A complete 6D cooling channel for a Muon Collider

Diktys Stratakis,

J. Scott Berg and Robert B. Palmer

Brookhaven National Laboratory

Special thanks to Valeri Balbekov (FNAL)

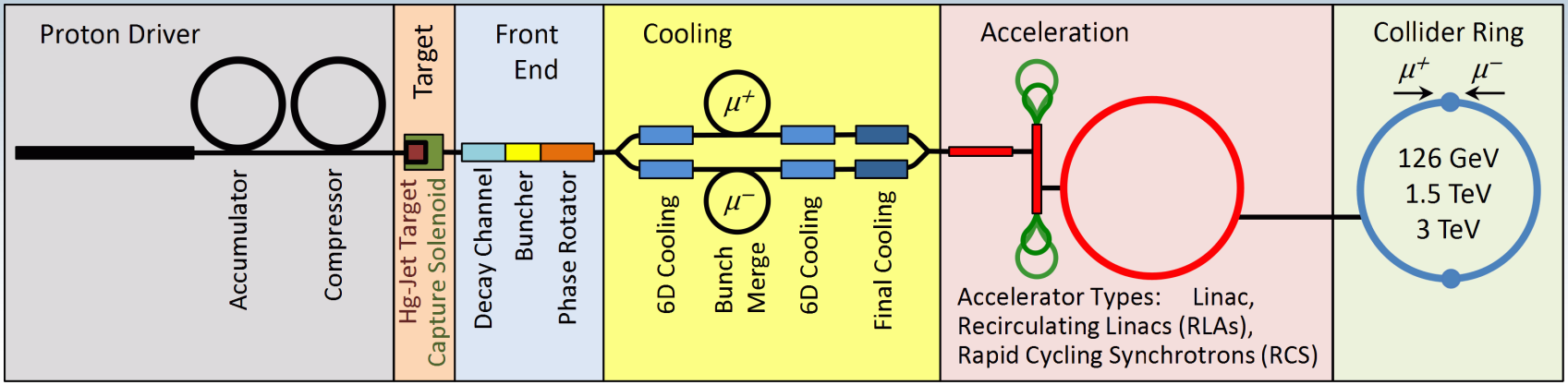
Vacuum RF Meeting 2

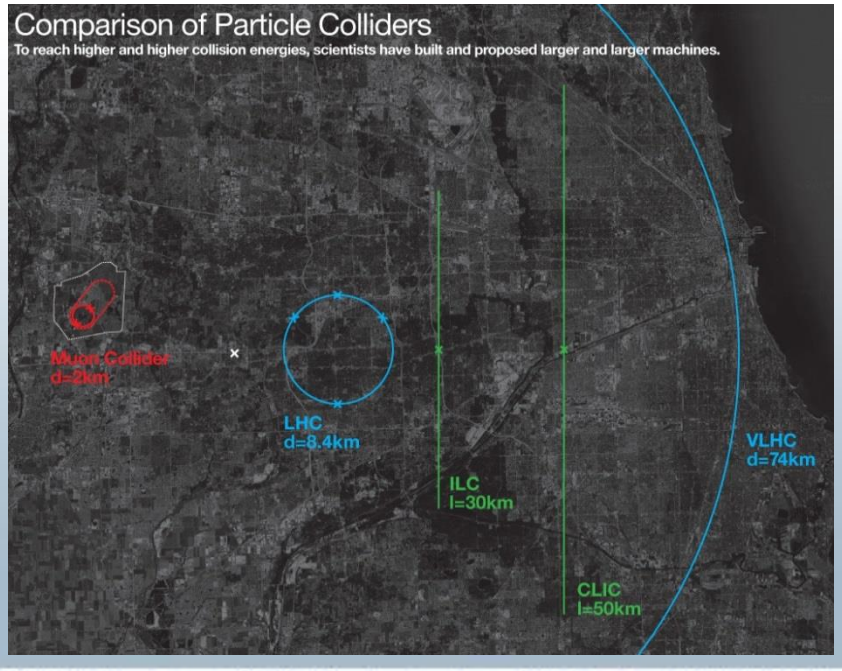
November 05, 2013

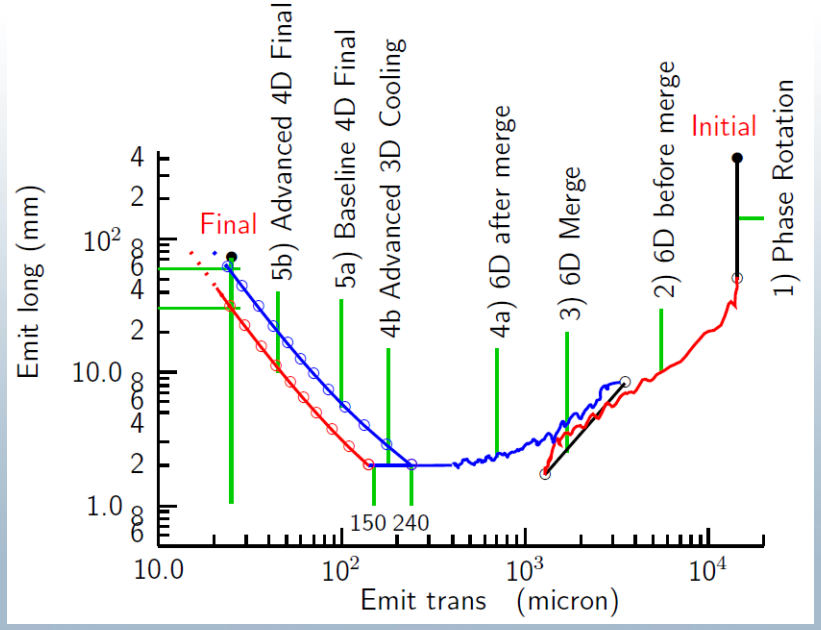
Outline

- Introduction
- Description of main lattice components
  - Capture, bunching & phase rotation
  - 6D cooling before merge [detail]
  - Bunch merger
  - 6D cooling after merge [detail]
- Review key lattice parameters
  - Identify the required rf freq., voltage, B-field, absorber length
- Evaluate Performance
  - Carry out a full “front-to-end” simulation

