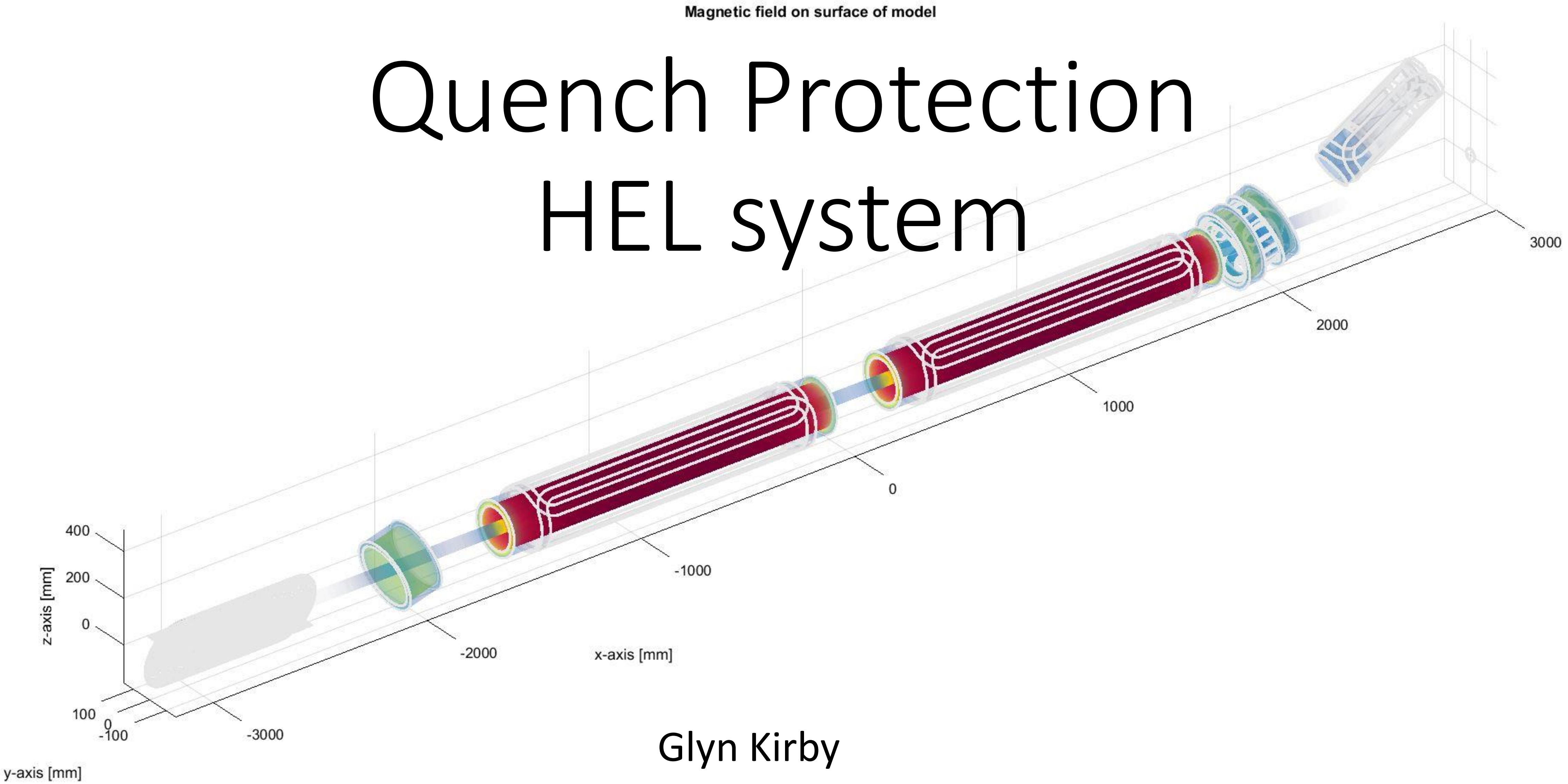
Quench Protection
HEL system



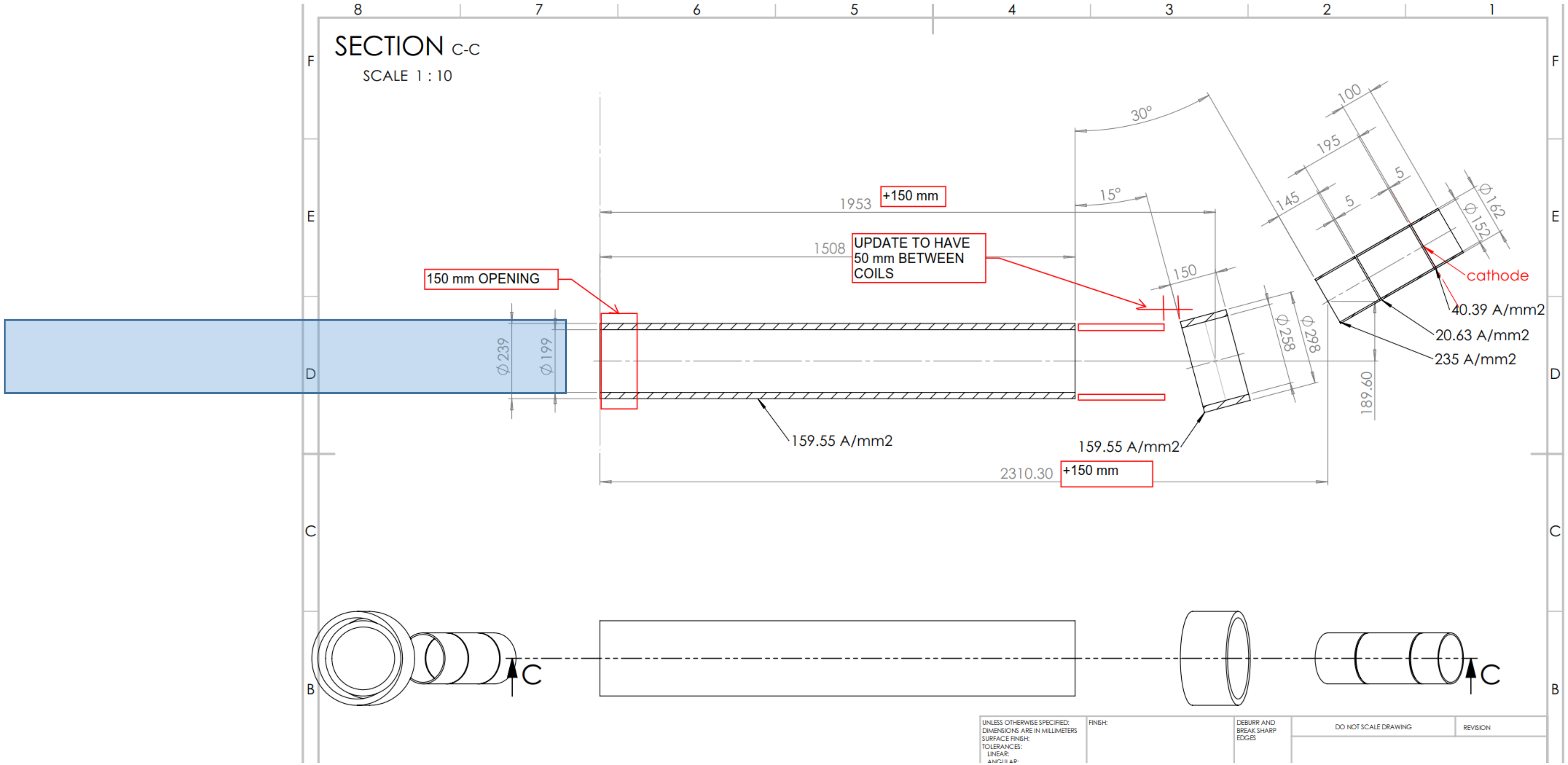
Glyn Kirby

Matthias Mentink & Jeroen Van Nugteren

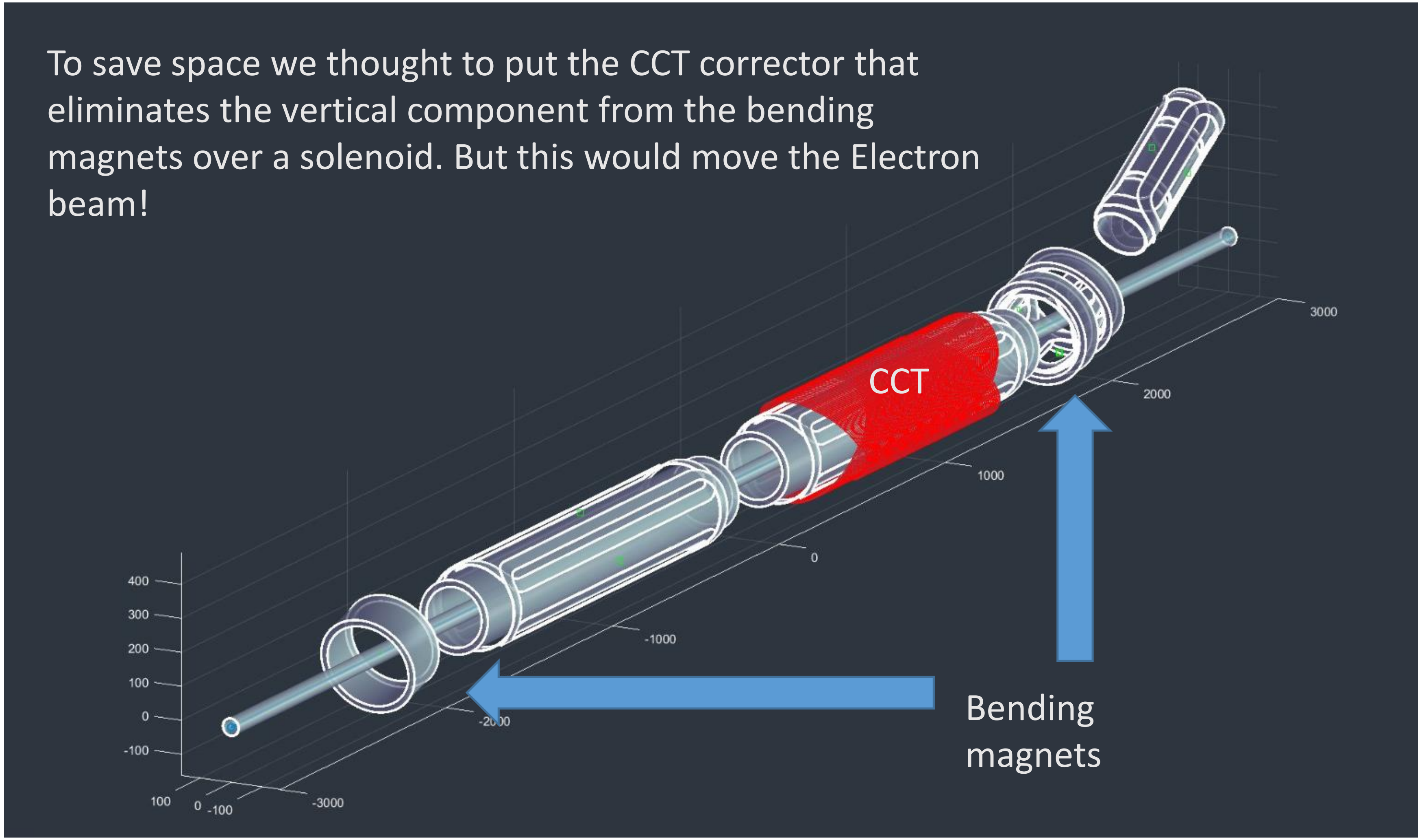
Overview

- Coil designs and some evolution
- Coil features, complexity, inductances matrix, forces,
- Quench calculation evolution.
- Conclusions / quench protection proposals for consideration.

