6D Cooling Options

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2. RFOFO Guggenheim
3. HCC Helical Cooling Channel
4. Comparison of performances
5. Critical R&D for Guggenheim
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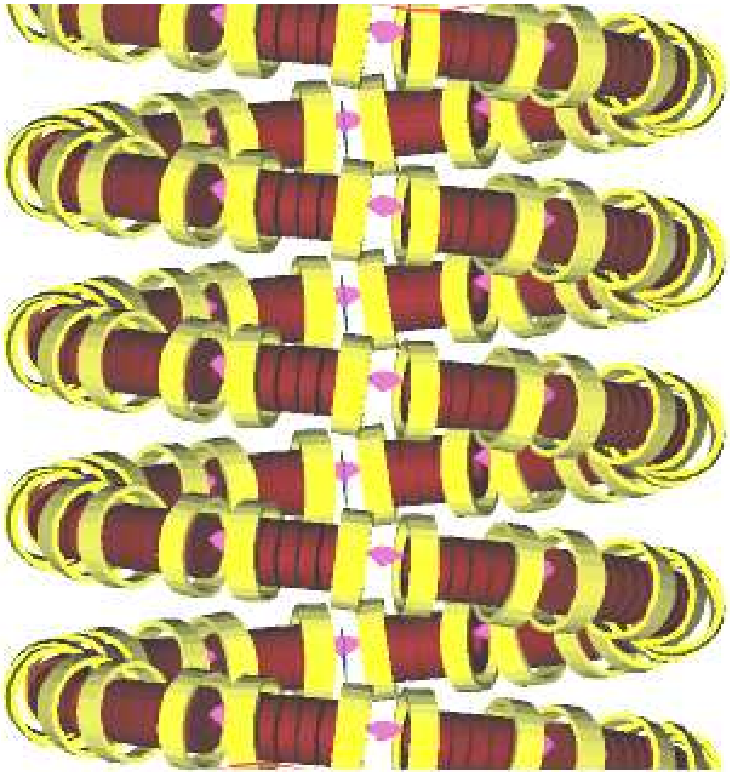
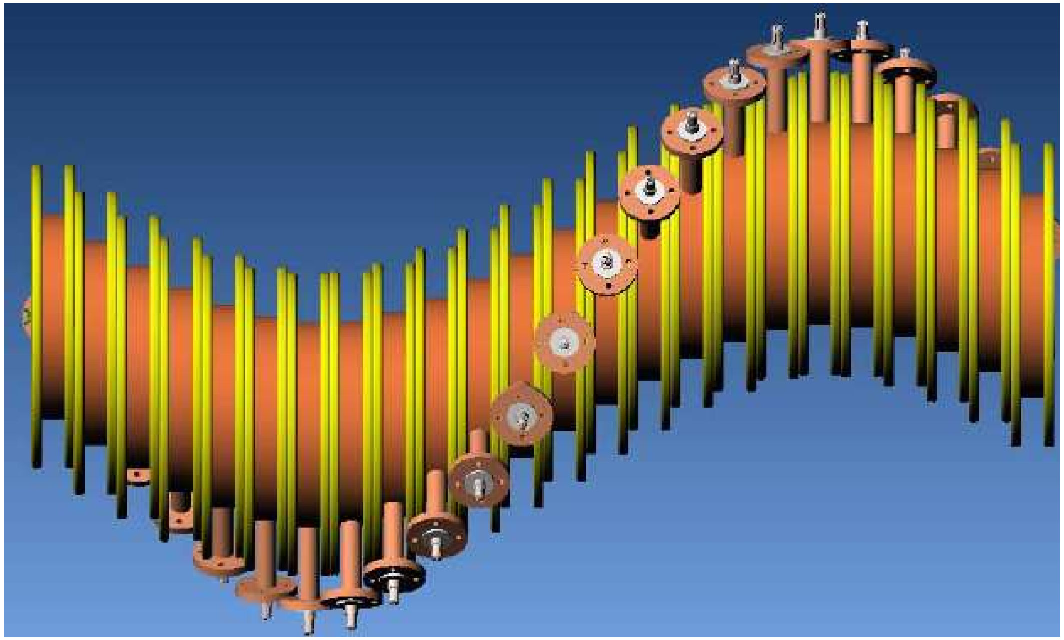
7. Conclusions

Leading Candidate 6D Cooling Lattices



Guggenheim (wedge)

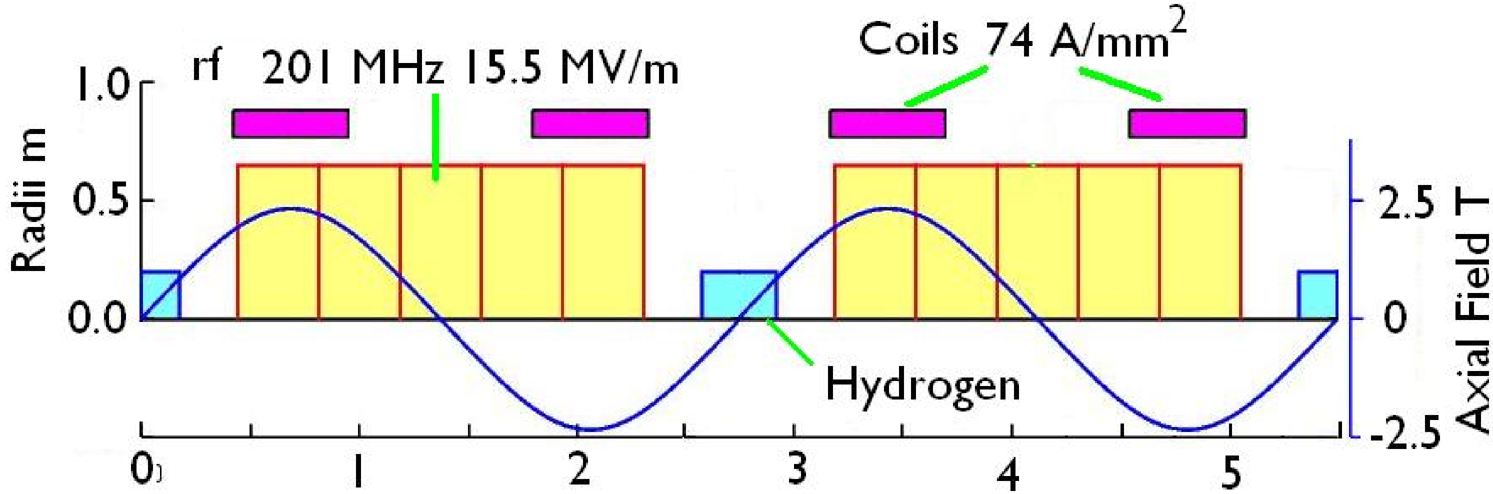


Helical Cooling Channel (path)
Outer solenoid not shown

I will not discuss a third option: FOFO Snake that could play a role in the early 6D cooling, but has not been shown to meet the later 6D cooling

