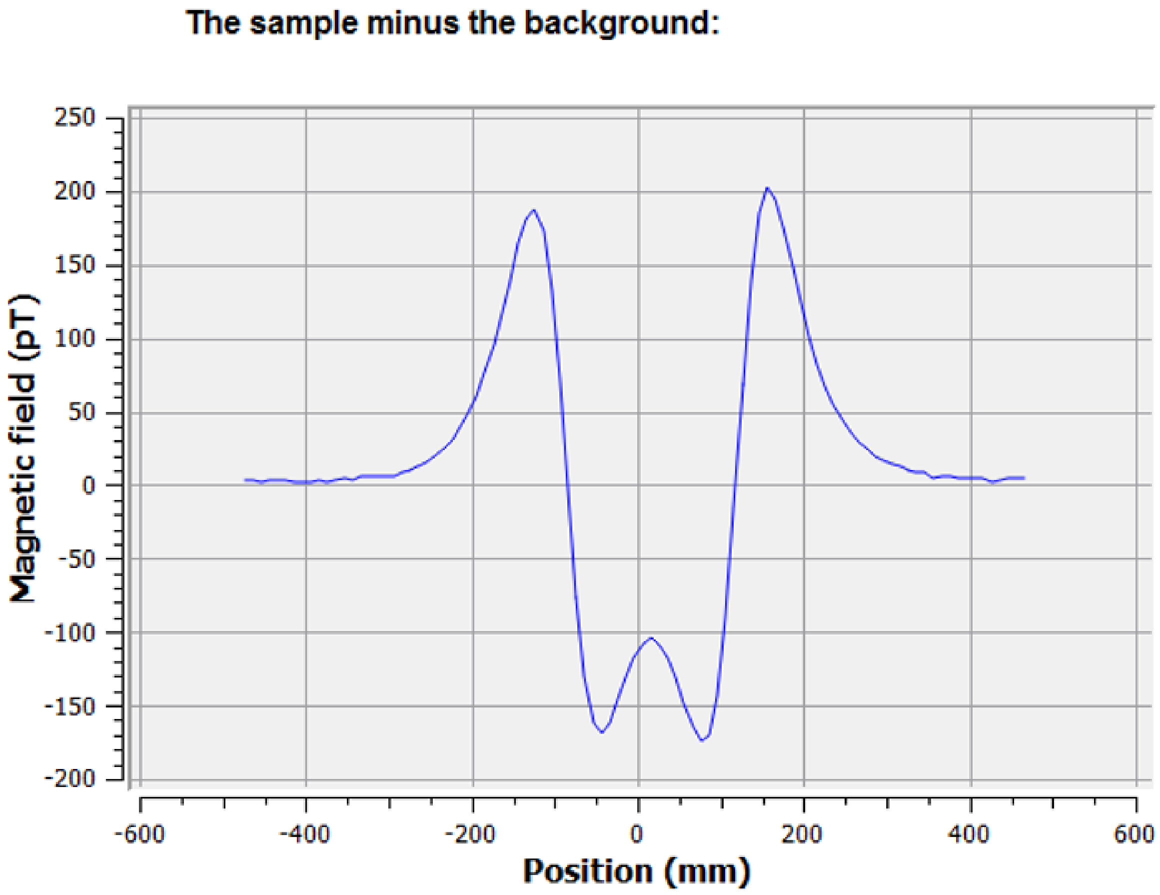
t = 0.7 mm:
$\sigma = 1.8 \times 10^{-17}$ T
$\rightarrow < 10^{-28}\ e \cdot$ cm

$$\sigma^2(X_n) = 2\, N_0\, BW = 2\, \sqrt{kT\sigma t}^{\,2}\, BW$$

C.o.m. offset h = -4.1 mm
$\sigma = 1.1 \times 10^{-16}$ T
$\rightarrow 5.5 \times 10^{-28}\ e \cdot$ cm

