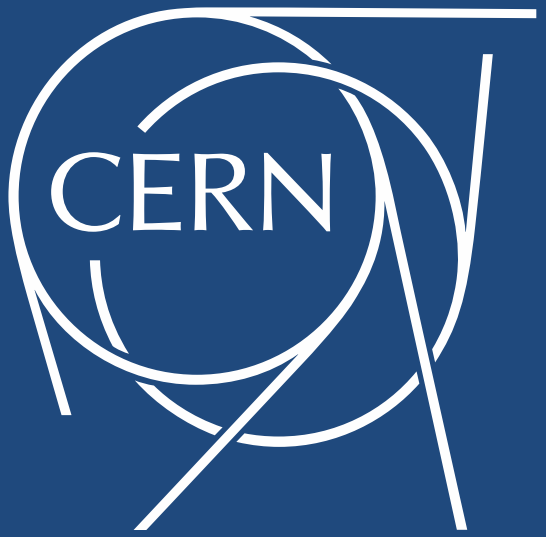

CERN

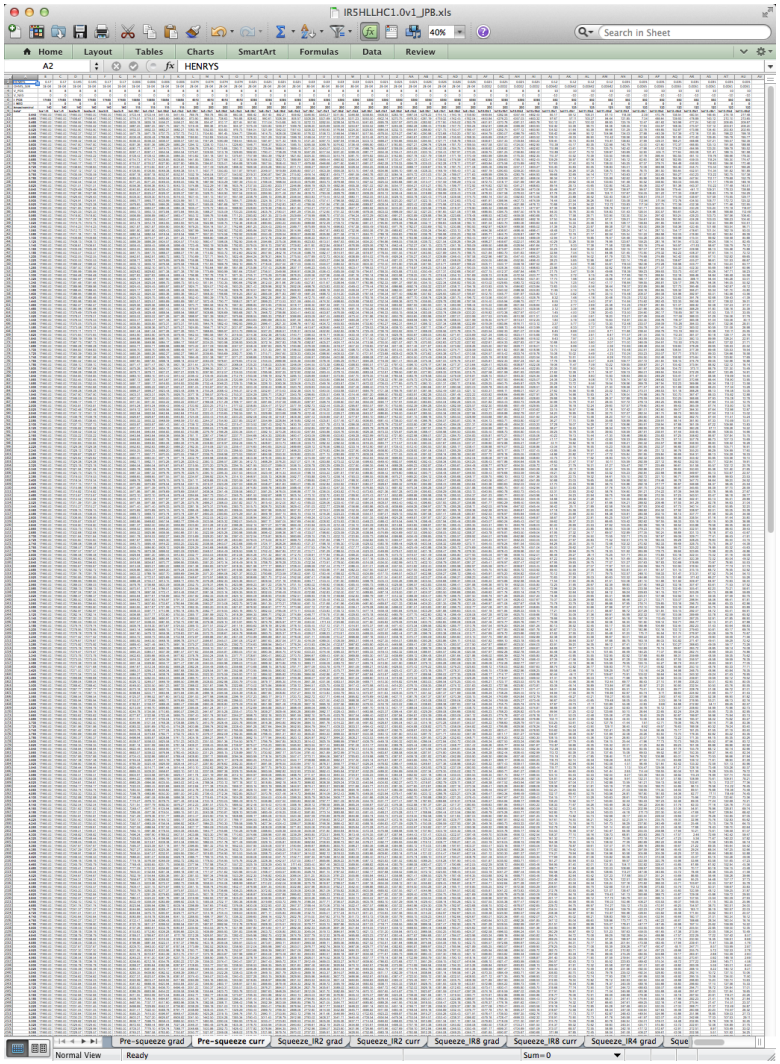
Analysis of time required for pre-squeeze and squeeze

HL-LHC Powering

Pre-Squeeze and Squeeze

Objective:

- Analyse pre-squeeze and squeeze optics file provided by Massimo Giovannozzi to estimate the time required for each circuit: https://indico.cern.ch/event/342270/
- Identify the slowest circuit
- Repeat for different types of power converter topology (1-quadrant, 1-quadrant with diodes, 2-quadrant)