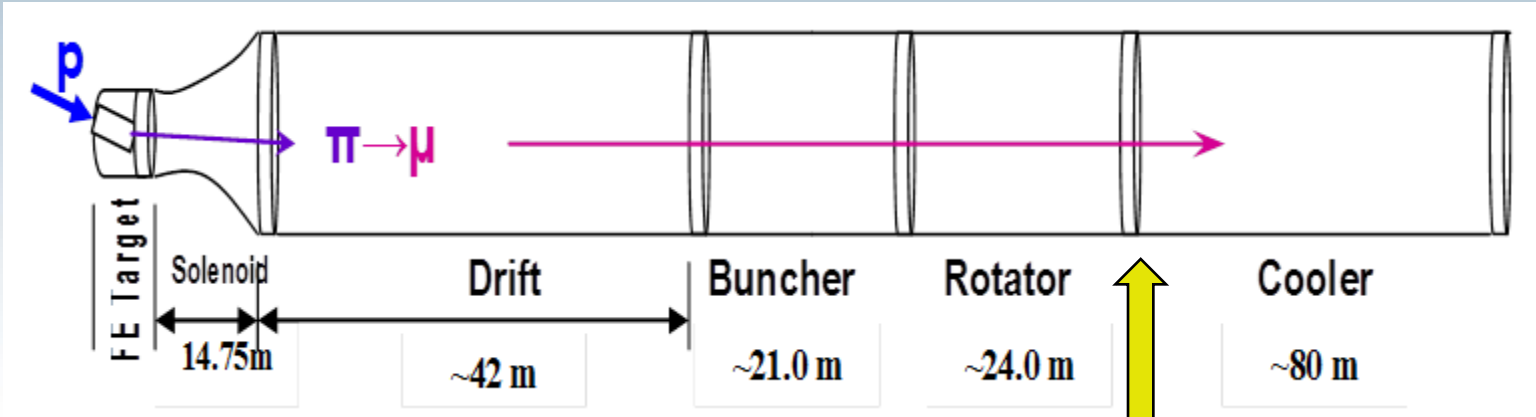
Muon Collider Components

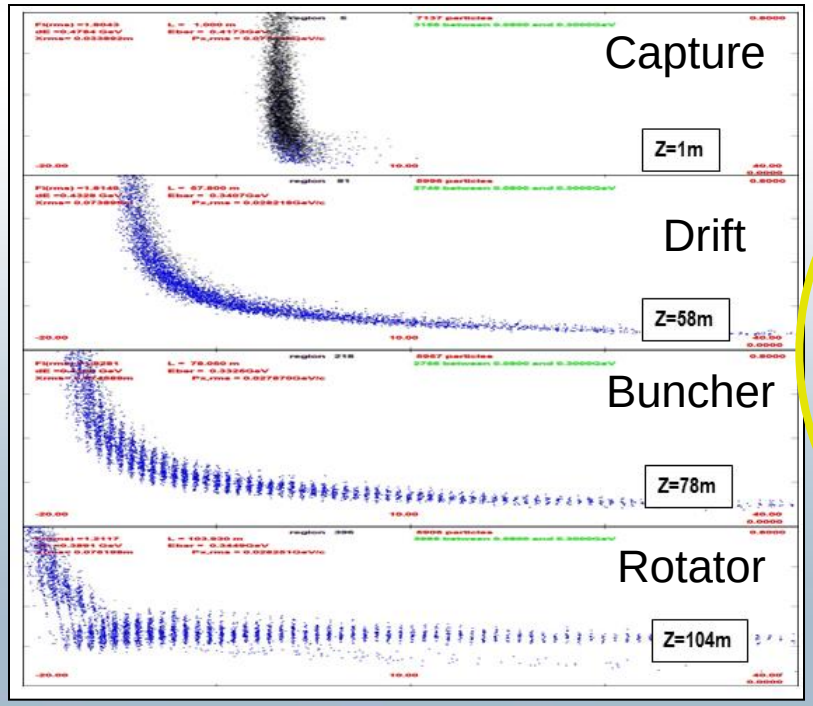




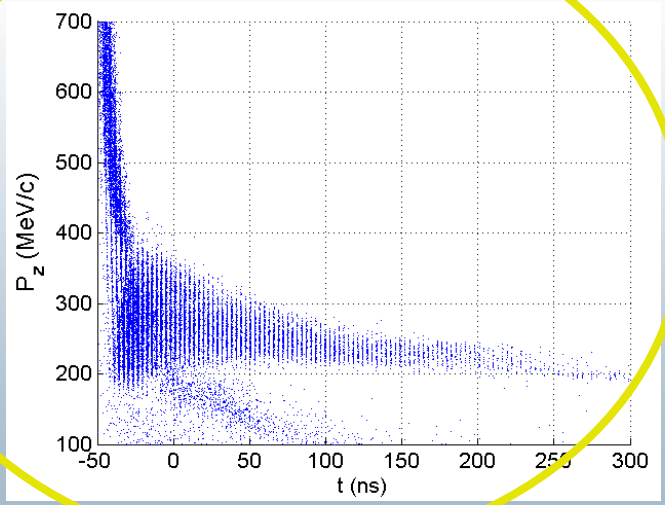