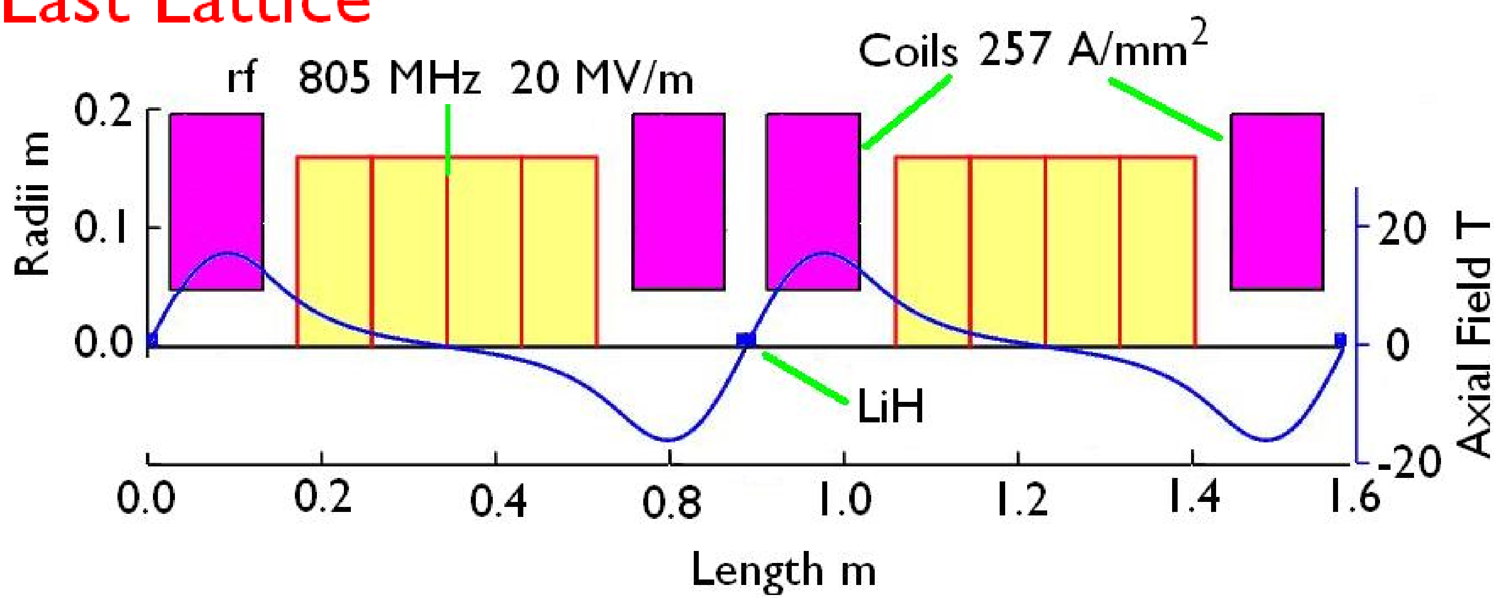
RFOFO Guggenheim lattices

First Lattice



Max field
on rf
2.4 T

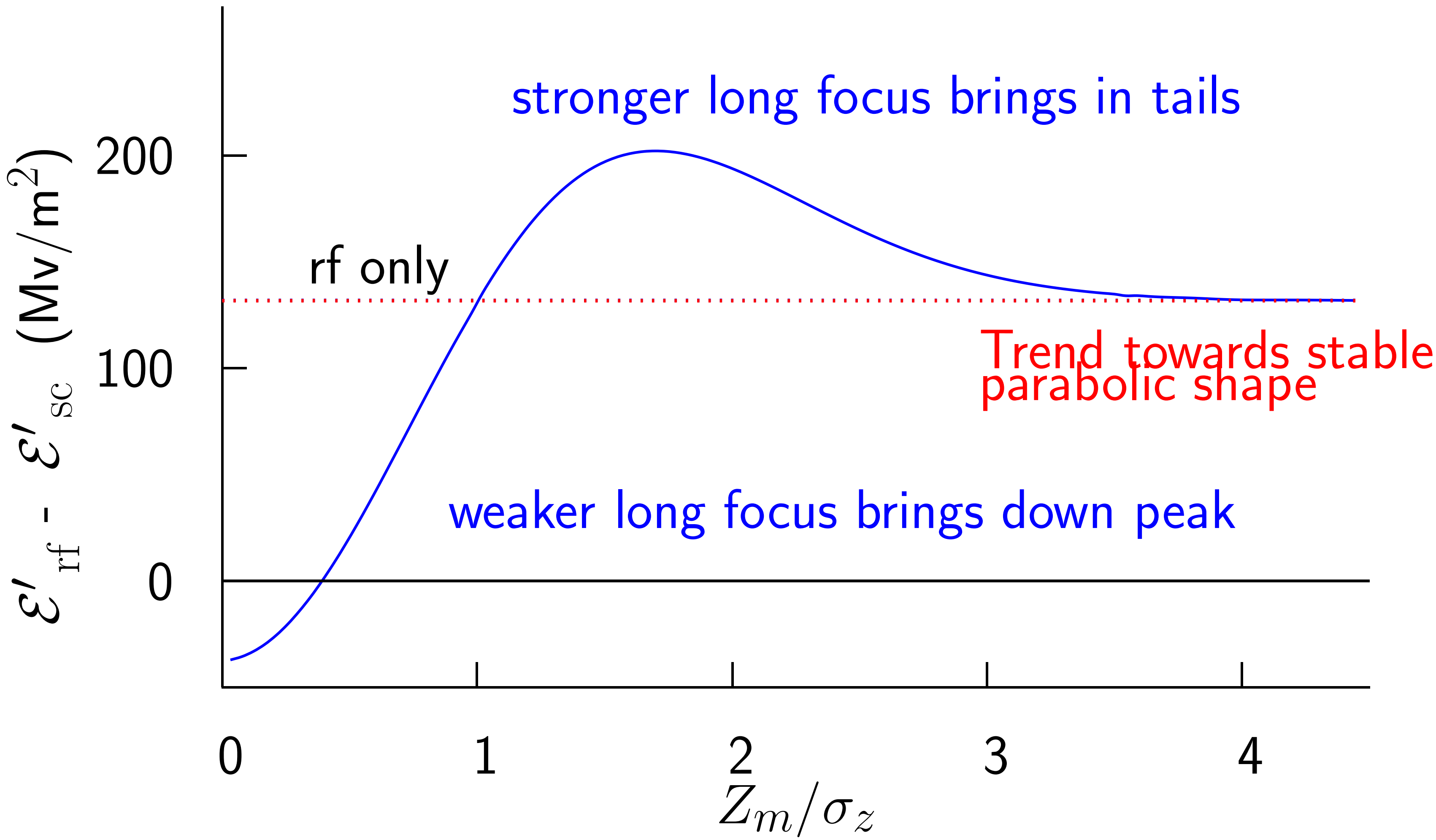
Last Lattice



Max field
on rf
6 T

- Coils tilted to generate transverse field (not shown)

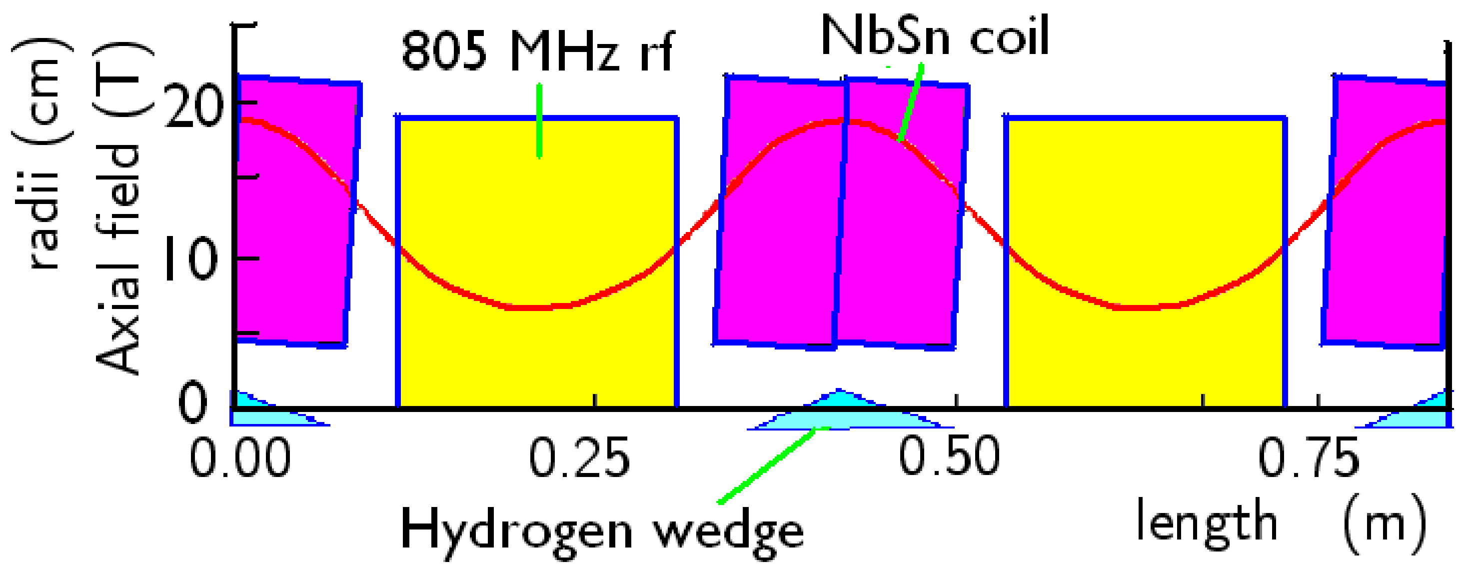
Longitudinal Space Charge effects in last stage