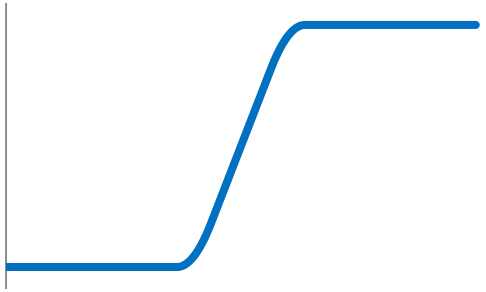
Squeeze Function by OP for LHC

The existing squeeze is based on relatively few optics points along the squeeze:

Optics name	Momentum	time [s]
A1100C1100A1000L1000_2014	6500	0
A900C900A900_0.00915L750_0.00932_2014	6500	155
A700C700A750_0.00897L600_0.00909_2014	6500	252
A400C400A600_0.00889L500_0.00900_2014	6500	374
A300C300A500_0.00889L375_0.00888_2014	6500	430
A250C250A450_0.00889L350_0.00882_2014	6500	462
A200C200A400_0.00889L325_0.00878_2014	6500	505
A160C160A350_0.00889L300_0.00875_2014	6500	547
A150C150A300_0.00889L300_0.00875_2014	6500	588
A120C120A300_0.00889L300_0.00875_2014	6500	630
A100C100A300_0.00889L300_0.00875_2014	6500	679
A90C90A300_0.00889L300_0.00875_2014	6500	720
A80C80A300_0.00889L300_0.00875_2014	6500	780
A70C70A300_0.00889L300_0.00875_2014	6500	905
A60C60A300_0.00889L300_0.00875_2014	6500	988

Parabola-Linear-Parabola segments

- OP use P-L-P segments to define the field as a function of time for all circuits between the optics points
- The circuit with the minimum linear rate is identified and this defines the segment time for all the circuits.
- The circuit with the minimum acceleration/deceleration is identified and this defines the acceleration/deceleration time for all circuits.
- It is essential that the parabolic-linear-parabolic sections start and end at the same time for all circuits.
- The time spent during the parabolas slows down the whole squeeze.



Time spent in the parabolas

- Between 6% and 24% of the time is spent in the parabolic sections:

Min. time [s]	Limiting circuit	min parabolic time	parabolic fraction
154.81	RQ4.R2B2	10.0	**0.06**
96.91	RQ4.R2B2	10.0	**0.10**
121.96	RQT12.L5B2	10.0	**0.08**
55.86	RQ5.R8B1	9.6	**0.17**
31.24	RQ6.R5B2	7.5	**0.24**
42.65	RQ6.L5B2	9.0	**0.21**
41.23	RQ6.L5B2	10.0	**0.24**
40.26	RQ4.L2B1	8.1	**0.20**
41.73	RQ6.L5B2	10.0	**0.24**
48.66	RQ6.L1B2	10.0	**0.21**
40.36	RQ6.L1B2	8.4	**0.21**
59.31	RQ6.R5B2	9.4	**0.16**
124.21	RQ6.R5B2	10.0	**0.08**
82.50	RQ6.L5B1	10.0	**0.12**