MC 325 MHz Front-End



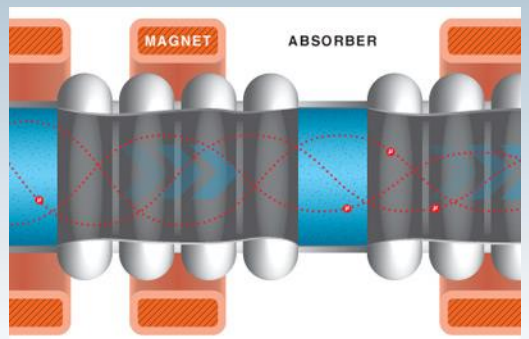


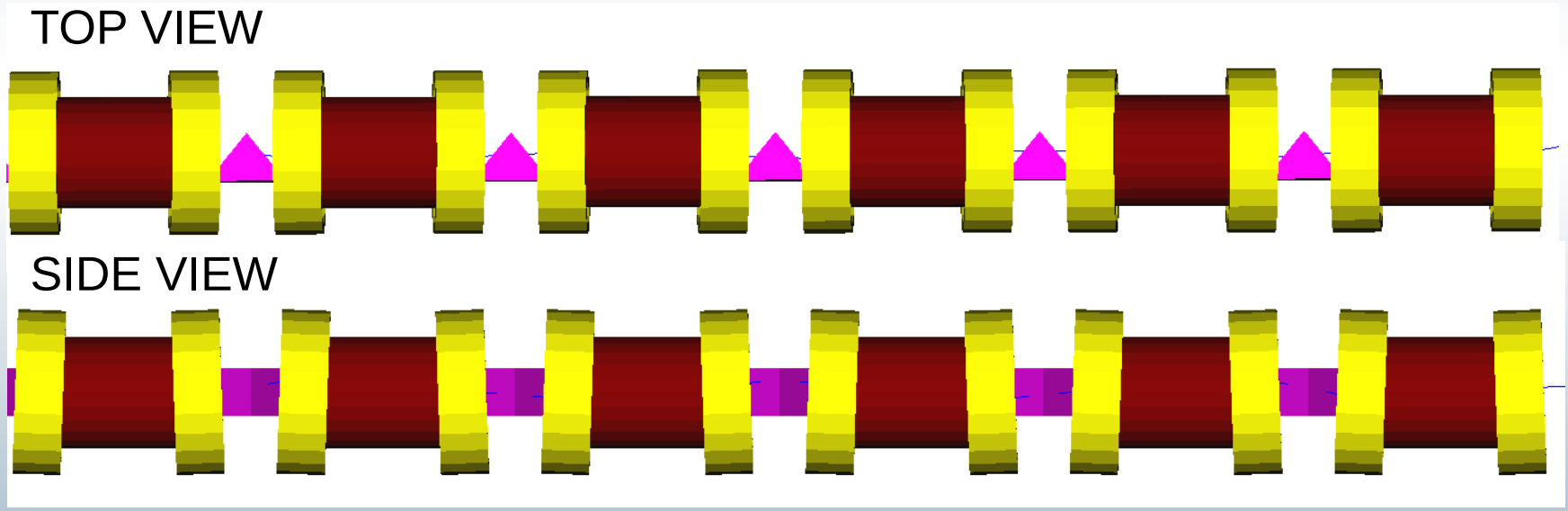
Begin 6D Cool



Rectilinear channel for 6D Cooling

Ionization cooling