- These effects are large
- Full simulations are essential
- Longitudinal cooling may have to be reduced

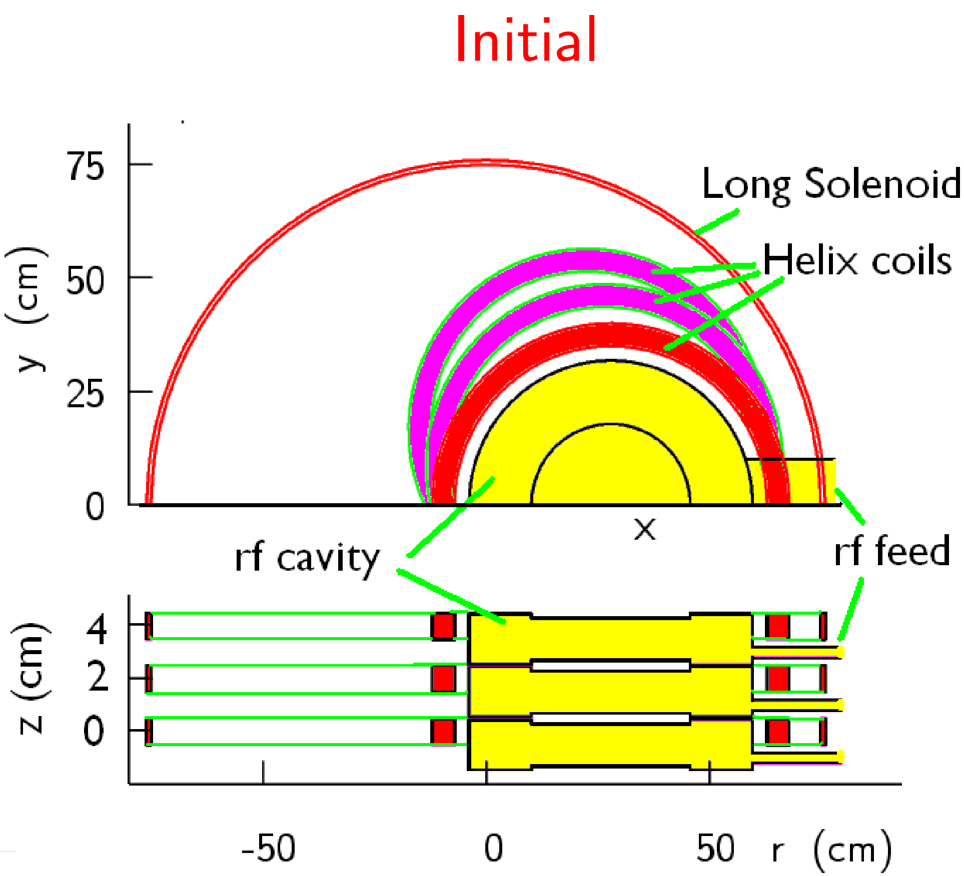
Non-flip lattice

- To offset reduction of long cooling requires more transverse cooling to emittance (0.24 mm)
- To achieve this a new lattice is required
- This lattice operates without frequent field reversals (non-flip)