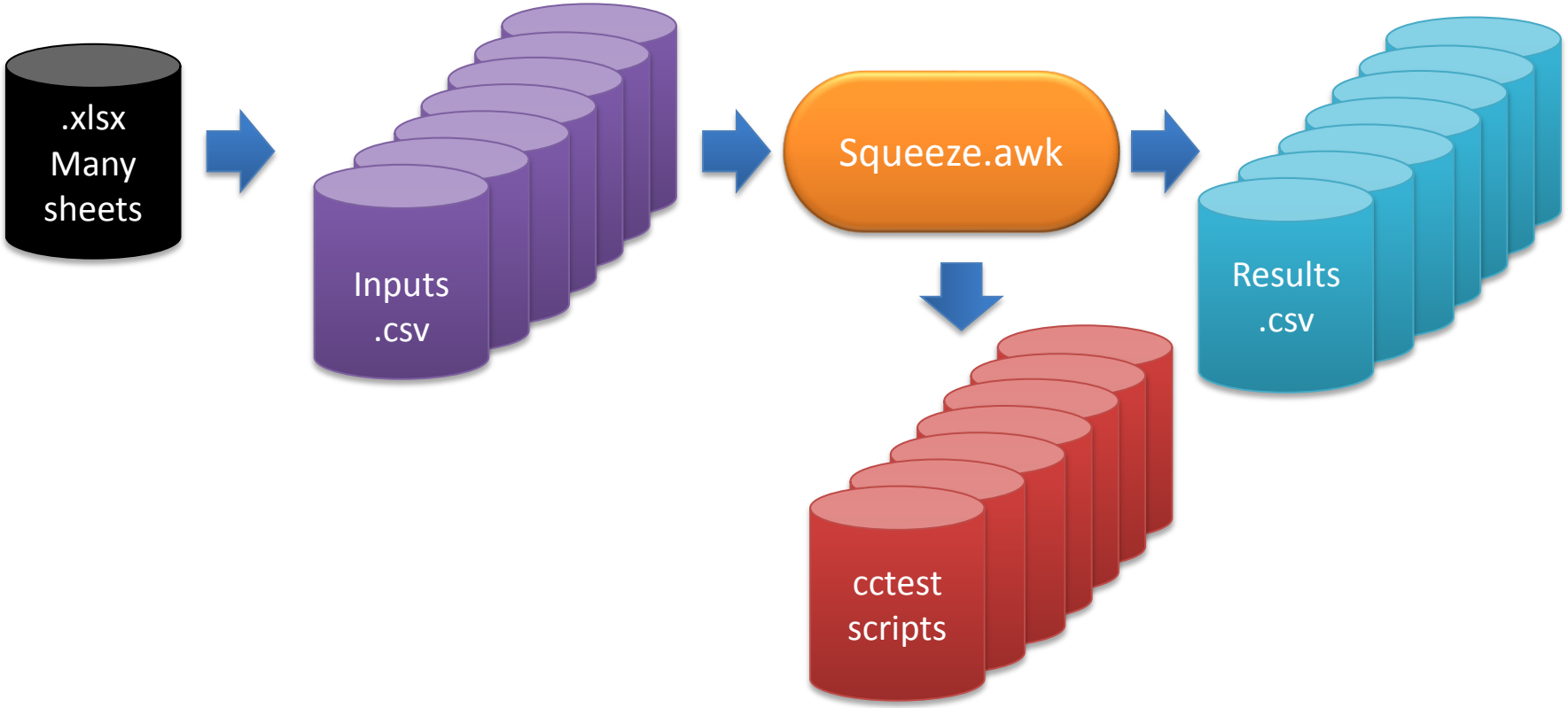
Field to Current

- Each P-L-P segment for field strength is converted into a linearly interpolated table of current against time, using the known calibration function for each circuit
- The FGCs receive and execute the tables

HL-LHC analysis

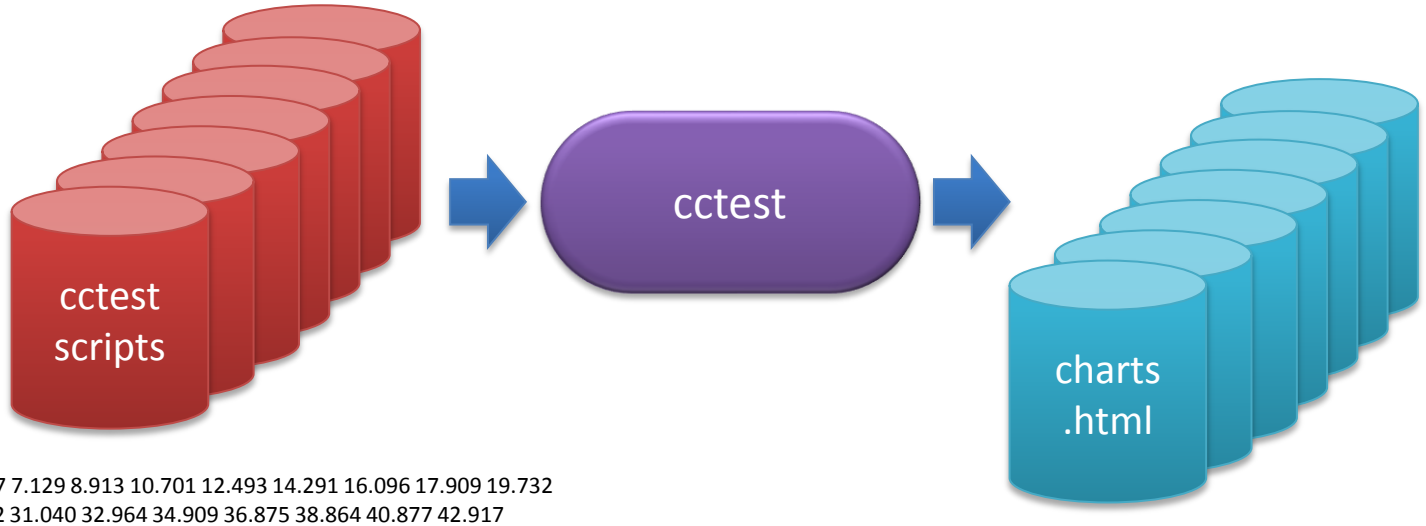
- Too many optics points (278) to apply the OP method.
- Simplistic first approach using linear interpolation between the 278 points resulting in one continuous squeeze function.
- No parabolic acceleration/deceleration so results will not be precise but will give an idea of the time needed for the squeeze.
- Allows comparison between different converter topologies.