Fine tuning and simplifying the design



Initial idea to CCT location that was an error !

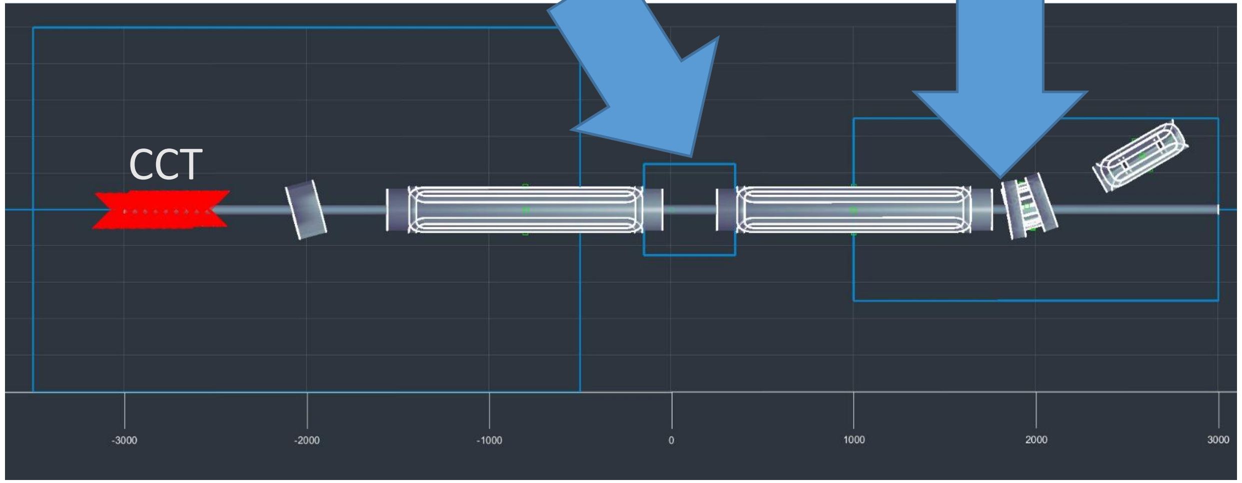


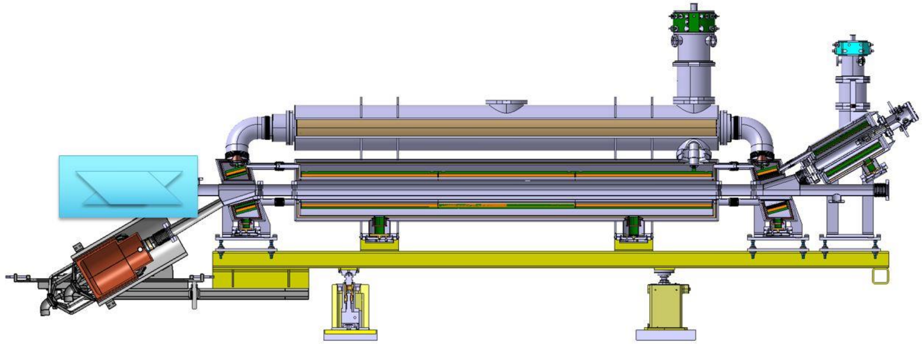
Magnet systems

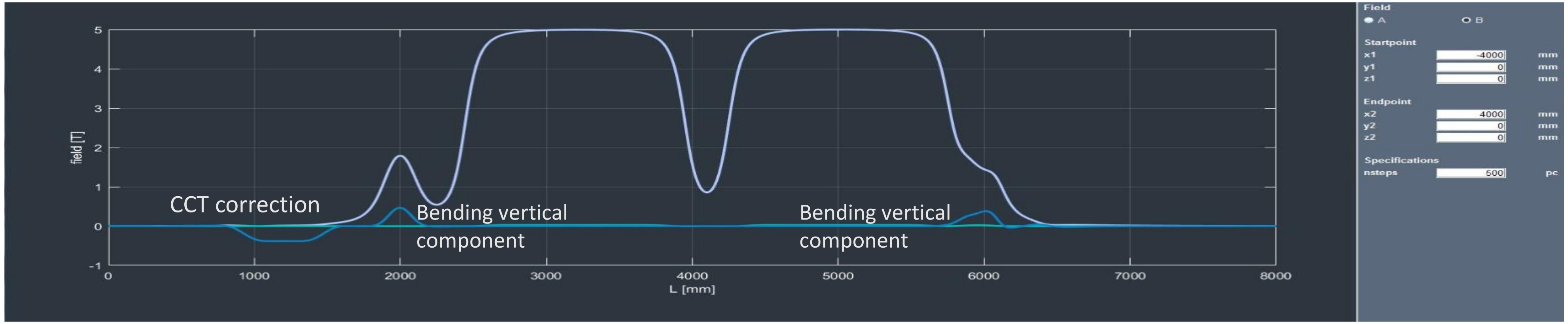
Partly updated to new proposed design

300 mm Gap between coils this will give space for cryostat open access for gas curtain added