Gradiometer





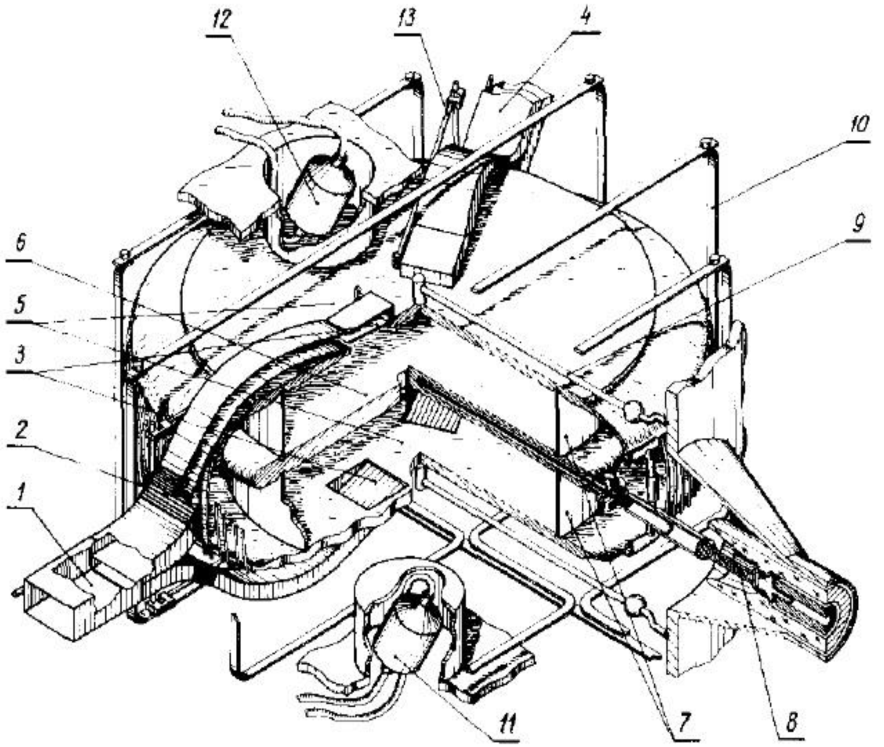
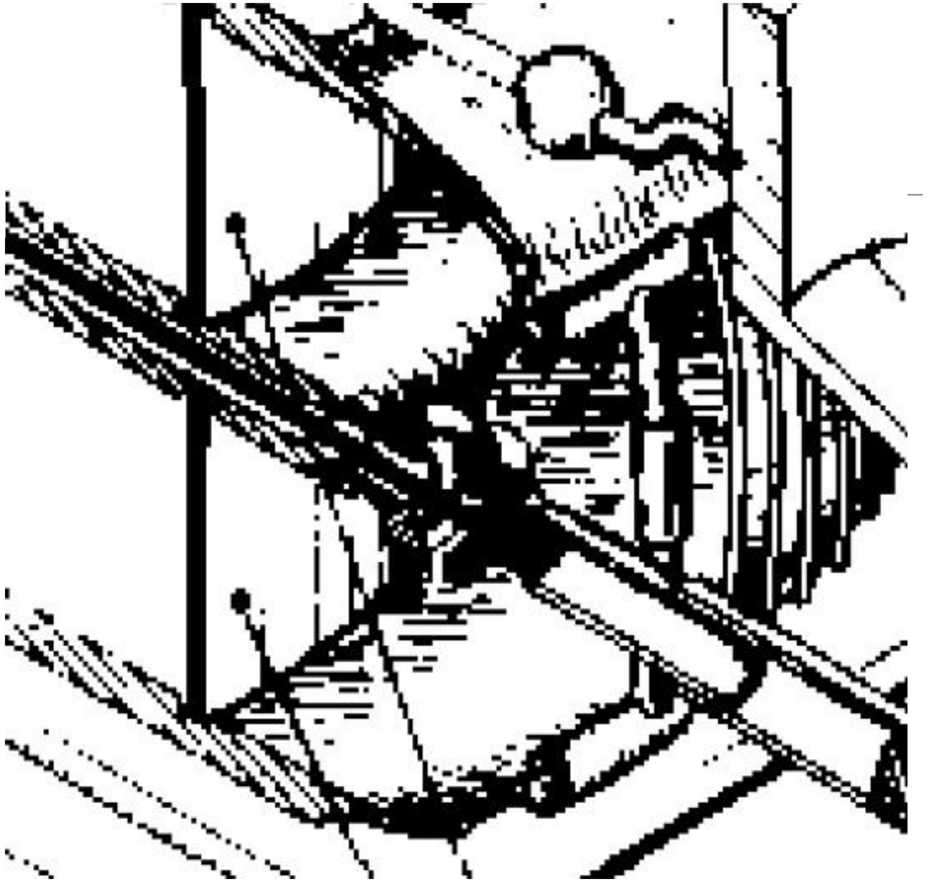


Fig. 1. Internal part of the EDM set-up. The permalloy shield, vacuum chamber, neutron polarizer and detection system are not shown. 1 is the input UCN guide, 2 is the insulating section of neutron guide, 3 are the entrance shutters, 4 is the output UCN guide, 5 are the upper and lower lids of neutron storage chambers, 6 is the central high voltage electrode, 7 is the quartz insulating ring, 8 is the vacuum high voltage input, 9 is the grounding bar of the upper lid, 10 is a part of the oscillating field coil, 11 is the lower Cs optically pumped magnetometer, 12 is the upper magnetometer, 13 is the shaft for shutter operation.



High voltage achieved: 120-150kV, average electric field +14.4kV/cm.

https://www.nature.com/news/dynamo-maker-ready-to-roll-1.9582