Analysis Method

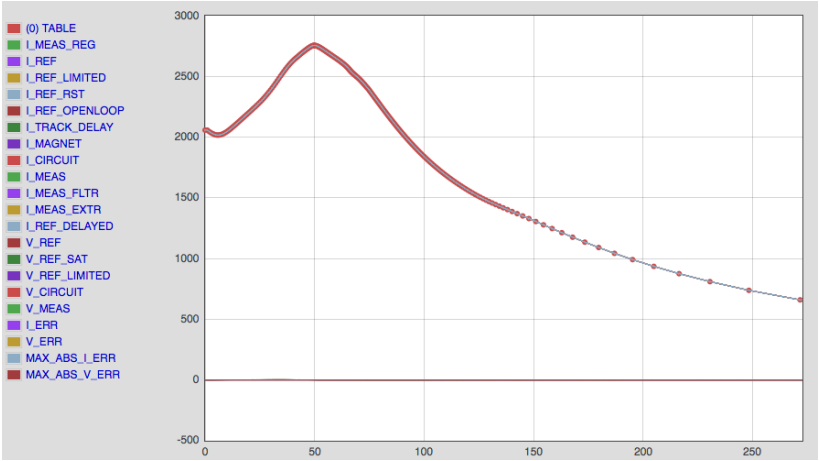


- Inputs are currents as a function of beta*
- Results are currents as a function of time