Gap between coil reduced





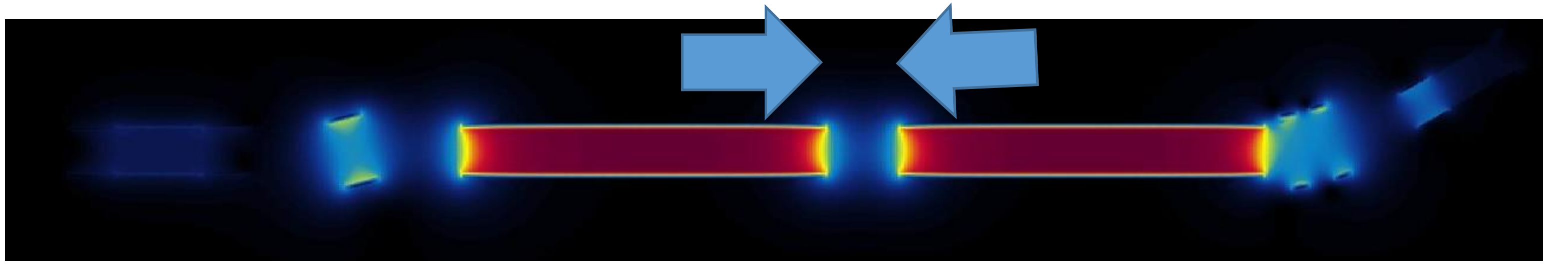


Inductance matrix

	BlueWhale	BlueWhale	Dump Sole	Bend Soler	Bend Soler	Gun 3	Gun 1	Gun 2	dipole y3 E	dipole y3 A	dipole x3 E	dipole x1 E	dipole x3 1	dipole x1 A	Gun Dipole	Gun Dipole	Gun Dipole	Gun Dipole	dipole y1 E	dipole y1 A	Bend Dipo	Bend Quac	Bend Dipo	Bend Quac	Bend Dipo	Bend Quac	Bend Dipo	Bend Quac	tube	Solenoid -	Solenoid - 2
BlueWhale Inner	558.8468	-101.762	1.886915	0.004175	0.003919	0.000827	0.000672	0.00074	0.1038	0.059883	-0.02279	-0.00129	0.022625	0.001282	0.00029	8.71E-05	-0.00019	-5.3E-07	0.011435	0.008958	-0.00015	-6.3E-05	0.00014	-5.6E-05	0.000947	0.000437	0.000567	-0.00029	0	0.186309	1.699736
BlueWhale Outer	-101.762	451.7353	-1.17548	-0.00277	-0.00219	-0.00041	-0.00037	-0.00039	0.048201	0.083085	0.018121	0.001028	-0.01799	-0.00102	0.002215	0.002219	-4.4E-05	-0.00015	0.007177	0.009147	8.08E-05	4.05E-05	-9.1E-05	4.58E-05	0.00174	0.000853	0.001889	-0.00089	0	-0.14831	-1.35149
Dump Solenoid	1.886915	-1.17548	132.3838	0.003482	0.002919	0.000558	0.000467	0.000508	0.078677	-0.2079	-0.14788	-0.00182	0.147815	0.001822	-0.00137	-0.00146	-7.7E-05	7.66E-05	-0.00114	-0.00465	-0.00013	-6.2E-05	0.000135	-6.2E-05	-0.00091	-0.00046	-0.0012	0.000551	0	0.209632	7.376508
Bend Solenoid 2	0.004175	-0.00277	0.003482	50.02633	9.570595	0.165652	0.038701	0.072146	-0.00326	8.06E-05	0.001734	0.616718	-0.00173	-0.61673	0.065187	-0.0861	-0.07989	0.079885	-0.68627	0.522006	-12.9707	-5.6455	12.97058	-5.64554	12.54367	4.696651	-16.7647	6.285107	0	29.482	0.178042
Bend Solenoid 1	0.003919	-0.00219	0.002919	9.570595	50.02614	0.397312	0.065958	0.139837	-0.00358	-0.00103	0.00132	0.210172	-0.00132	-0.21017	0.153462	-0.23641	-0.20695	0.206948	-0.24829	0.164011	13.60256	5.815318	-13.6025	5.815382	-13.9441	-5.18448	16.82939	-6.14036	0	9.850146	0.14316
Gun 3	0.000827	-0.00041	0.000558	0.165652	0.397312	13.24438	0.172154	1.378188	-0.00065	-0.00026	0.000197	0.00872	-0.0002	-0.00872	6.390806	-6.39112	-5.82139	5.82137	-0.00875	0.008193	0.087545	0.038072	-0.08754	0.038073	-0.10567	-0.0379	0.105974	-0.03842	0	0.491779	0.024296
Gun 1	0.000672	-0.00037	0.000467	0.038701	0.065958	0.172154	16.646	1.690634	-0.00032	-6.1E-05	0.000133	0.002831	-0.00013	-0.00283	-6.86262	6.137787	5.874348	-5.87435	-0.00049	0.004767	0.00977	0.004268	-0.00977	0.004268	-0.00667	-0.00173	0.016275	-0.00638	0	0.197319	0.018152
Gun 2	0.00074	-0.00039	0.000508	0.072146	0.139837	1.378188	1.690634	10.82061	-0.00045	-0.00014	0.000159	0.00467	-0.00016	-0.00467	-8.7E-06	-7.7E-06	8.87E-08	1.43E-08	-0.00279	0.006082	0.024782	0.010783	-0.02478	0.010783	-0.02385	-0.00778	0.035109	-0.01329	0	0.293982	0.020784
dipole y3 B	0.1038	0.048201	0.078677	-0.00326	-0.00358	-0.00065	-0.00032	-0.00045	100.0425	19.52868	7.446952	0.01323	-7.44843	-0.01312	-0.00521	-0.00464	0.000105	-0.00011	-0.13386	-0.10453	0.000265	6.69E-05	-0.00027	6.71E-05	-0.00692	-0.00333	-0.00585	0.002797	0	-0.67173	0.3082
dipole y3 A	0.059883	0.083085	-0.2079	8.06E-05	-0.00103	-0.00026	-6.1E-05	-0.00014	19.52868	100.2308	-7.43519	-0.01353	7.432458	0.013225	-0.00558	-0.00516	2.42E-05	-2.4E-05	-0.10453	-0.13446	3.06E-05	-2.9E-05	-3.1E-05	-2.9E-05	-0.00719	-0.00349	-0.00673	0.00319	0	0.672654	-0.30782
dipole x3 B	-0.02279	0.018121	-0.14788	0.001734	0.00132	0.000197	0.000133	0.000159	7.446952	-7.43519	100.7126	-0.13838	17.60541	-0.10595	-0.00026	-0.00032	-0.0055	-0.0054	0.01323	-0.01353	-0.00649	-0.00341	-0.0062	0.003265	-0.00016	-0.00011	-0.00045	0.00019	0	0.695858	-0.30829
dipole x1 B	-0.00129	0.001028	-0.00182	0.616718	0.210172	0.00872	0.002831	0.00467	0.01323	-0.01353	-0.13838	100.7126	-0.10595	17.60541	-0.0007	-0.0068	-0.06777	-0.05928	7.445487	-7.43344	-0.46085	-0.2343	-0.08475	0.055189	0.171906	0.04326	-0.22021	0.074983	0	0.308293	-0.69586
dipole x3 1	0.022625	-0.01799	0.147815	-0.00173	-0.00132	-0.0002	-0.00013	-0.00016	-7.44843	7.432458	17.60541	-0.10595	100.525	-0.13779	0.000257	0.000317	-0.0054	-0.0055	-0.01312	0.013225	-0.0062	-0.00327	-0.00649	0.003407	0.000165	0.000108	0.000454	-0.00019	0	-0.69524	0.308655
dipole x1 A	0.001282	-0.00102	0.001822	-0.61673	-0.21017	-0.00872	-0.00283	-0.00467	-0.01312	0.013225	-0.10595	17.60541	-0.13779	100.525	0.000703	0.00689	-0.0592	-0.06783	-7.44708	7.430707	-0.08443	-0.05543	-0.4594	0.232747	-0.17285	-0.04325	0.220641	-0.07499	0	-0.30864	0.695241
Gun Dipole y B	0.00029	0.002215	-0.00137	0.065187	0.153462	6.390806	-6.86262	-8.7E-06	-0.00521	-0.00558	-0.00026	-0.0007	0.000257	0.000703	128.5037	23.85087	11.81771	-11.8176	-0.07302	-0.06386	0.036716	0.011437	-0.03672	0.011436	-0.25674	-0.12376	-0.12493	0.061541	0	-0.03524	-0.03433
Gun Dipole y A	8.71E-05	0.002219	-0.00146	-0.0861	-0.23641	-6.39112	6.137787	-7.7E-06	-0.00464	-0.00516	-0.00032	-0.0068	0.000317	0.00689	23.85087	128.5037	-11.8175	11.81732	-0.05859	-0.06498	-0.04599	-0.02116	0.045981	-0.02116	-0.12601	-0.06886	-0.22584	0.10105	0	-0.38283	-0.04097
Gun Dipole x B	-0.00019	-4.4E-05	-7.7E-05	-0.07989	-0.20695	-5.82139	5.874348	8.87E-08	0.000105	2.42E-05	-0.0055	-0.06777	-0.0054	-0.0592	11.81771	-11.8175	129.4773	20.47591	0.002427	-0.00407	-0.21716	-0.11262	-0.11156	0.062883	0.051527	0.014554	-0.05843	0.018961	0	-0.1929	-0.00458
Gun Dipole x A	-5.3E-07	-0.00015	7.66E-05	0.079885	0.206948	5.82137	-5.87435	1.43E-08	-0.00011	-2.4E-05	-0.0054	-0.05928	-0.0055	-0.06783	-11.8176	11.81732	20.47591	129.4778	-0.00244	0.004078	-0.11156	-0.06288	-0.21716	0.112621	-0.05153	-0.01455	0.058426	-0.01896	0	0.192292	0.004584
dipole y1 B	0.011435	0.007177	-0.00114	-0.68627	-0.24829	-0.00875	-0.00049	-0.00279	-0.13386	-0.10453	0.01323	7.445487	-0.01312	-7.44708	-0.07302	-0.05859	0.002427	-0.00244	100.0425	19.52868	0.177217	0.065897	-0.17784	0.065687	-0.56587	-0.26076	-0.0218	0.025979	0	-0.30818	0.671726
dipole y1 A	0.008958	0.009147	-0.00465	0.522006	0.164011	0.008193	0.004767	0.006082	-0.10453	-0.13446	-0.01353	-7.43344	0.013225	7.430707	-0.06386	-0.06498	-0.00407	0.004078	19.52868	100.2308	-0.13472	-0.06259	0.134704	-0.06236	-0.16053	-0.10069	-0.45957	0.198928	0	0.307825	-0.67265
Bend Dipole x B	-0.00015	8.08E-05	-0.00013	-12.9707	13.60256	0.087545	0.00977	0.024782	0.000265	3.06E-05	-0.00649	-0.46085	-0.0062	-0.08443	0.036716	-0.04599	-0.21716	-0.11156	0.177217	-0.13472	89.21986	33.43516	6.188043	-2.81708	-17.0952	7.395411	17.09524	7.395364	0	-8.82157	-0.01081
Bend Quadrupole 1	-6.3E-05	4.05E-05	-6.2E-05	-5.6455	5.815318	0.038072	0.004268	0.010783	6.69E-05	-2.9E-05	-0.00341	-0.2343	-0.00327	-0.05543	0.011437	-0.02116	-0.11262	-0.06288	0.065897	-0.06259	33.43516	51.73834	2.817082	-1.32683	-0.77355	3.633786	0.773559	3.63377	0	-3.92811	-0.00483
Bend Dipole x A	0.00014	-9.1E-05	0.000135	12.97058	-13.6025	-0.08754	-0.00977	-0.02478	-0.00027	-3.1E-05	-0.0062	-0.08475	-0.00649	-0.4594	-0.03672	0.045981	-0.11156	-0.21716	-0.17784	0.134704	6.188043	2.817082	89.2198	-33.4352	17.09491	-7.39542	-17.0949	-7.39541	0	8.819744	0.010812
Bend Quadrupole 3	-5.6E-05	4.58E-05	-6.2E-05	-5.64554	5.815382	0.038073	0.004268	0.010783	6.71E-05	-2.9E-05	0.003265	0.055189	0.003407	0.232747	0.011436	-0.02116	0.062883	0.112621	0.065687	-0.06236	-2.81708	-1.32683	-33.4352	51.73833	-0.77355	3.633809	0.773553	3.633795	0	-3.92661	-0.00483
Bend Dipole y B	0.000947	0.00174	-0.00091	12.54367	-13.9441	-0.10567	-0.00667	-0.02385	-0.00692	-0.00719	-0.00016	0.171906	0.000165	-0.17285	-0.25674	-0.12601	0.051527	-0.05153	-0.56587	-0.16053	-17.0952	-0.77355	17.09491	-0.77355	103.2477	31.91919	13.60859	-3.88262	0	10.67804	-0.02069
Bend Quadrupole 2	0.000437	0.000853	-0.00046	4.696651	-5.18448	-0.0379	-0.00173	-0.00778	-0.00333	-0.00349	-0.00011	0.04326	0.000108	-0.04325	-0.12376	-0.06886	0.014554	-0.01455	-0.26076	-0.10069	7.395411	3.633786	-7.39542	3.633809	31.91919	51.73774	3.882621	-1.32683	0	3.696475	-0.01165
Bend Dipole y A	0.000567	0.001889	-0.0012	-16.7647	16.82939	0.105974	0.016275	0.035109	-0.00585	-0.00673	-0.00045	-0.22021	0.000454	0.220641	-0.12493	-0.22584	-0.05843	0.058426	-0.0218	-0.45957	17.09524	0.773559	-17.0949	0.773553	13.60859	3.882621	103.2476	-31.9191	0	-10.8613	-0.04493
Bend Quadrupole 4	-0.00029	-0.00089	0.000551	6.285107	-6.14036	-0.03842	-0.00638	-0.01329	0.002797	0.00319	0.00019	0.074983	-0.00019	-0.07499	0.061541	0.10105	0.018961	-0.01896	0.025979	0.198928	7.395364	3.63377	-7.39541	3.633795	-3.88262	-1.32683	-31.9191	51.73784	0	3.99868	0.019851
tube	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solenoid - 1	0.186309	-0.14831	0.209632	29.482	9.850146	0.491779	0.197319	0.293982	-0.67173	0.672654	0.695858	0.308293	-0.69524	-0.30864	-0.03524	-0.38283	-0.1929	0.192292	-0.30818	0.307825	-8.82157	-3.92811	8.819744	-3.92661	10.67804	3.696475	-10.8613	3.99868	0	7873.996	36.62357
Solenoid - 2	1.699736	-1.35149	7.376508	0.178042	0.14316	0.024296	0.018152	0.020784	0.3082	-0.30782	-0.30829	-0.69586	0.308655	0.695241	-0.03433	-0.04097	-0.00458	0.004584	0.671726	-0.67265	-0.01081	-0.00483	0.010812	-0.00483	-0.02069	-0.01165	-0.04493	0.019851	0	36.62357	7873.996

Inductance Given in	mH
Stored Energy	0.92563 MJ
Total Inductance	19221.9227 [mH]

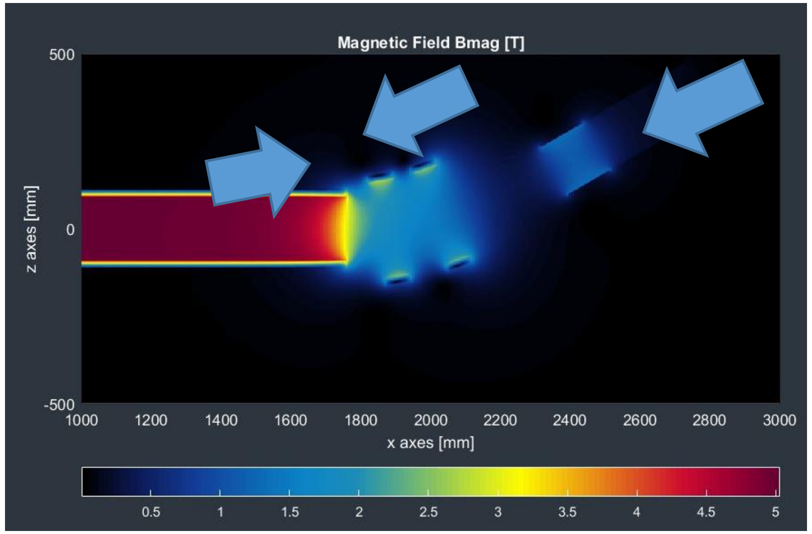
Not final but very close !