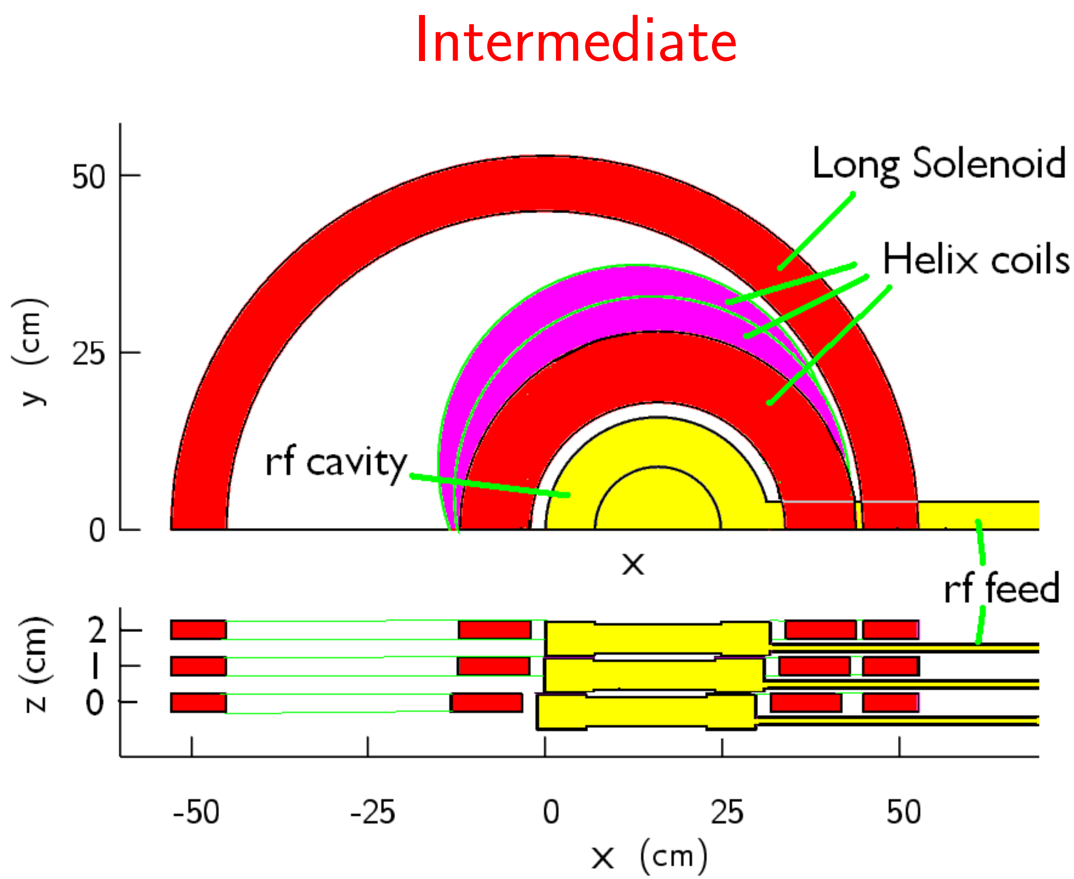


- Note the higher magnetic field (12 T) on the cavity

HCC Lattices



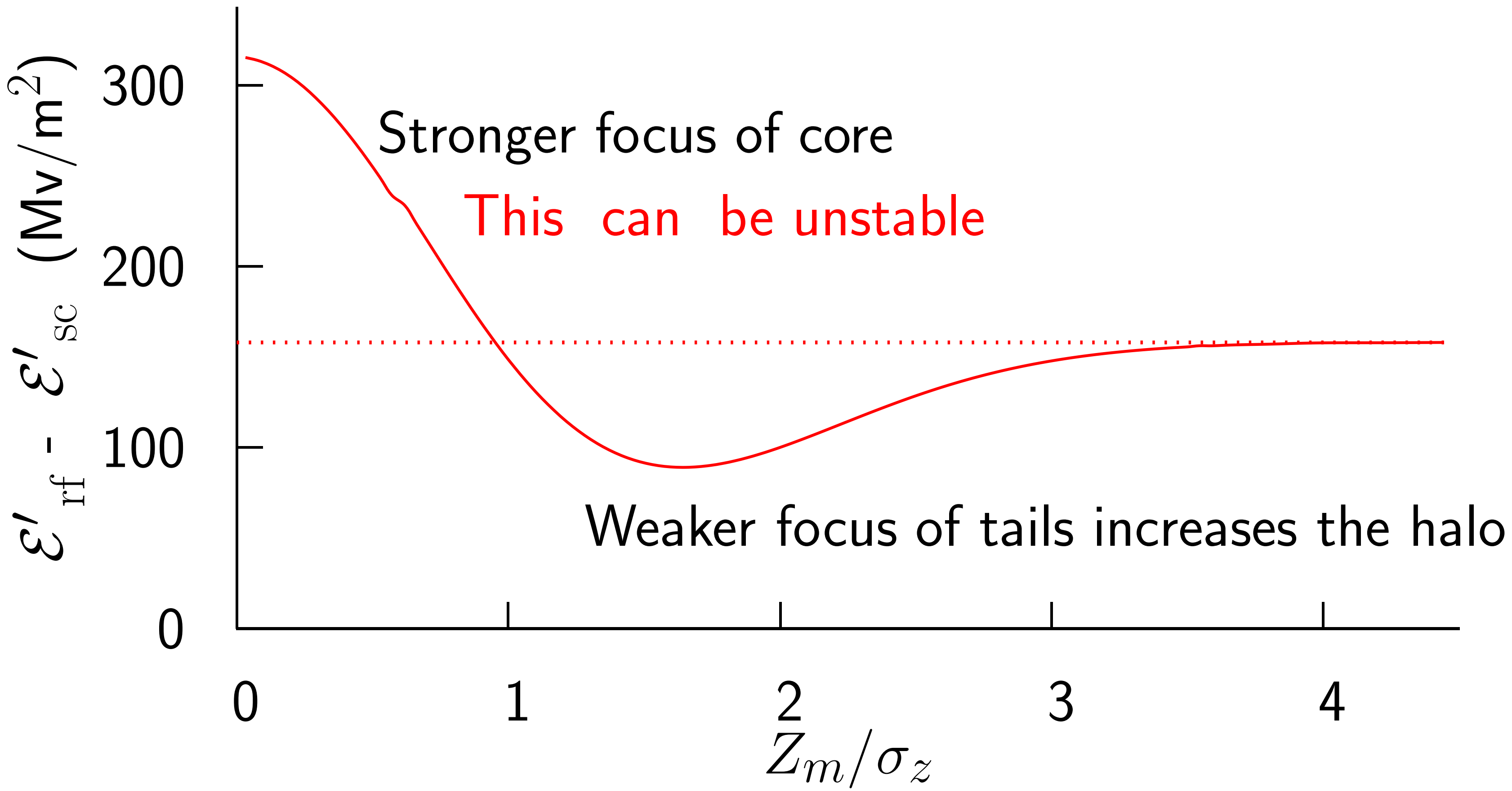
Max field on beam=4.4 T



Max field on beam= 10.3 T

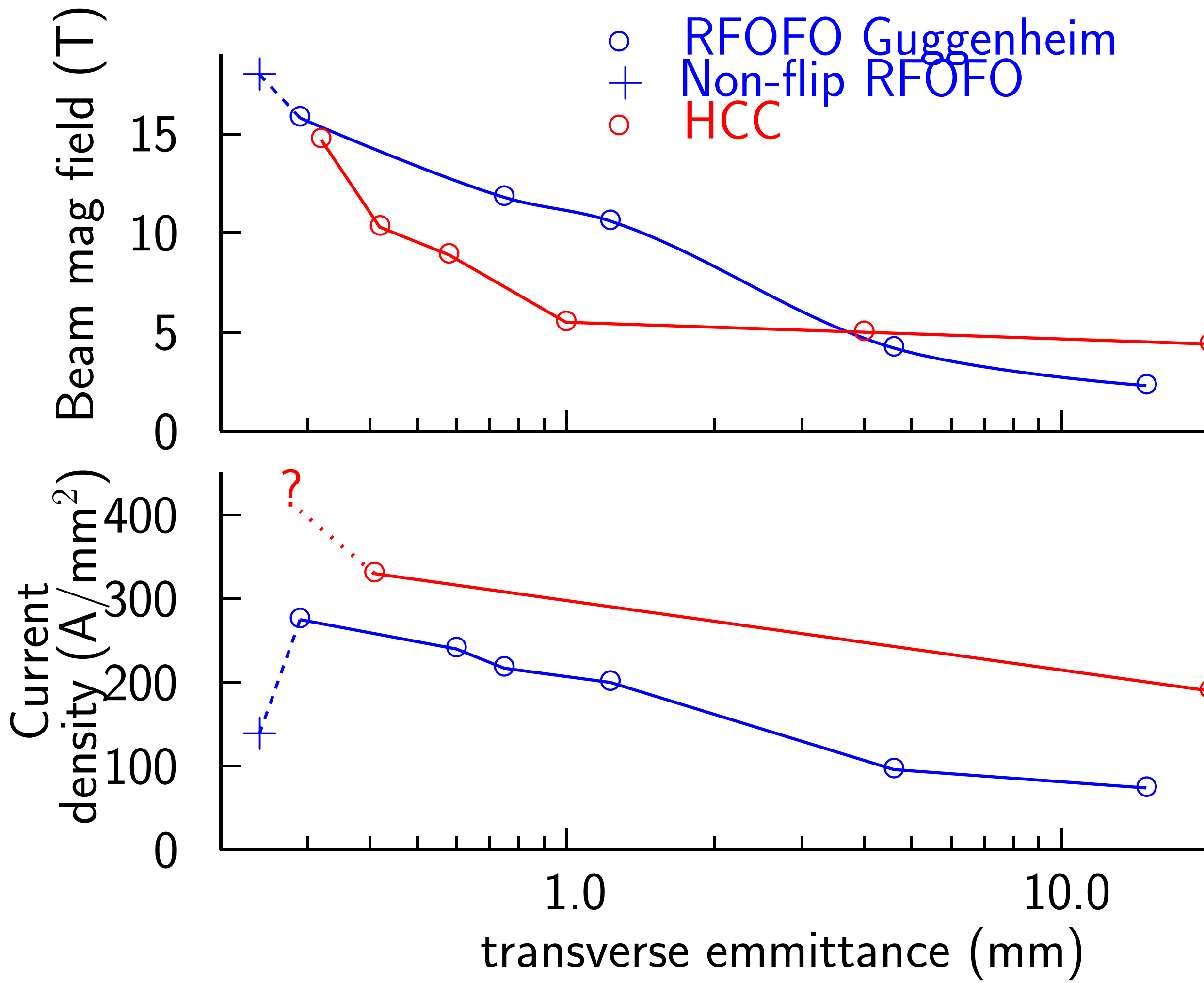
- Cavities modified to gain space between them and the helix coils
- Coils for Final Stage not yet defined, but max field on beam=14.7 T