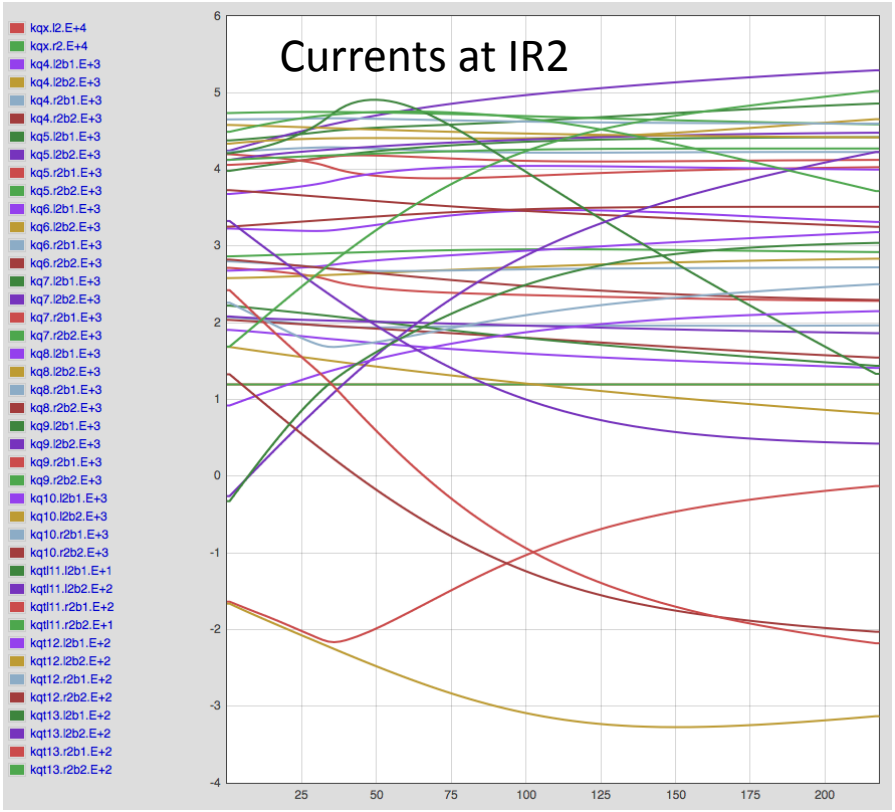
cctest simulations

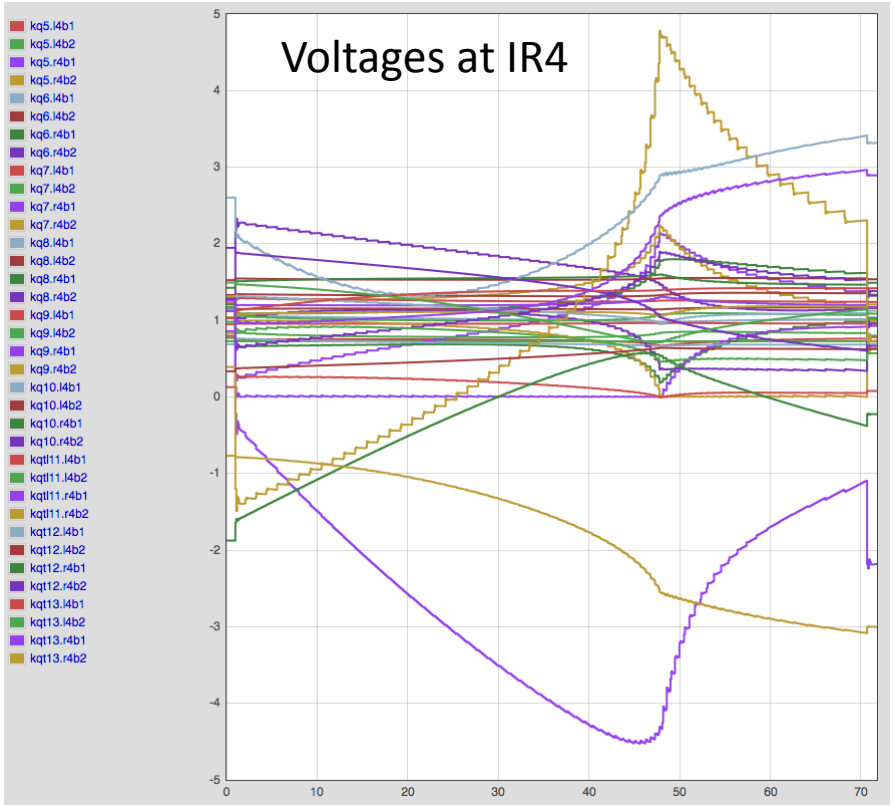



```
# cctest script for IR2-kq4.l2b1

LOAD HENRYS   0.148
LOAD OHMS_SER 0.00049
LIMIT I_POS   3610
LIMIT I_NEG   0
LIMIT V_POS   8
LIMIT V_NEG   0

TABLE TIME 0.000 1.784 3.566 5.347 7.129 8.913 10.701 12.493 14.291 16.096 17.909 19.732
21.565 23.436 25.295 27.224 29.112 31.040 32.964 34.909 36.875 38.864 40.877 42.917
44.984 47.082 49.210 51.372 53.568 55.803 58.073 60.389 62.742 65.147 67.591 70.093
72.636 75.245 77.896 80.621 83.391 86.243 89.140 92.131 95.169 98.313 101.507 104.821
108.189 111.693 115.260 118.981 122.779 126.752 130.820 135.089 139.483 144.109 148.900
153.964 159.249 164.858 170.763 177.060 183.750 190.928 198.631 206.955 215.983
TABLE REF 1906.944 1902.167 1897.221 1892.091 1886.76 1881.209 1875.418 1869.368
1863.129 1856.626 1849.916 1842.938 1835.75 1828.327 1820.72 1812.999 1805.332 1797.91
1791.062 1784.571 1778.237 1771.382 1764.417 1756.847 1749.421 1741.559 1734.08
1726.329 1718.963 1711.43 1704.2 1696.84 1689.775 1682.578 1675.681 1668.635 1661.867
1654.928 1648.229 1641.335 1634.648 1627.747 1621.032 1614.09 1607.324 1600.321
1593.49 1586.418 1579.515 1572.367 1565.382 1558.147 1551.079 1543.753 1536.569
1529.111 1521.723 1514.037 1506.336 1498.302 1490.159 1481.635 1473.042 1464.007
1454.491 1444.454 1433.85 1422.628 1410.731

RUN

# EOF
```