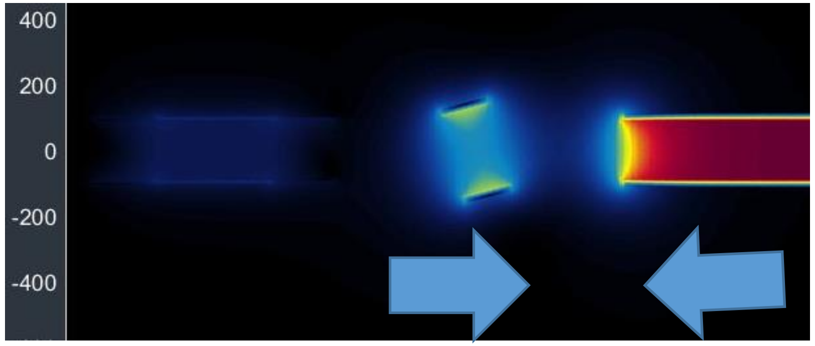


Mechanical design next steps !

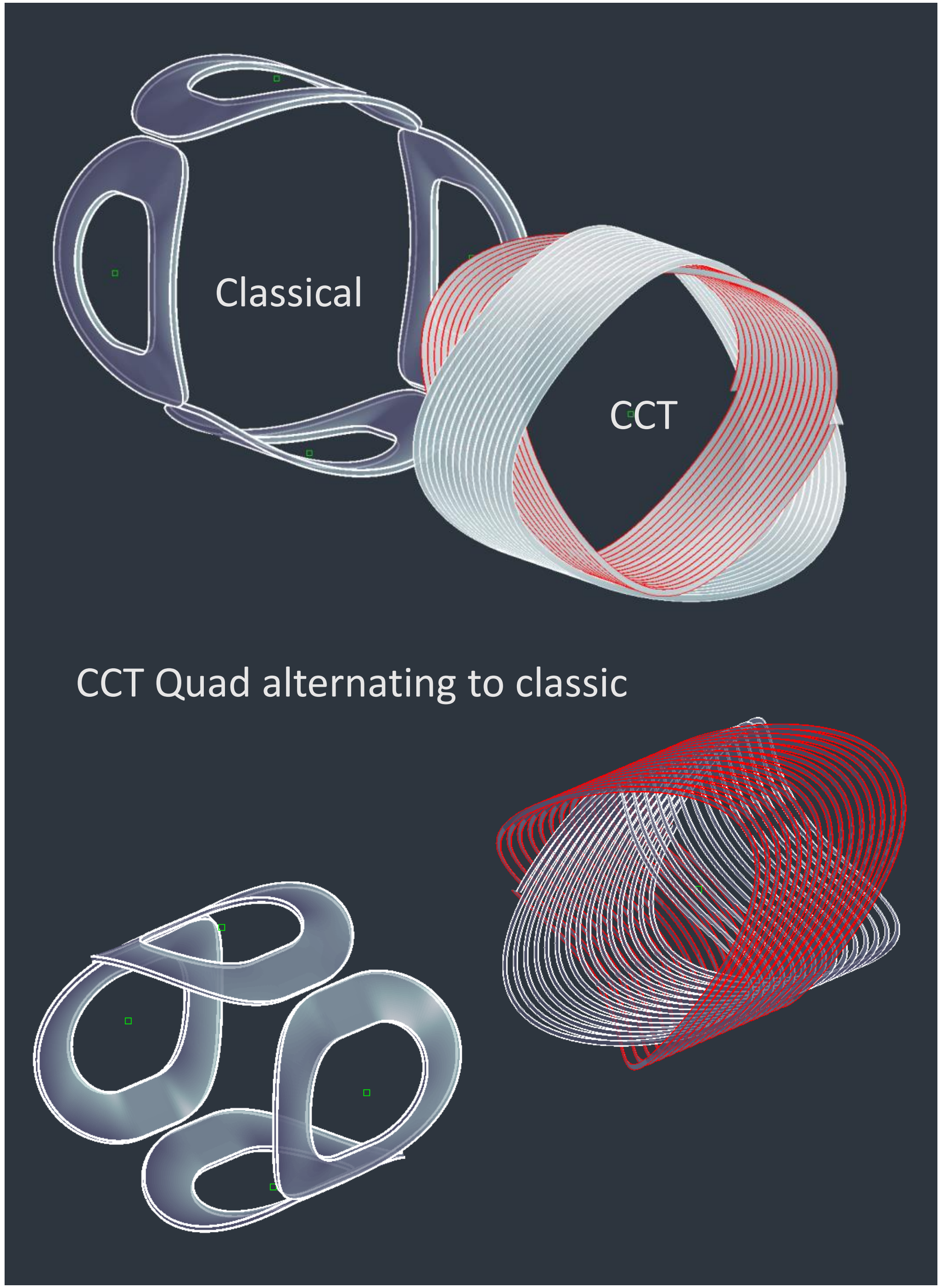
Force matrix between coils

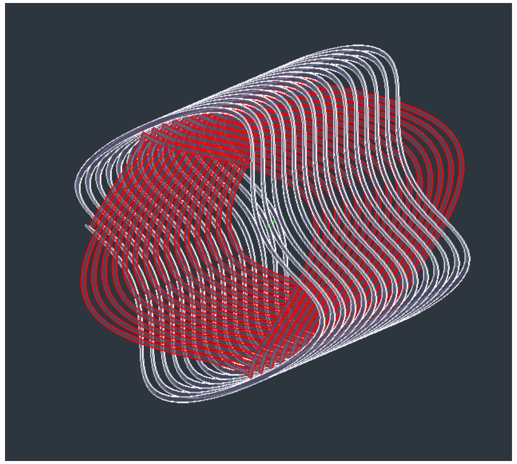
Name	x [mm]	y [mm]	z [mm]	Fx [N]	Fy [N]	Fz [N]	Fmag [N]	Tx [N.mm]	Ty [N.mm]	Tz [N.mm]	Tmag [N.mm]
BlueWhale Inner	-2800	0	0	419.5939	-142.283	137.8501	464.0108	-0.00117	1.362151	-0.00032	1.362151925
BlueWhale Outer	-2800	0	0	-275.371	224.8831	170.0032	394.0846	0.000328	-1.57579	0.000659	1.575792106
Dump Solenoid	-2003	0	0	6606.085	43.12382	-948.576	6673.98	0.000286	0.276781	-0.00106	0.276782743
Bend Solenoid 2	1880	0	0	-14831.4	-2119.74	8349.828	17151.79	-0.04995	0.079012	0.283393	0.29841198
Bend Solenoid 1	2030	0	40	-47107.8	2292.043	-10328.2	48281.12	-0.07133	-0.27555	0.195932	0.345551928
Gun 3	2413.5	0	200	-713.628	-26.5563	-86.0654	719.2896	0.000527	0.037969	-0.00091	0.037984043
Gun 1	2733.5	0	388.76273	-64.0543	-0.11955	-37.9795	74.46748	1.09E-05	0.000181	-1.9E-05	0.000182683
Gun 2	2583.5	0	298.150005	-533.785	-0.5751	-298.567	611.612	2.59E-05	0.001215	-4.5E-05	0.001216559
dipole y3 B	-800	0	125.5	0	0	0	0	0	0	0	0
dipole y3 A	-800	0	-125.5	0	0	0	0	0	0	0	0
dipole x3 B	-800	-130.5	0	-478.077	43.29852	-0.92312	480.0349	-0.00072	0.000834	0.155905	0.155909354
dipole x1 B	1000	-130.5	0	-411.108	39.77156	-0.27669	413.0276	-0.00163	0.001185	0.124855	0.124870996
dipole x3 1	-800	130.5	0	477.9714	-73.1284	1.079853	483.5345	-0.00066	-0.00025	0.155335	0.15533654
dipole x1 A	1000	130.5	0	410.5824	-77.4883	0.41131	417.8307	-0.0015	-0.00108	0.124221	0.124235248
Gun Dipole y B	2540.5	0	372.628185	0	0	0	0	0	0	0	0
Gun Dipole y A	2626.5	0	223.671631	0	0	0	0	0	0	0	0
Gun Dipole x B	2583.5	-91	298.15	0	0	0	0	0	0	0	0
Gun Dipole x A	2583.5	91	298.15	0	0	0	0	0	0	0	0
dipole y1 B	1000	0	125.5	0	0	0	0	0	0	0	0
dipole y1 A	1000	0	-125.5	0	0	0	0	0	0	0	0
Bend Dipole x B	1950	-128	20	-956.312	-52.3112	-298.292	1003.119	0.180272	-0.07553	-0.72624	0.752085176
Bend Quadrupole 1	1950	-120	20	0	0	0	0	0	0	0	0
Bend Dipole x A	1950	128	20	0	0	0	0	0	0	0	0
Bend Quadrupole 3	1950	120	20	0	0	0	0	0	0	0	0
Bend Dipole y B	1917.906438	0	139.774802	0	0	0	0	0	0	0	0
Bend Quadrupole 2	1918.941715	0	135.911099	0	0	0	0	0	0	0	0
Bend Dipole y A	1982.093562	0	-99.7748025	0	0	0	0	0	0	0	0
Bend Quadrupole 4	1981.058285	0	-95.9110992	0	0	0	0	0	0	0	0
tube	0	0	0	0	0	0	0	0	0	0	0
Solenoid - 1	1004	0	0	48546.32	161.9534	2065.729	48590.52	-2.8E-05	-1.71414	-0.39234	1.75846782
Solenoid - 2	-804	0	0	8787.729	177.2842	77.13138	8789.856	-2.8E-05	0.543656	-0.32524	0.633515815



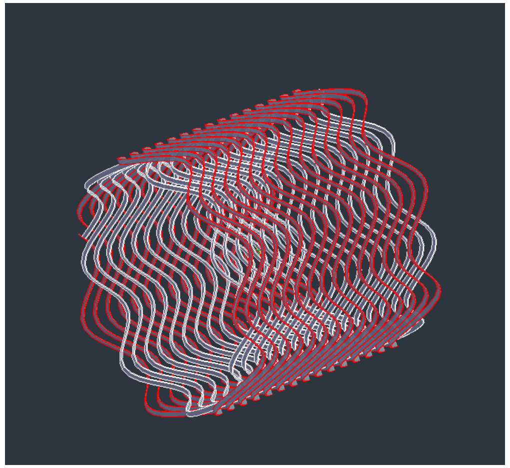


Not final but very close !