Longitudinal Space Charge effects in last stage



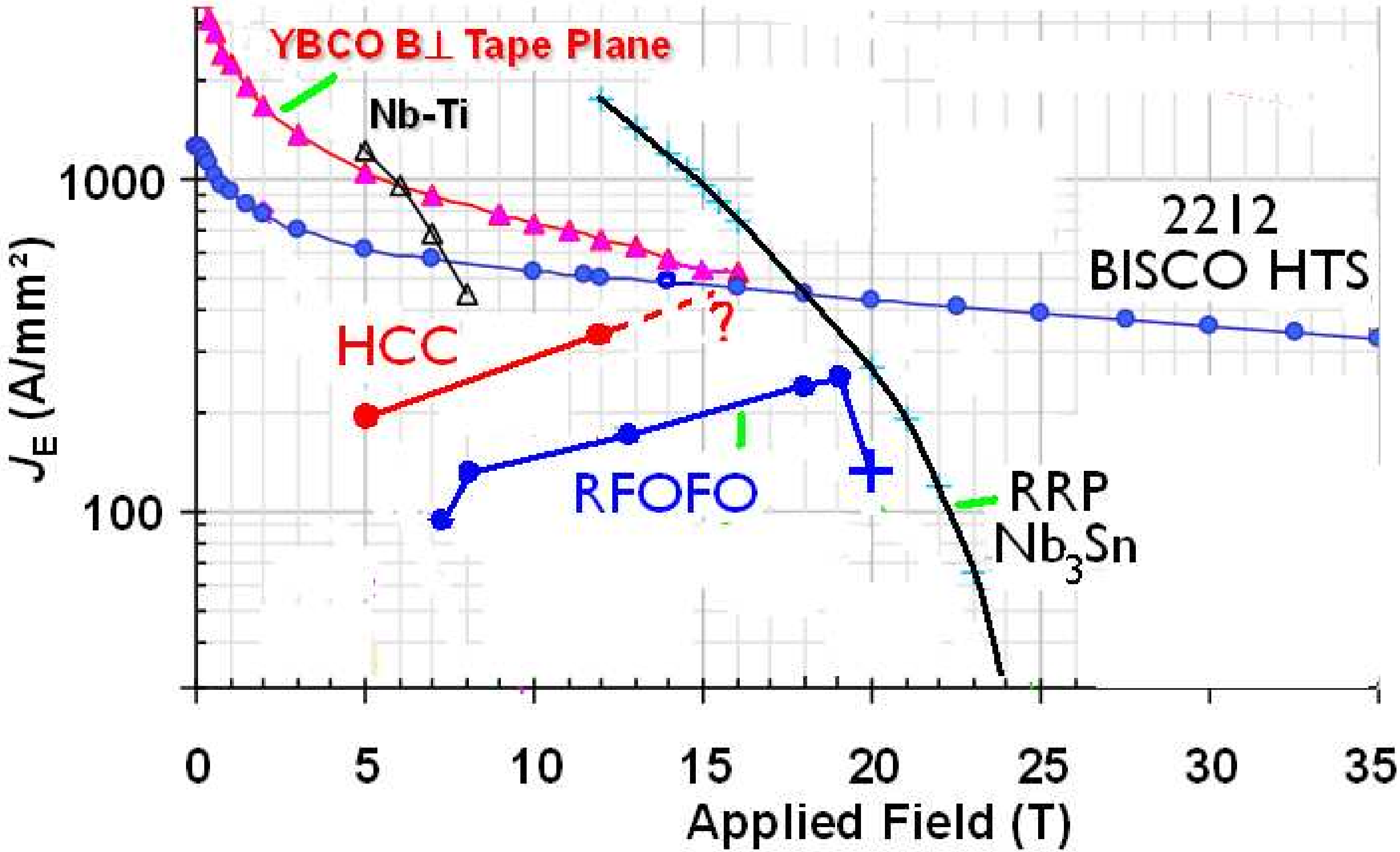
- Magnitude of effects somewhat less than in Guggenheim
- But HCC operates above transition
- Particles have negative mass and could be unstable
- Full simulations are essential

Compare magnet parameters



- Maximum fields are similar Peak fields on coils will be higher
- Current densities higher for HCC

Super-conductor Performance Requirements



- Guggenheim near Nb_3Sn limits ok for HTS
- Assuming HCC fields on coils 1.2 x B_{beam} then ok to emit=0.41 mm
- HCC design of the final stage is a critical task

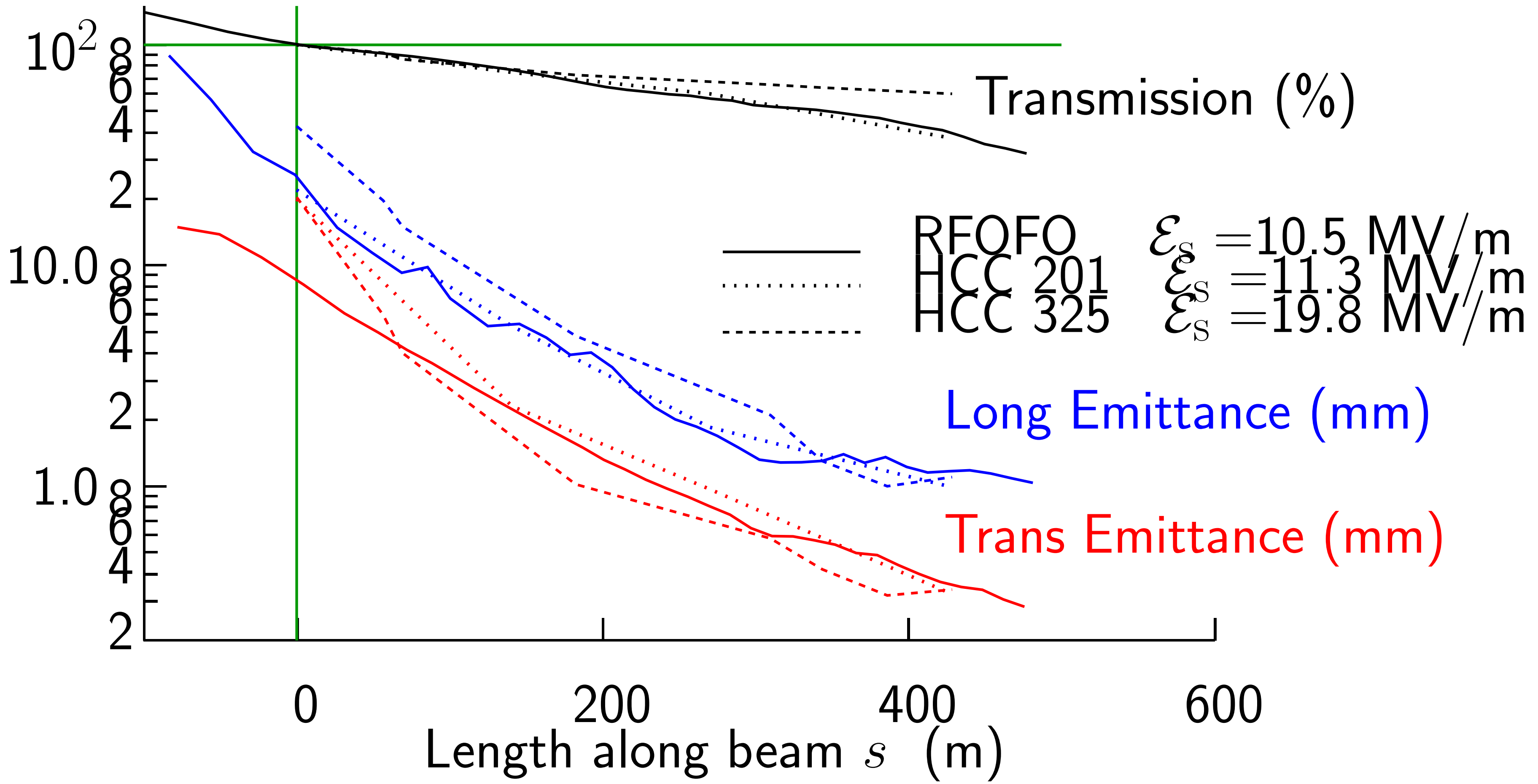
Guggenheim & HCC Parameters

		RFOFO	HCC	HCC	
Init freq.	f	201	325	201	MHz
Init beqm mag field	B_1	2.4	5	5	T
Final beam mag field	B_n	16	14.7	14.7	T
Ave Hydrogen density	ρ_{H2}	0.011	0.013	0.013	gm/cm^2
rf gradient	$\mathcal{E}$	15.5	32^*	18.5^*	MV/m
Ave beam rf gradient	$\mathcal{E}_s$	10.5	19.8	11.3	MV/m