Merged charts for current and voltage for all circuits at a point





http://project-cclibs.web.cern.ch/project-cclibs/cclibs/cctest/results/html/tests/HL_LHC/

Input CSV files

IR5.csv – OpenOffice Calc

A1: HENRYS

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	HENRYS	0.17	0.17	0.145	0.145	0.17	0.17	0.006	0.006	0.006	0.006	0.074	0.074	0.074	0.074	0.021	0.021	0.021	0.021	0.03	0.03	(
2	OHMS_SER	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.000252	0.000252	0.000
3	V_POS	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	
4	V_NEG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5	I_POS	17460	17460	17460	17460	17460	17460	15650	15650	15650	15650	4510	4510	4510	4510	5390	5390	5390	5390	5390	5390	5
6	I_NEG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7	kmax/nominal	140	140	140	140	140	140	115	115	115	115	200	200	200	200	200	200	200	200	200	200	
8	beta*	lqx1.l5	lqx1.r5	lqx2a.l5	lqx2a.r5	lqx3.l5	lqx3.r5	lq4.l5b1	lq4.r5b1	lq4.l5b2	lq4.r5b2	lq5.l5b1	lq5.r5b1	lq5.l5b2	lq5.r5b2	lq6.l5b1	lq6.r5b1	lq6.l5b2	lq6.r5b2	lq7.l5b1	lq7.r5b1	lq7.l5b
9	0.44	17460	17460	17460	17460	17460	17460	5703.44	5703.44	5411.45	5411.45	789.78	789.78	660.08	660.08	686.42	857.4	892.21	659.62	5346.9	5343.27	53
10	0.46	17460	17460	17458.47	17458.47	17460	17460	5774.51	5774.51	5485.8	5485.8	873.9	866.05	738.63	745.88	828.62	990.61	1028.39	806.57	5308.28	5301.69	527
11	0.48	17460	17460	17456.95	17456.95	17460	17460	5835.18	5835.18	5556.21	5556.21	950.06	934.47	810.17	827.44	957.6	1111.04	1145.88	943.1	5272.13	5262.55	523
12	0.5	17460	17460	17455.42	17455.42	17460	17460	5887.25	5887.25	5621.75	5621.75	1019.46	996.36	875.64	904.37	1075.49	1220.8	1249.37	1069.78	5238.2	5225.69	520
13	0.52	17460	17460	17453.9	17453.9	17460	17460	5932.33	5932.33	5682.21	5682.21	1083.18	1052.83	935.83	976.73	1184.04	1321.59	1342.02	1187.43	5206.32	5190.93	517
14	0.54	17460	17460	17452.37	17452.37	17460	17460	5971.78	5971.78	5737.73	5737.73	1142.13	1104.8	991.45	1044.71	1284.65	1414.75	1426.08	1296.9	5176.32	5158.13	514
15	0.56	17460	17460	17450.85	17450.85	17460	17460	6006.48	6006.48	5788.96	5788.96	1196.9	1152.89	1043.04	1108.78	1378.33	1501.29	1502.56	1399.18	5148.04	5127.13	512
16	0.58	17460	17460	17449.32	17449.32	17460	17460	6036.33	6036.33	5836.57	5836.57	1247.53	1197.26	1090.89	1169.44	1465.53	1581.67	1571.32	1495.15	5121.2	5097.73	509
17	0.6	17460	17460	17447.8	17447.8	17460	17460	6061.36	6061.36	5880.29	5880.29	1294.12	1238.1	1135.14	1226.6	1546.71	1656.37	1633.04	1585.15	5095.58	5069.76	507

Sheet1

Sheet 1 / 1 | Default | STD | Sum=0 | 90 %

Simulated Squeeze Times

(ignoring acceleration/deceleration and intermediate stopping points)

```
IR2          :    Total time: 215.983
IR4          :    Total time:  69.691
IR5          :    Total time: 825.683
IR6          :    Total time:  14.070
IR8          :    Total time:  81.242
IR8_3m       :    Total time: 175.908
```

IR5 (IR1 is the same) dominates the squeeze time.