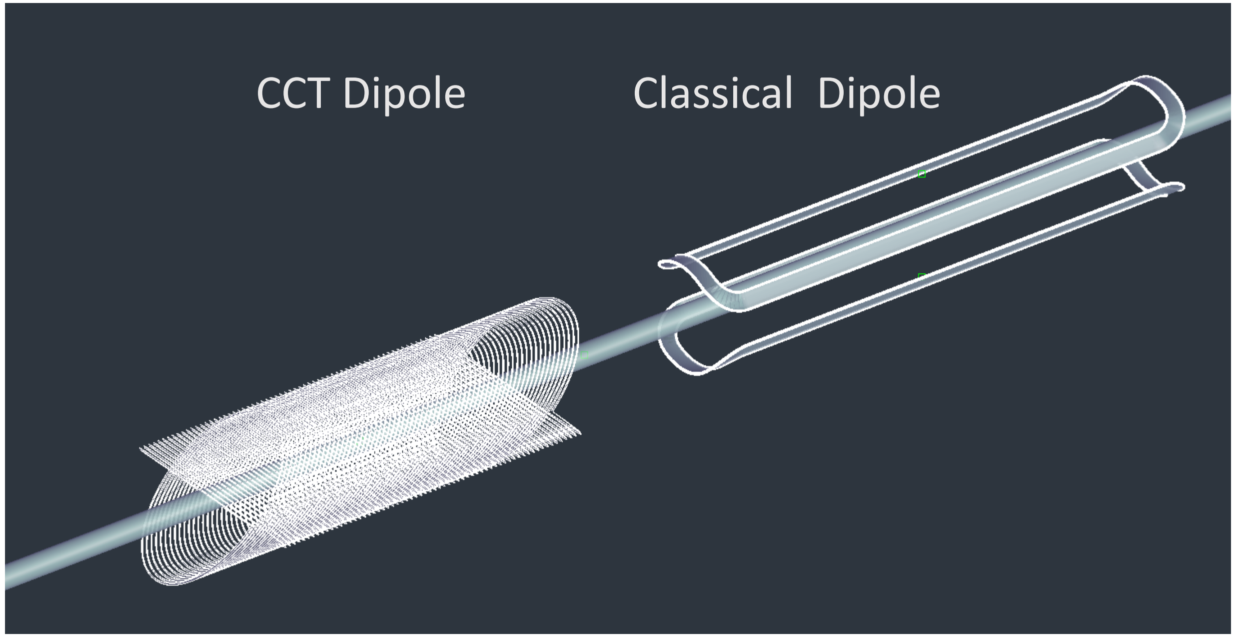
Sextepole



14 pole

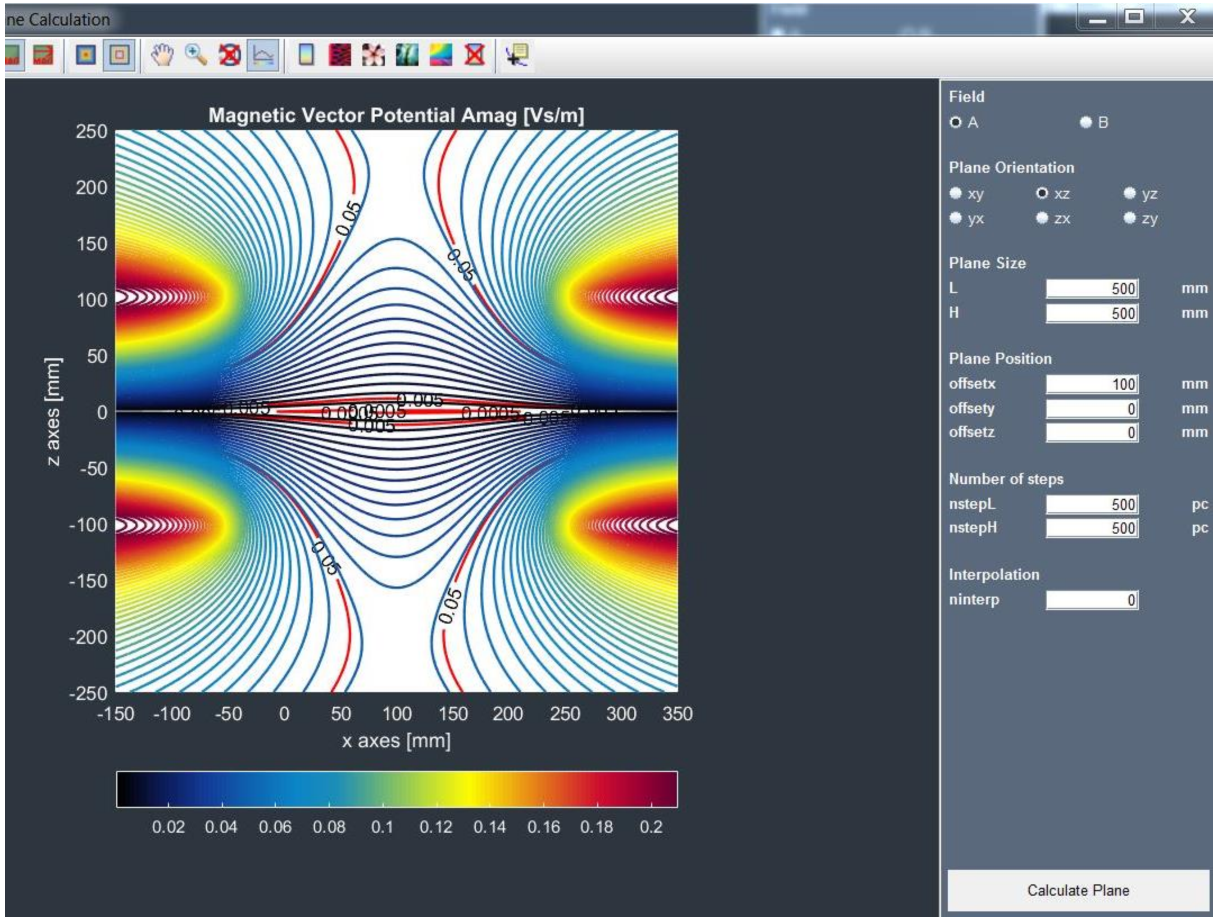
Examples, we can make any harmonic correction coil

Need to look at cost! of low current CCT, but forces will be easier to support !

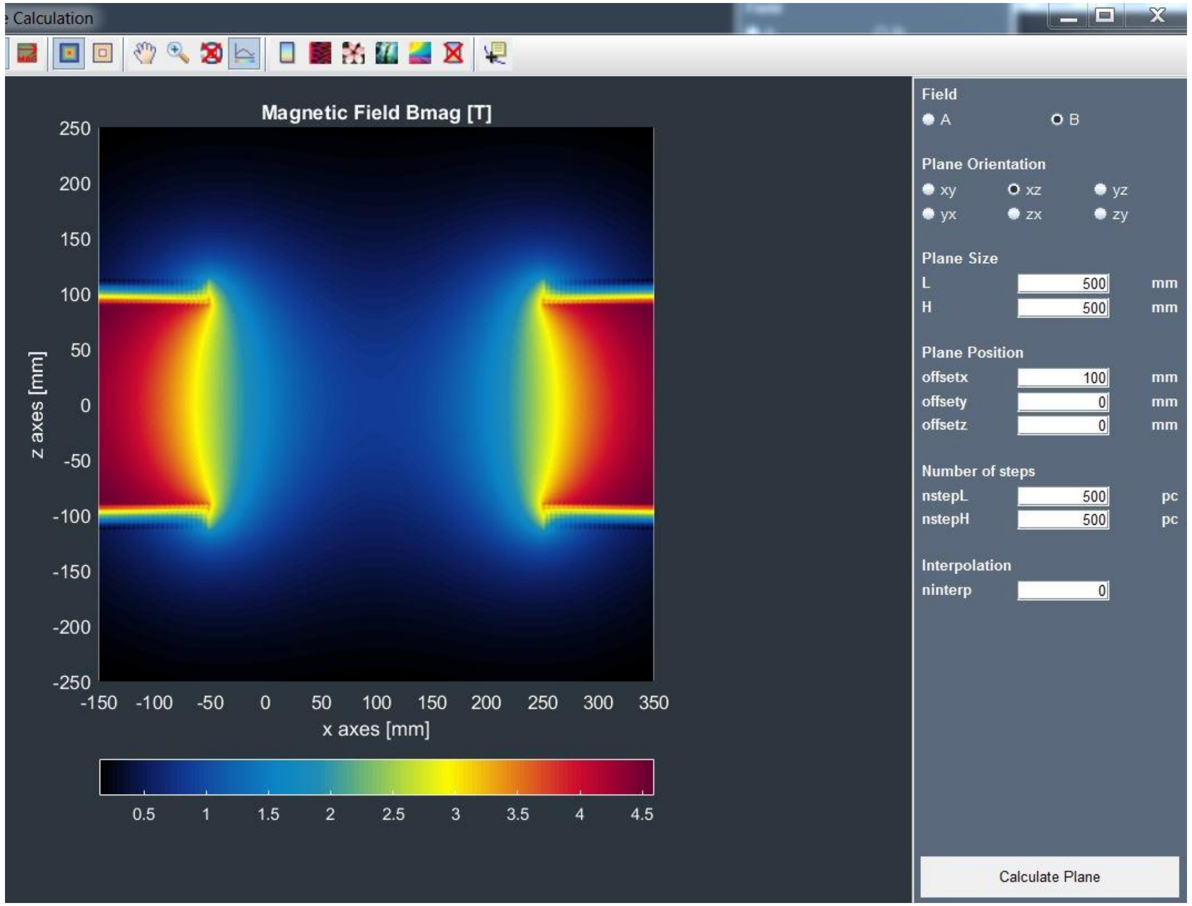


Gap between the the two 5T 1.5 m long coils

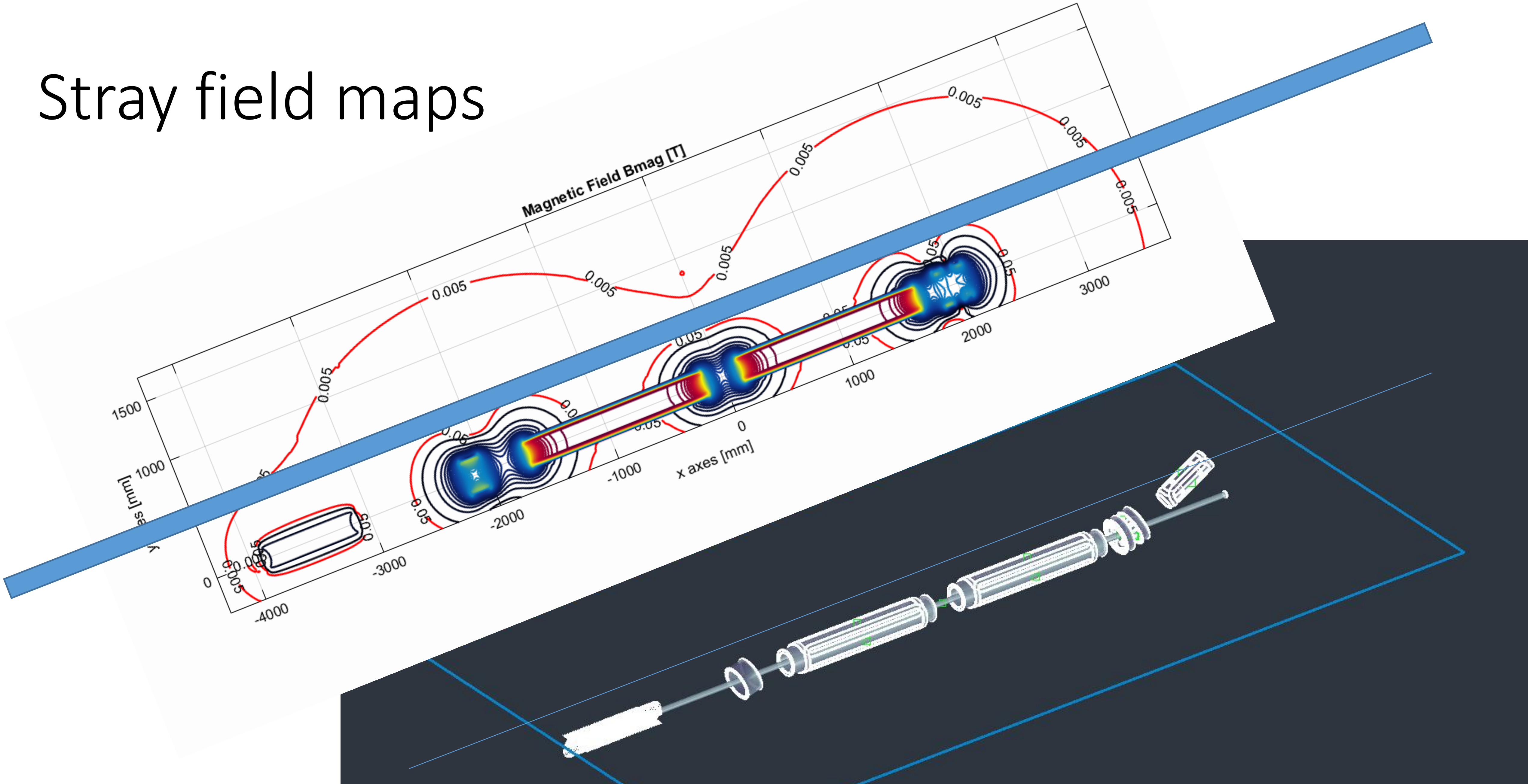
Vector potential between the two 5T coils
so can think of it as flux lines, could play with
the gap!