* Fields increased 15% with indented cavity design

- Average hydrogen densities are similar
- Average rf beam gradients for 201 cases are similar

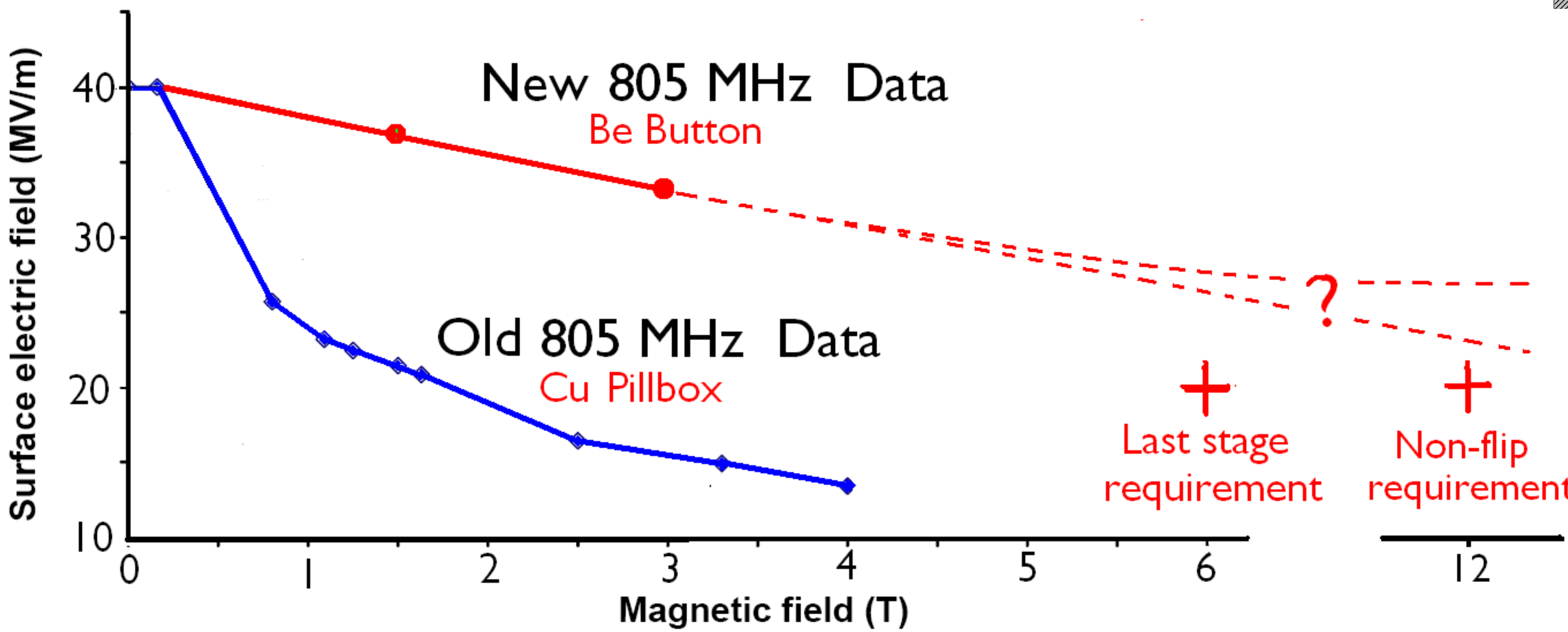
Performance

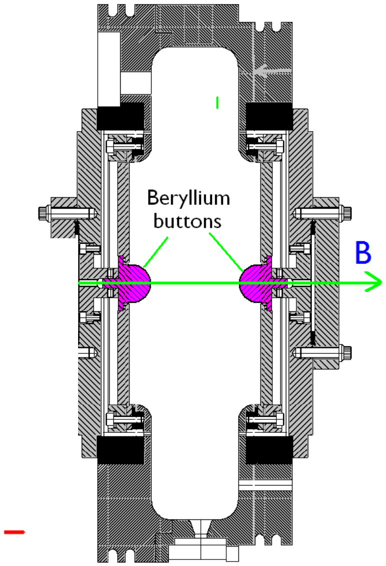


- Cooling rates similar
  HCC slightly higher as expected from hydrogen density
- Transmissions similar for similar gradients,
  better for HCC with higher rf gradient

Critical RFOFO Guggenheim R&D

- Vacuum rf breakdown in magnetic fields

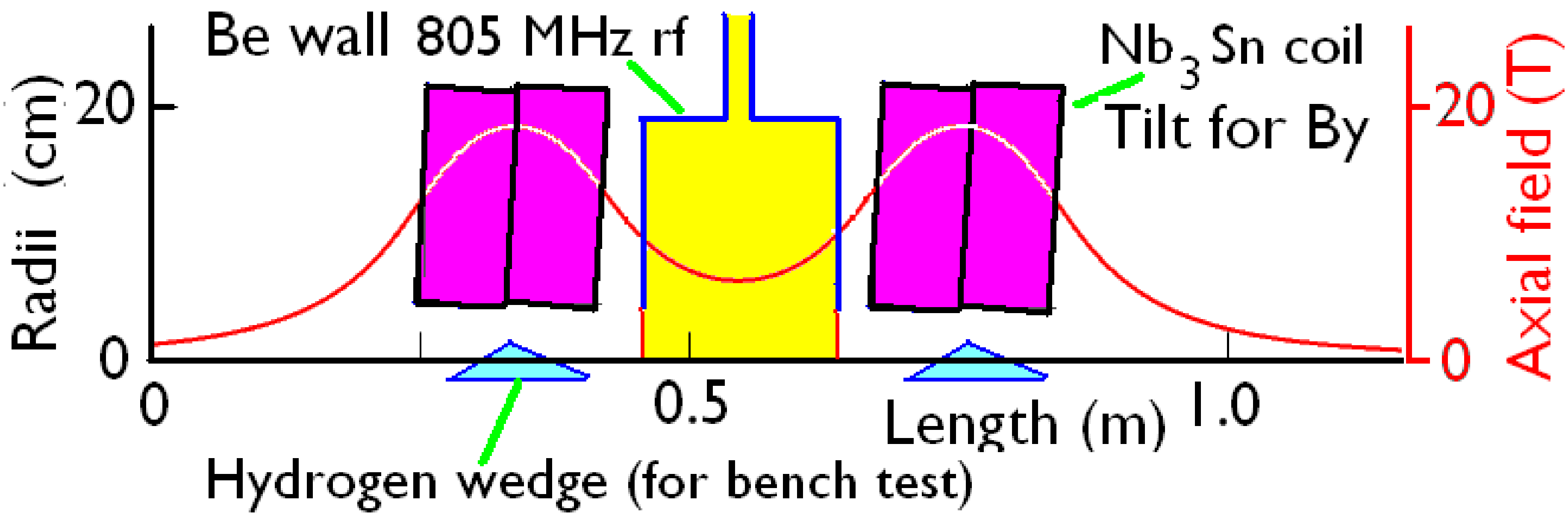




- Be Button data very encouraging
- Remains to be tested in real Be wall cavity under design
- To test breakdown at the higher fields, see below
- Tests also at 201 MHz: 1st with Be buttons, then Be cavity