Squeeze times at IR5

```
IR5          :      Iq4.l5b1:   1.943
IR5          :      Iq4.r5b1:  14.666
IR5          :      Iq5.r5b1:  91.888
IR5          :      Iq5.l5b2: 216.857
IR5          :      Iq5.r5b2: 500.330
IR5          :   Total time: 825.683
```

Within IR5, it is the Iq5 circuits that are the slowest.

IR5 times with 2-quandrant q5 converters

If the q5 converters are 2-quadrant, the time is reduced:

```
IR5-q5-2Q      :      Iq4.l5b1:  16.450
IR5-q5-2Q      :      Iq4.r5b1:  22.428
IR5-q5-2Q      :      Iq4.l5b2:   6.142
IR5-q5-2Q      :      Iq6.l5b1:   5.849
IR5-q5-2Q      :      Iq6.r5b1:  16.400
IR5-q5-2Q      :      Iq6.l5b2:  58.631
IR5-q5-2Q      :      Iq6.r5b2: 149.010
IR5-q5-2Q      :   Total time: 274.911
```

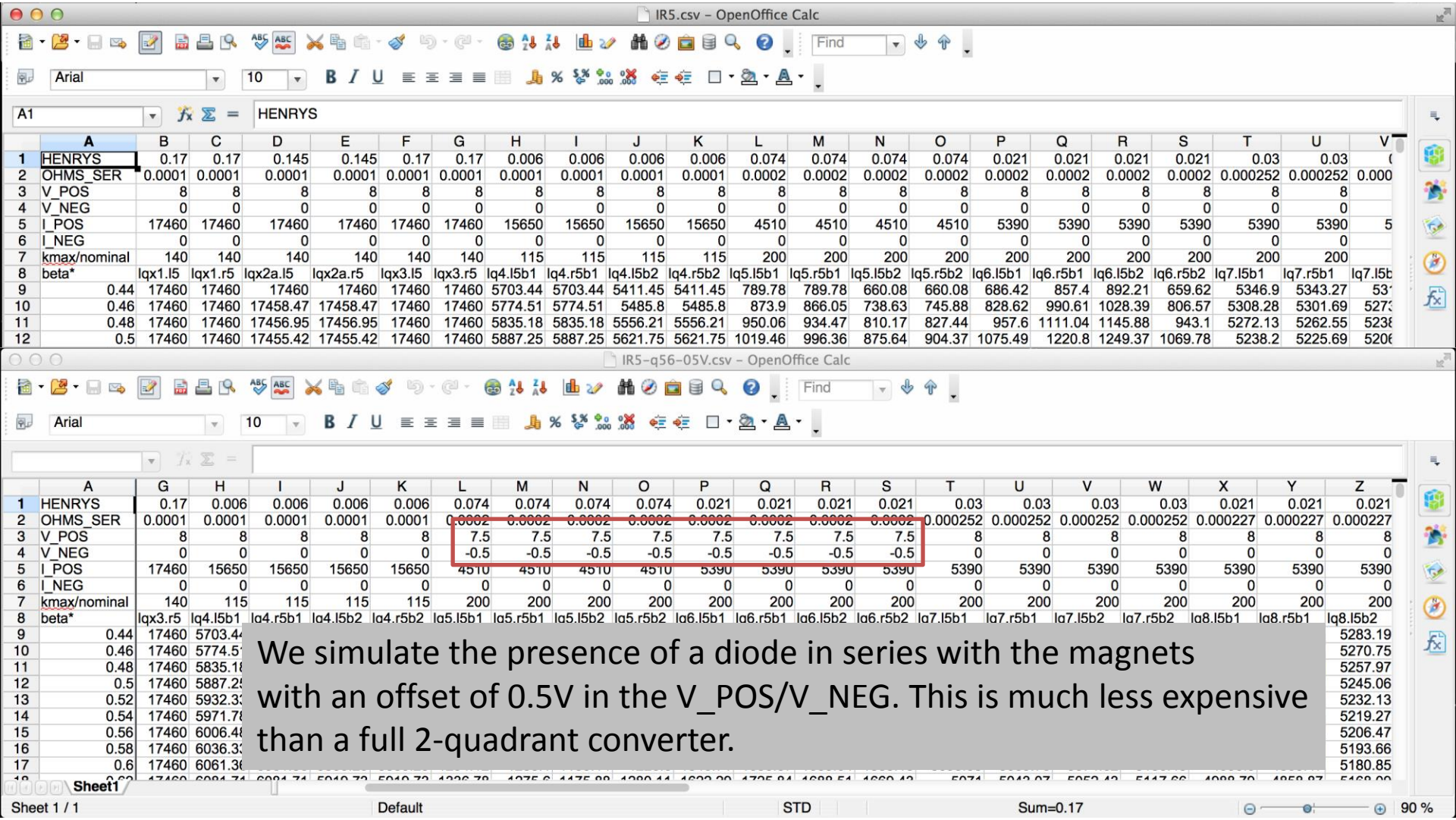
Now the Iq6 converters are the slowest.