Field in the gap

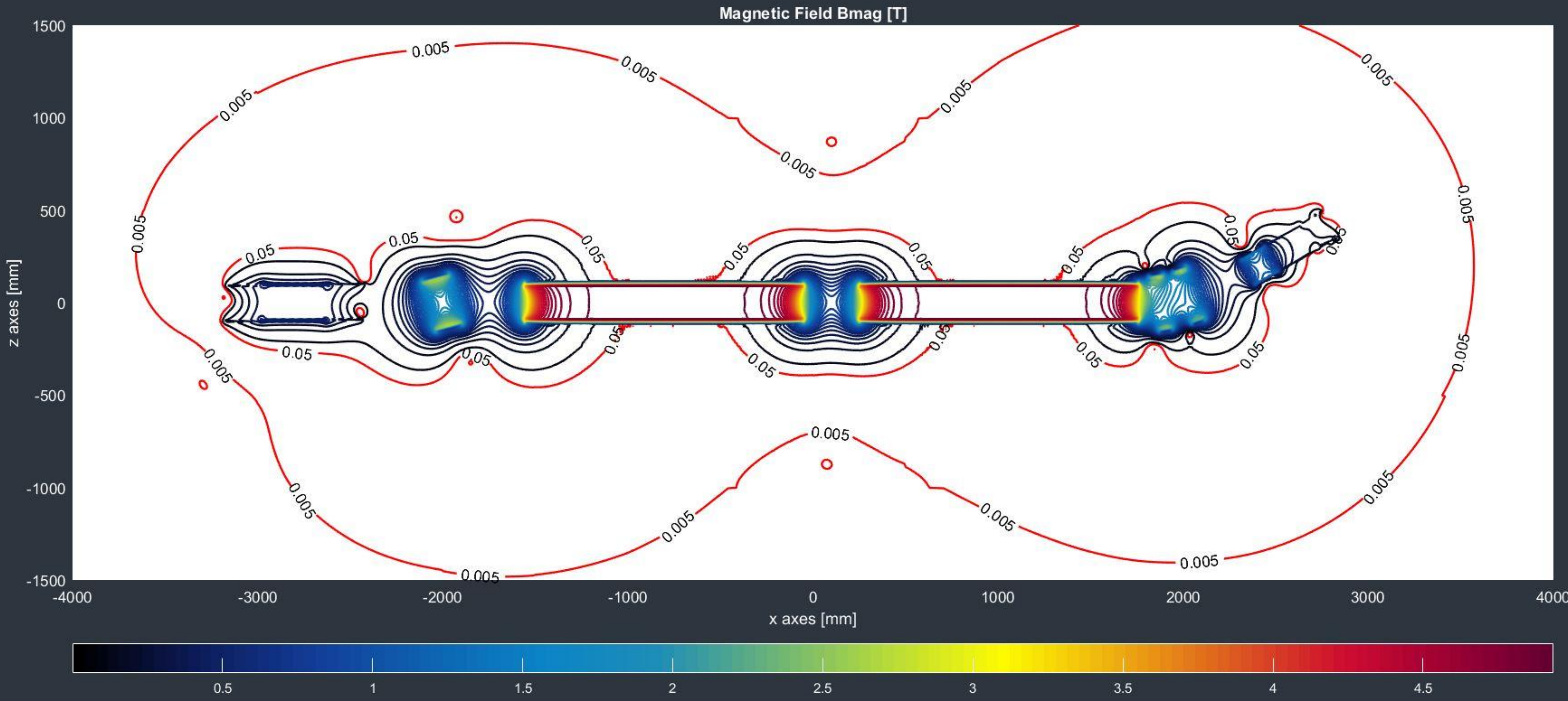


Stray field maps

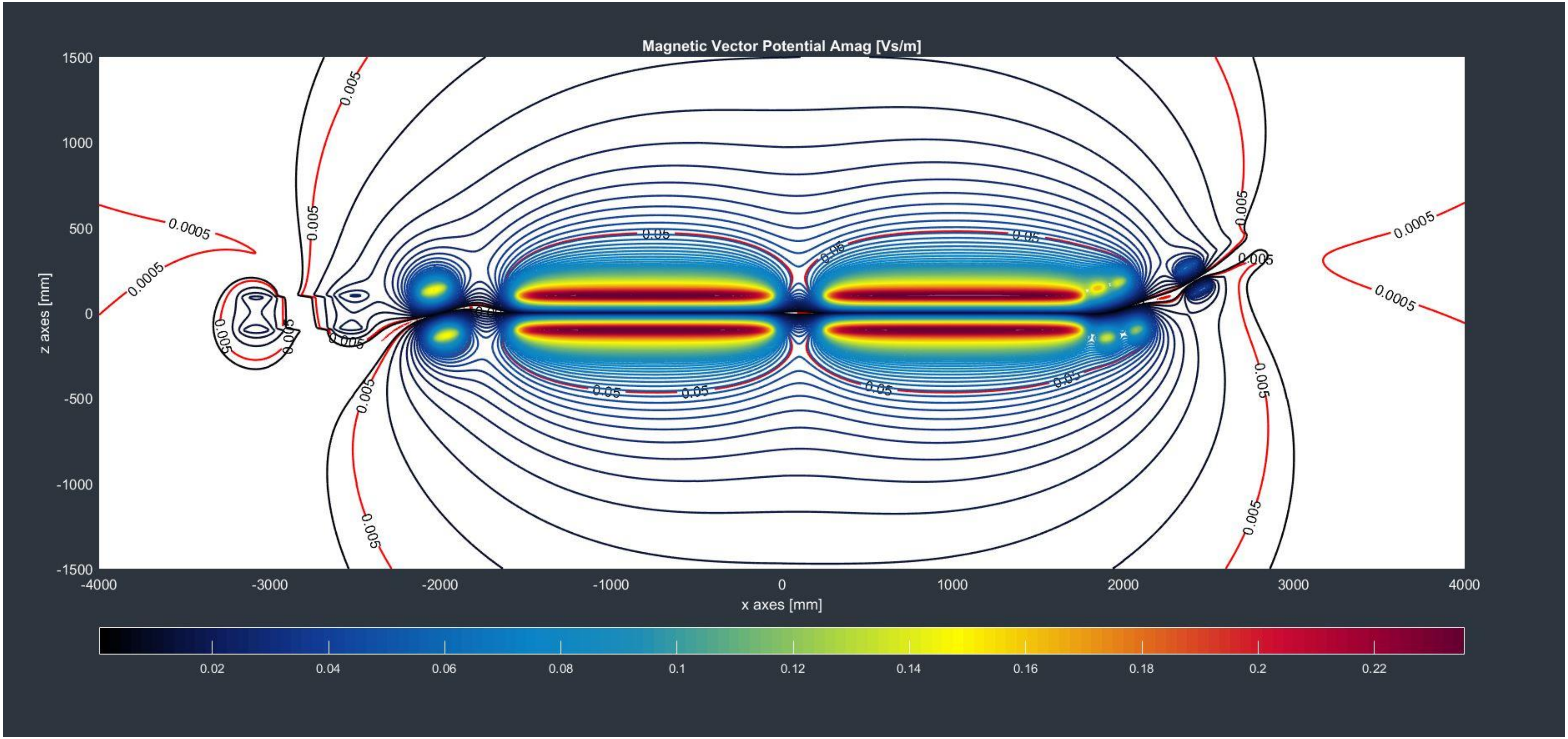


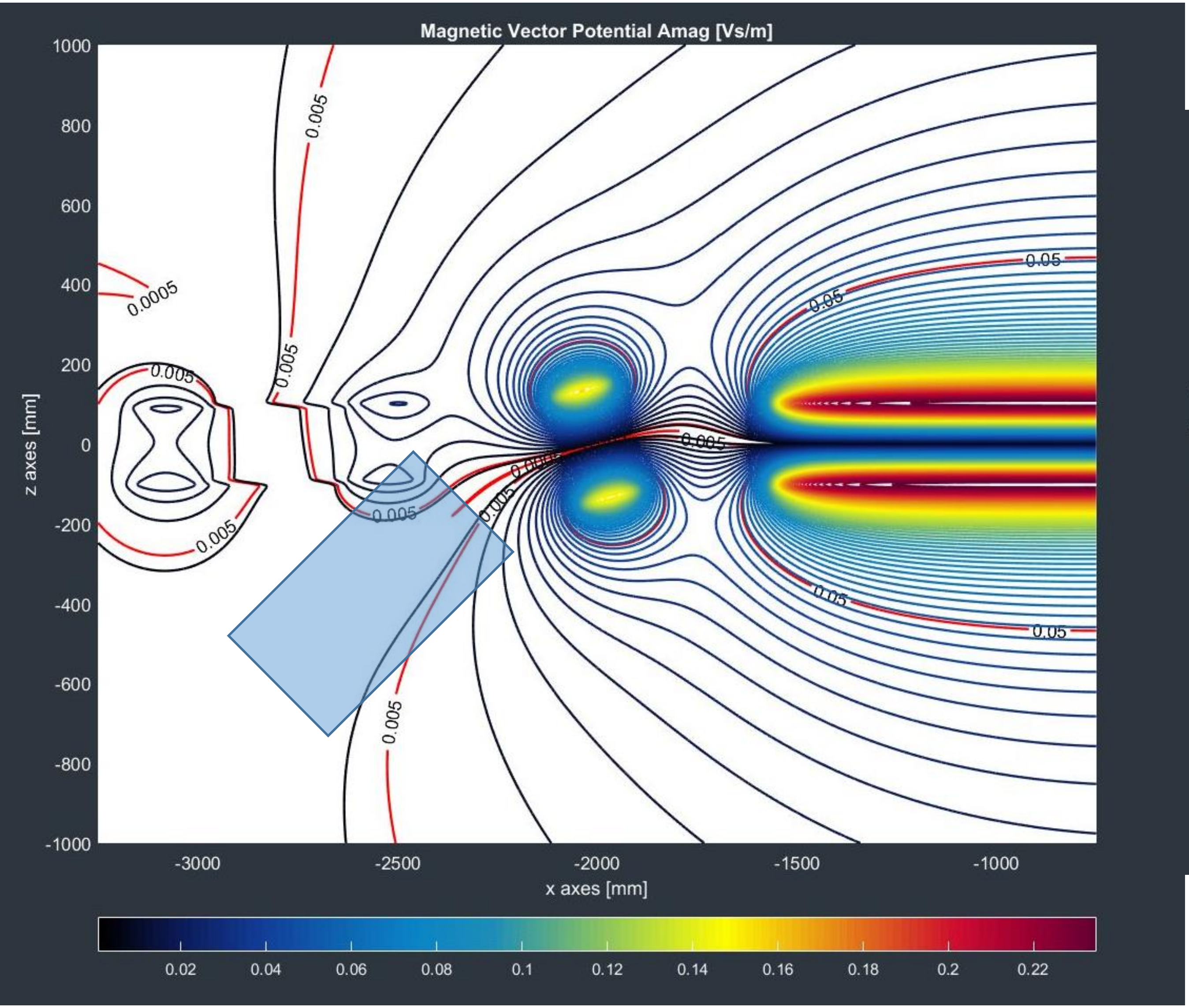
Stray field T need to look at the fields in the other adjacent beam when we have final design .