Guggenheim R&D Continued

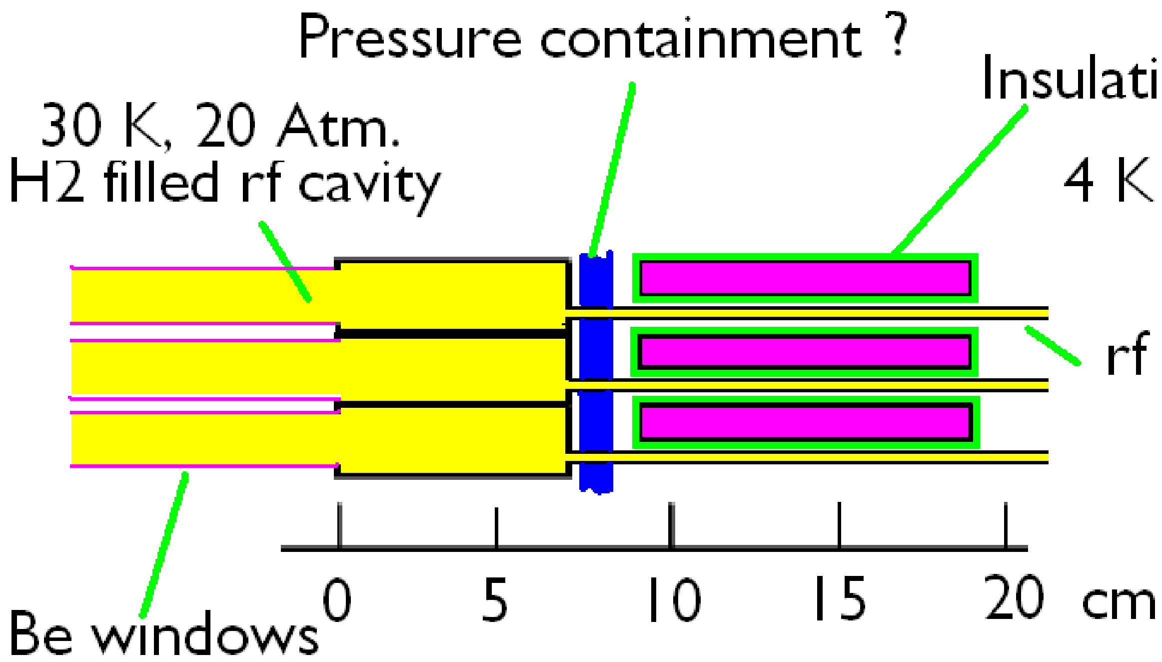
- Test 805 MHz in 12 T: Phase I of 6D Bench Test
  - 6D Bench Test is a defined MAP objective
  - The final, and hardest, stage is appropriate
  - 2 coils + 1 cavity tests rf in 12 T
  - With addition of hydrogen wedges → Bench Test



  - Would also be tested also with field reversal

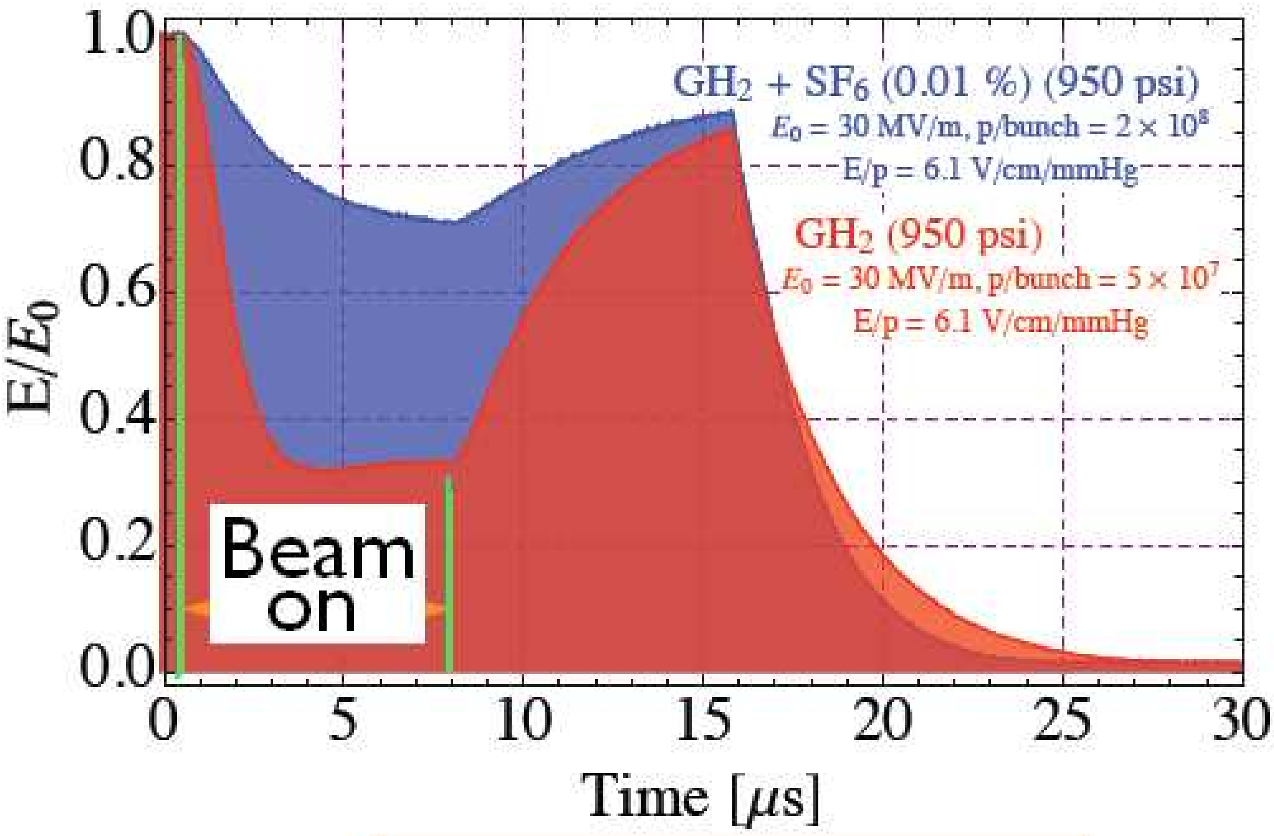
Critical HCC Helical Cooling R&D

- Design (for Bench Test) last stage 6D cooling
  - Natural scaling ($j \propto B^2$) gives very high current densities
  - rf at 20 atmospheres and 30 K, but coils at 4 K
    If vacuum insulation needed, then pressure containment must be between coil and rf, where space is limited
  - New input from outside could be of great value



HCC R&D Continued

- Understand plasma losses in gas
  - Define cryogenic electro-negative admixture



  - Good progress in ongoing study at Muon Test Area

Conclusion

- Performances of two options are similar
- Both require full space charge/wake field simulation
- Guggenheim critical R&D is rf breakdown in magnetic fields
  - 805 MHz Button test very encouraging
  - Requires real Be cavity demonstration
  - Requires test with higher fields and 201 MHz
- HCC critical R&D is design of last stage 6D cooling
  - Magnet design is hard and integration of rf is hard
  - Plasma effects must be understood
  - Electro-negative gas must be defined

Possible collaborations

- Space Charge/ wake field Simulations of both options
- For Guggenheim:
  1. Theory and exp study of vacuum rf in magnetic fields
  2. Collaborate on 18 T 805 MHz test stand & eventual beam test
- For HCC:
  1. Theory and exp study of plasma effects in gas filled rf cavities
  2. Engineering study of last stage HCC