IR5 times with 2-quandrant q5 & q6 converters

```
IR5-q56-2Q    :      Iq4.l5b1:  17.197
IR5-q56-2Q    :      Iq4.r5b1:  32.389
IR5-q56-2Q    :      Iq4.l5b2:  14.466
IR5-q56-2Q    :      Iq5.r5b1:   4.473
IR5-q56-2Q    :      Iq5.l5b2:   0.342
IR5-q56-2Q    :      Iq5.r5b2:   3.386
IR5-q56-2Q    :      Iq9.r5b2:   1.423
IR5-q56-2Q    :     Iq10.r5b1:   3.758
IR5-q56-2Q    :     Iq10.l5b2:  14.059
IR5-q56-2Q    :    Total time:  91.493
```

If both Iq5 and Iq6 converters are 2-quadrant, the time is reduced unnecessarily because IR2 will take more than 200 s.

An alternative to real 2-quadrant converters



I5 squeeze times with 1 series diode

```
IR5-q56-05V   :      Iq4.l5b1:  13.201
IR5-q56-05V   :      Iq4.r5b1:  16.980
IR5-q56-05V   :      Iq5.r5b1:  82.254
IR5-q56-05V   :      Iq5.l5b2:  56.743
IR5-q56-05V   :      Iq5.r5b2: 146.648
IR5-q56-05V   :   Total time: 315.827
```

If both Iq5 and Iq6 converters have one diode in series the time is reduced by about 500 seconds

I5 squeeze times with 2 series diodes

```
IR5-q56-1V    :      Iq4.l5b1:  15.683
IR5-q56-1V    :      Iq4.r5b1:  20.122
IR5-q56-1V    :      Iq5.r5b1:  58.627
IR5-q56-1V    :      Iq5.l5b2:  29.382
IR5-q56-1V    :      Iq5.r5b2:  84.767
IR5-q56-1V    :    Total time: 208.581
```

If both Iq5 and Iq6 converters have **two** diodes in series (1V offset) then the time is reduced by a further 100 seconds and is now less than IR2.

I5 squeeze times with 4 series diodes

```
IR5-q56-2V    :      Iq4.l5b1:  14.717
IR5-q56-2V    :      Iq4.r5b1:  24.826
IR5-q56-2V    :      Iq4.l5b2:   7.236
IR5-q56-2V    :      Iq5.r5b1:  33.193
IR5-q56-2V    :      Iq5.l5b2:  15.305
IR5-q56-2V    :      Iq5.r5b2:  41.535
IR5-q56-2V    :   Total time: 136.811
```

If both Iq5 and Iq6 converters have **four** diodes in series (2V offset) then the time is reduced by a further 70 seconds.

Summary of Squeeze Times

```
IR2           :    Total time: 215.983
IR4           :    Total time:  69.691
IR6           :    Total time:  14.070
IR8           :    Total time:  81.242
IR8_3m        :    Total time: 175.908

IR5           :    Total time: 825.683
IR5-q5-2Q     :    Total time: 274.911
IR5-q56-2Q    :    Total time:  91.493

IR5-q56-05V   :    Total time: 315.827
IR5-q56-1V    :    Total time: 208.581
IR5-q56-2V    :    Total time: 136.811
```

The *two diodes in series* option

- Two diodes in series for the q5 and q6 circuits will balance IR5/1 and IR2 squeeze times at around 200s.
- 1V at 5kA = 5kW
- 8 circuits -> 40 kW
- Water cooling needed but it's feasible
- This would be a much cheaper option than new 2-quadrant converters

- This presentation and the link to the cctest simulation results are here: https://indico.cern.ch/event/369635/

www.cern.ch