Vertical stray field map

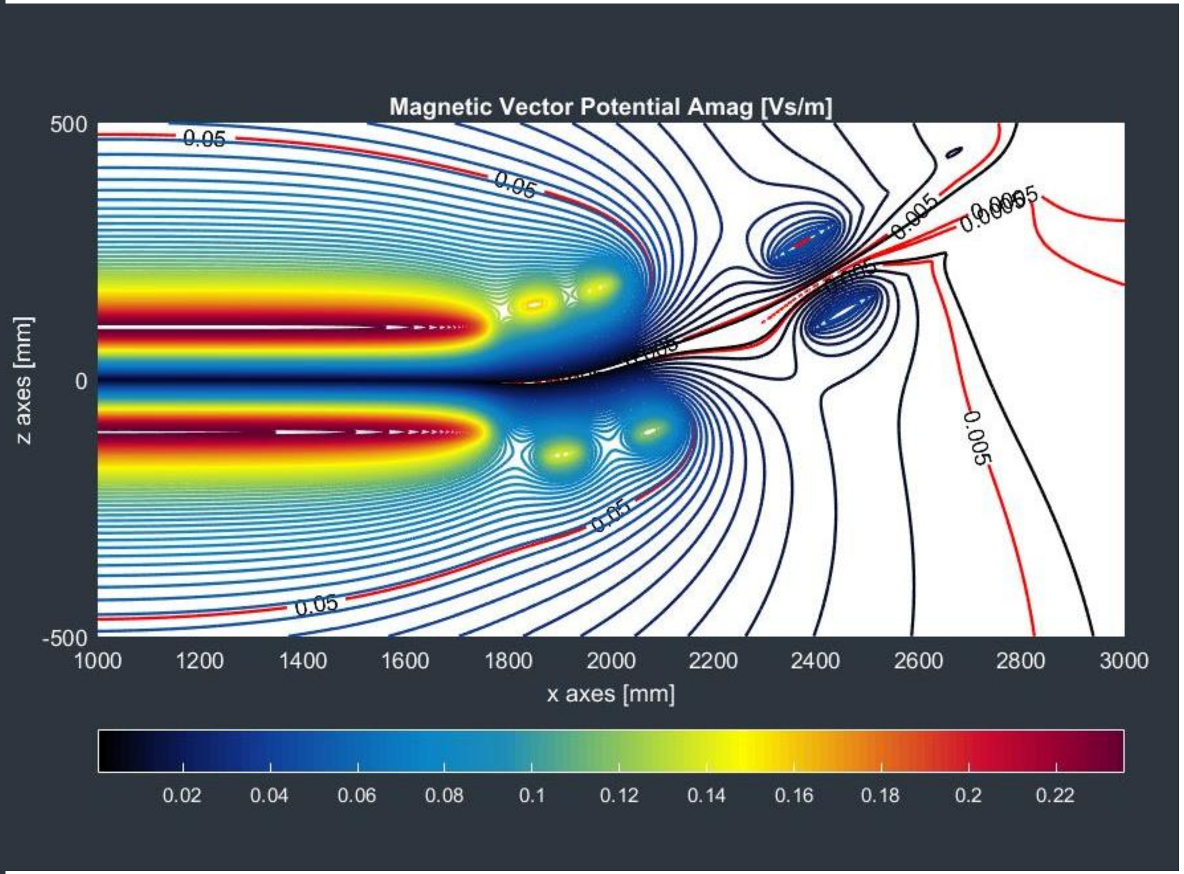


Vector Potential ~ flux lines



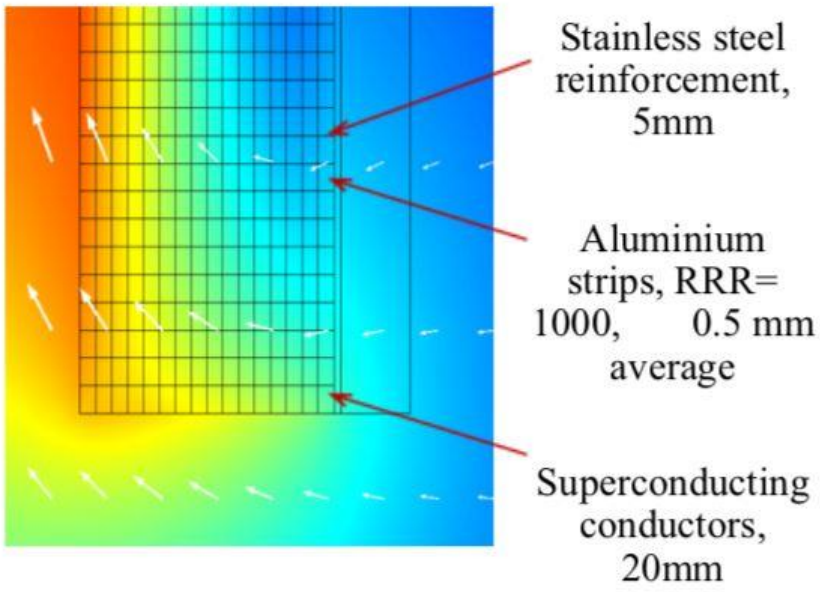


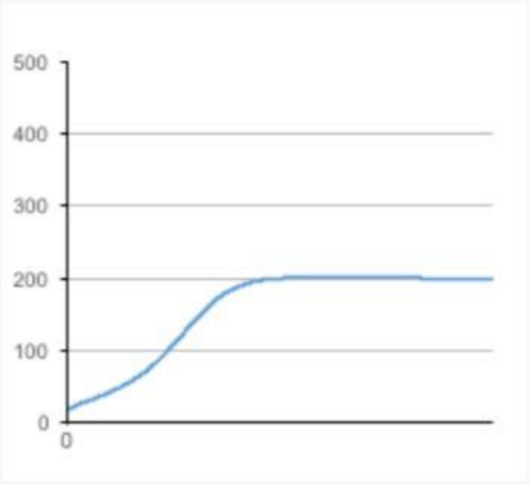
Path from solenoid to dump

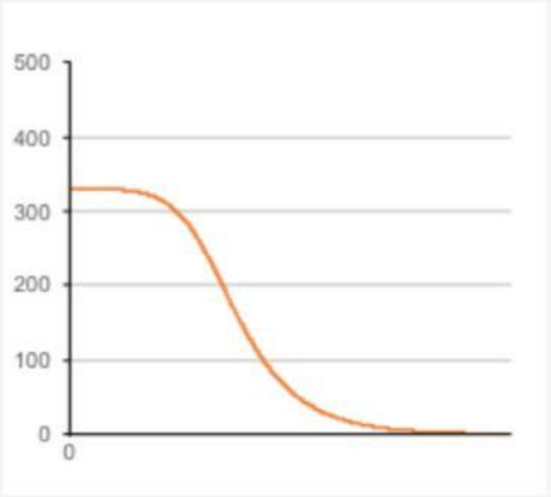


Path from electrons gun to bend coils to main solenoids

Aluminium quench propagation strips







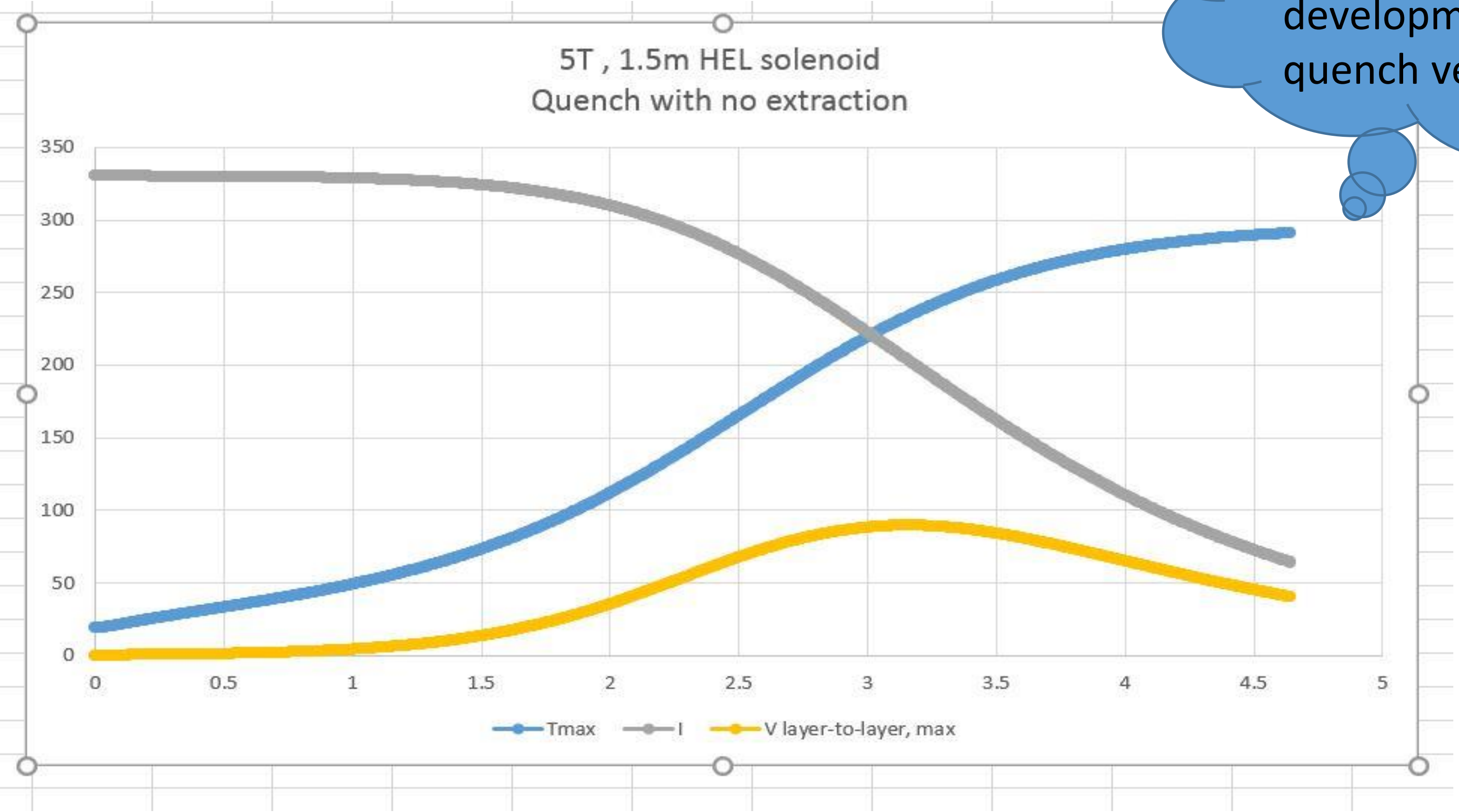
- Aluminium quench propagation strips □ Accelerates quench propagation
- Hotspot temperature reduced from 440 K to 202 K
- Intrinsically self-protected magnet
- Compatible with extraction (redundant protection mechanism in case of dump extraction switch failure)

natural quench, no extraction system, but with high purity aluminium strips. its the 4 T ` 3m coil , so we need to repeat the calculation for the 5T ~ 1.5m coil hot spot should go down as energy/volume magnet half as long/coil.