Appendix
325 MHz HCC Beam Parameters

stages	z	b1	b'	Bz	λ	f	$\epsilon_\perp$	$\epsilon_\parallel$	transm.
	m	T	T/m	T	m	MHz	mm	mm	
1	0	0	0	0	0	0	20.4	42.8	1.0
2	40	1.3	-.5	-4.2	1	325	5.97	19.7	.92
3	49	1.4	-.6	-4.8	.9	325	4.01	15	.86
4	129	1.7	-.8	-5.2	.8	325	1.02	4.8	.73
5	219	2.6	-2	-8.5	.5	650	.58	2.1	.66
6	243	3.2	-3.1	-9.8	.4	650	.42	1.3	.64
7	273	4.3	-5.6	-14.1	.3	650	.32	1	.62
8	303	4.3	-5.6	-14.1	.3	1300	.34	1.1	.6

325 MHz HCC Magnet Parameters

stage	R_c	λ	Bz	R1	R2	n	Lc	j	L
	m	m	T	m	m		m	A/mm^2	m
1	0 $\rightarrow$0.28	1.9	0.55	0.35	0.4	20	0.025	220$\rightarrow$194	5.5
2	.28	1	.55	.35	.4	20	.025	194	
6	.16	.4	6.73	.18	.28	20	.01	332.9	

200 MHz HCC Beam Parameters

stage	z m	λ m	Rref cm	Bz T	b1 T	b' T/m	f MHz	Es MV/m	L_{cav} cm	P_{peak} MW/m	$\epsilon_\perp$ mm	$\epsilon_\parallel$ mm	transm. %
1	100	1.0	16	4.21	1.24	0.21	200	16	10	43			
2	191	0.7	11	6.01	1.78	0.42	400	16	7	23			
3		0.4	6	10.7	3.11	1.29	800	16	4	15			
4	301	0.3	4.8	14.0	4.15	2.29	800	16	4	15			

RFOFO Guggenheim parameters

file in tapr	file in beta	β cm	cell cm	rf f MHz	$\mathcal{E}$ MV/m	rf frac		abs L/2 cm	coil 1 z1-z2 cm	coil 1 r1-r2 cm	coil 1 j A/mm^2	coil 1 $\hat{B}$ T	coil 2 z1-z2 cm	coil 2 r1-r2 cm	coil 2 j A/mm^2	coil 2 $\hat{B}$ T	B_o T
041	rfoxb5	66	275	201	15.48	0.68	H	22.6	30.00-80.00	77.00-88.00	95.6	7.3					2.33
042	rfoxb4	57	275	201	15.48	0.68	H	32.6	42.50-95.00	77.00-88.00	80.6	6.2					2.51
043	rfoxb3	50	275	201	15.48	0.68	H	42.6	42.00-94.50	77.00-88.00	86.2	6.6					2.69
044	rfoxb1	50	275	201	15.48	0.68	H	42.6	38.00-88.00	77.00-88.00	91.6	7.0					2.72
045	rfoxb	39	275	201	15.48	0.68	H	42.6	30.00-80.00	77.00-88.00	95.6	7.3					2.75
022	rfoxb12	34	235.7	235	15.48	0.68	H	36.5	12.86-30.00	42.86-51.43	68.3	5.1	25.72-94.29	66.00-74.58	75.7	5.1	3.08
023	rfoxb13	29	202.1	273	15.48	0.68	H	31.3	11.02-25.72	36.74-44.09	93.0	5.9	22.05-80.84	56.58-63.93	103.0	5.8	3.60
024	rfoxb14	25	173.2	319	15.48	0.68	H	26.8	9.45-22.05	31.50-37.80	126.5	6.9	18.90-69.30	48.51-54.81	140.1	6.7	4.20
025	rfoxb21	21	148.5	372	15.48	0.68	H	23.0	7.02-19.98	27.00-36.18	93.4	7.8	16.20-59.40	41.58-55.08	86.3	8.0	4.91
026	rfoxb22	18	127.3	435	15.48	0.68	H	19.7	6.02-17.13	23.15-31.01	127.2	9.0	13.89-50.92	35.64-47.22	117.5	9.5	5.73
027	rfoxb23	18	109.1	507	15.48	0.68	H	16.9	5.16-14.68	19.84-26.59	173.1	10.6	11.90-43.65	30.55-40.47	159.9	10.9	6.68
028	rfoxb31	13	93.55	591	15.48	0.68	H	14.5	4.42-12.59	13.61-26.20	102.7	11.1	10.21-37.42	26.20-46.61	123.0	13.5	7.80
029	rfoxb32	11	80.20	690	15.48	0.68	H	12.4	3.79-10.79	11.66-22.45	139.8	14.7	8.75-32.08	22.45-39.95	167.4	15.7	9.10
030	rfoxb33	10	68.75	805	15.48	0.68	H	10.6	3.25-9.25	10.00-19.25	190.2	15.8	7.50-27.50	19.25-34.25	227.7	18.4	10.6
031	rbk7a2	8.2	68.75	805	15.48	0.68	H	10.6	2.50-9.25	9.25-19.25	276.0	15.7	10.50-28.00	19.25-34.25	222.2	17.3	10.9
032	rbk8b	6.9	68.75	805	20.05	0.5	H	10.6	3.25-12.50	10.00-19.25	217.7	18.0	3.25-22.00	19.25-34.25	203.1	18.0	11.8
033	rbk8c	5.9	68.75	805	20.05	0.5	H	10.6	3.25-12.50	10.00-19.25	287.8	20.0	3.25-19.50	19.25-34.25	191.4	20.0	12.3
034	rbk8d	4.9	68.75	805	20.05	0.5	H	10.6	3.25-12.50	7.00-21.25	239.7	18.5	13.25-23.25	19.25-34.25	163.8	12.0	13.1
035	rbk8e2	4.1	68.75	805	20.05	0.5	LH	1.9	3.25-12.50	6.50-21.75	259.7	19.4	13.25-23.25	19.25-29.25	133.2	12.0	13.9
036	rbk8f2	3.4	68.75	805	20.05	0.5	LH	1.9	3.00-13.00	6.50-21.75	291.9	20.8					14.8
037	rbk8g2	2.8	68.75	805	20.05	0.5	LH	1.9	2.50-13.00	4.88-19.63	257.5	19.2					15.8

Before the merge the simulation (run tapr7g) uses the following numbers of the cells with parameters corresponding to the numbers given above.

Cells	12	10	8	8	8	8	9	11	12	15	17	20	24	65	40	80	347
Files	41	42	43	44	45	22	23	24	25	26	27	28	29	30	31	32	16

The total length of hydrogen is 112 m. With energy loss per meter of $dE/dx = 29$ MeV/m, and average beam intensity 21×10^{12}, and repetition rate of 15 Hz, then the total power dissipated in the hydrogen is given by:

$$\text{Power at 20 K} = 112 \times 29\ 10^6 \times 21\ 10^{12} \times 1.6\ 10^{-19} \times 15 = 0.16 \text{ MW}$$

With our assumed cryogenic efficiency of 20% of the Carnot efficiency of $0.2 \times 20/293 = 1.4\%$, the wall power to cool the hydrogen is $0.16/1.4\% = 11.4$ MW

The simulation (run tapr12f) after the merge used:

Cells	8	8	9	11	12	15	17	20	24	40	40	40	40	40	40	51	20	584
Files	45	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	17

The total length of of hydrogen is 93 m. With energy loss per meter of $dE/dx = 29$ MeV/m, and average beam intensity 8×10^{12}, and repetition rate of 15 Hz, then the total power dissipated in the hydrogen is given by:

$$\text{Power at 20 K} = 93 \times 29\ 10^6 \times 8\ 10^{12} \times 1.6\ 10^{-19} \times 15 = 0.05 \text{ MW}$$

With our assumed cryogenic efficiency of 20% of the Carnot efficiency of 1.4 %, the wall power to cool the hydrogen is 0.05 / 1.4% =3.6 MW