5T coil 1.5m long

A little too hot for me!

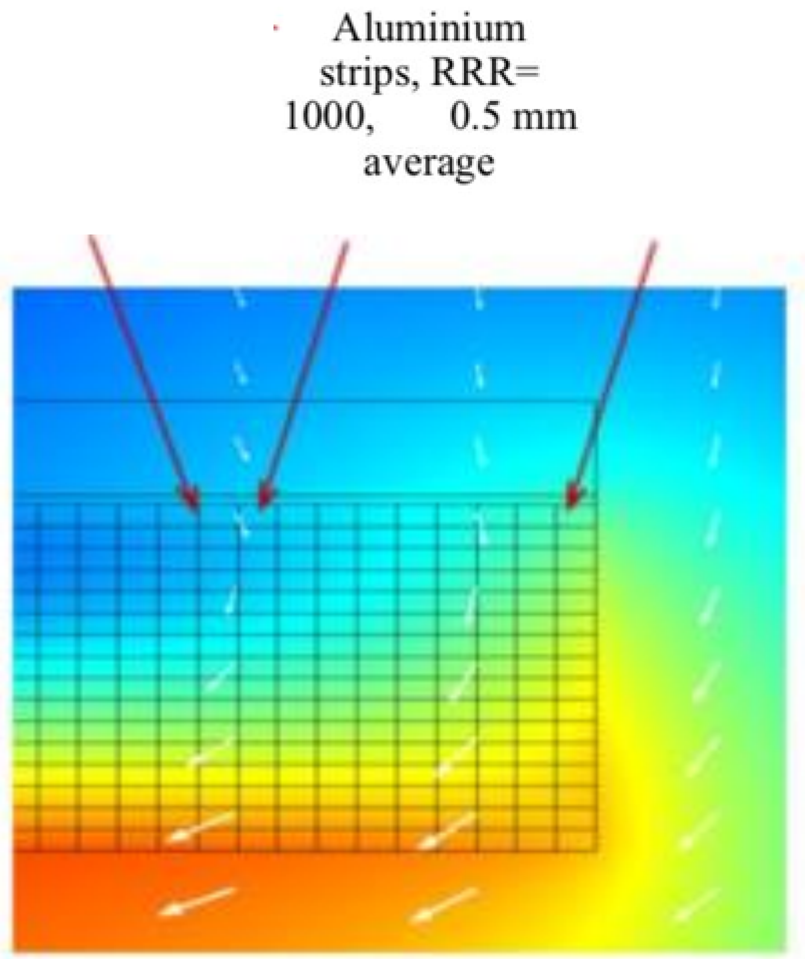
So! EE or some coil development to accelerate quench velocity



Natural quench no extraction 5T -1.5m coil. 300K 100V

Hot spot too high! Voltage ok

5T coil 1.5 m long with high purity Aluminum Propagation strips.



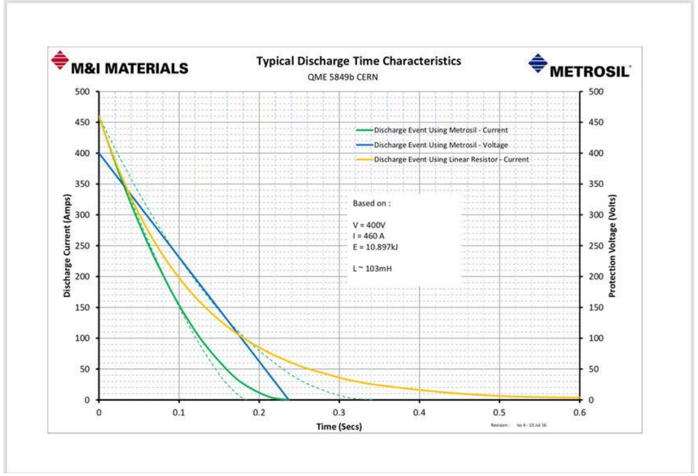
- With Aluminium quench propagation strips, the 1.5 m 5T HEL solenoids would be self-protected. But it ended up above 200 K, something like 240?.
- There are some other things to look at:

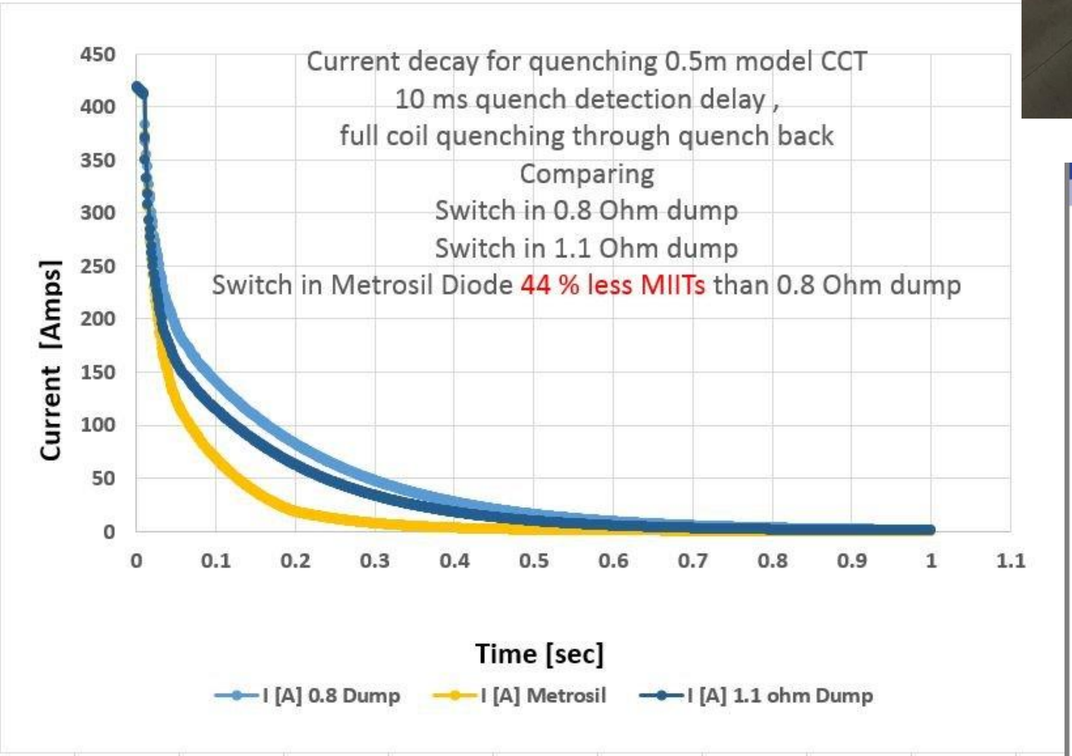
  Quench-back cylinder would help a lot.

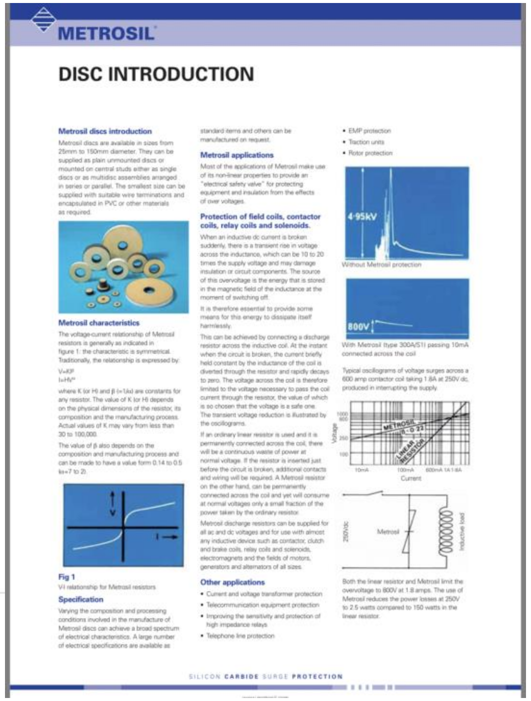
Base line!! should be that we protect these magnets with extraction, so an active system with detection , to trigger switch and either, std Resistor or Metrosil! Constant voltage extraction.

Metrosil new High performance energy extraction system

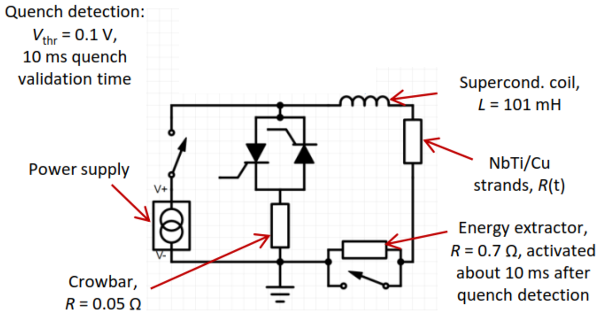
We see an impressive reduction in MIITs with the Metrosil 44% for the High Luminosity D2 CCT orbit corrector being tested







Extraction switch and dump



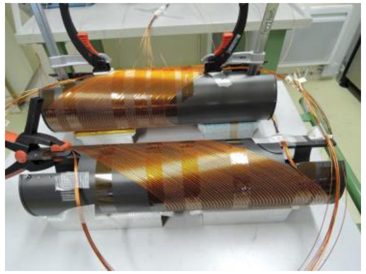
Conclusions (1): Magnetic design

- The two - 5 tesla 1.5 m coil design is in the fine tuning stage.
- The other solenoid will use the same conductor and follow the detailed insulation and construction.
- The CCT coil used to correct the vertical integral component of the two bending coils. Is a copy of the 0.5m D2 corrector with smaller aperture.
- The coil layout in terns of relative position is still evolving but will not effect the coil design.
- The Vertical, Horizontal, Dipole low current coils could follow a classical design or possibly a CCT design. Just need to look at which has the lowest cost.

Conclusion (2): Quench

- The 5 Tesla 1.5 m long solenoids.
  - Base line, is energy extraction (EE) with switch and ether classical resistor or Mertosil (better result).
  - Need to check bus bar protection, but if we stay with the EE this is probably covered.
  - Still looking for a fully passive solution (this will require a model test coil, may be the E-gun coil to fully understand quench velocity through insulation).

- Bending coils
  - This is a low inductance coil identical constriction to the 1.5 m so the Aluminum propagation will give low hot spot and voltages.



- CCT integral correction
  - Coil is very close to the CCT LHC High-Lumi D2 corrector 0.5 m model, this is self protecting.

- Vertical , Horizontal ,and Quad - fine tuning Correctors.
  - All very low current so can be self protecting.

- Bus Bar Protection
  - Assumption: short superconducting bus distance ~3m max from coil to cold-to-warm current leads, then resistive leads to power supply. The cold section can be sized to be self protecting using copper shunt.