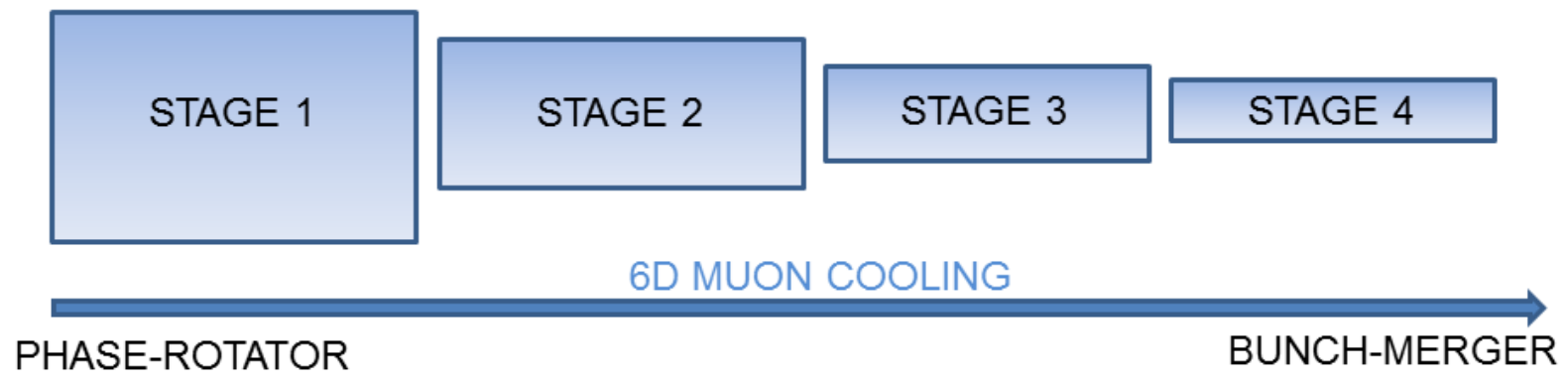




- **The idea was proposed by Valeri Balbekov**
- See V. Balbekov, MAP-Document No. 4365

Tapered 6D Channel

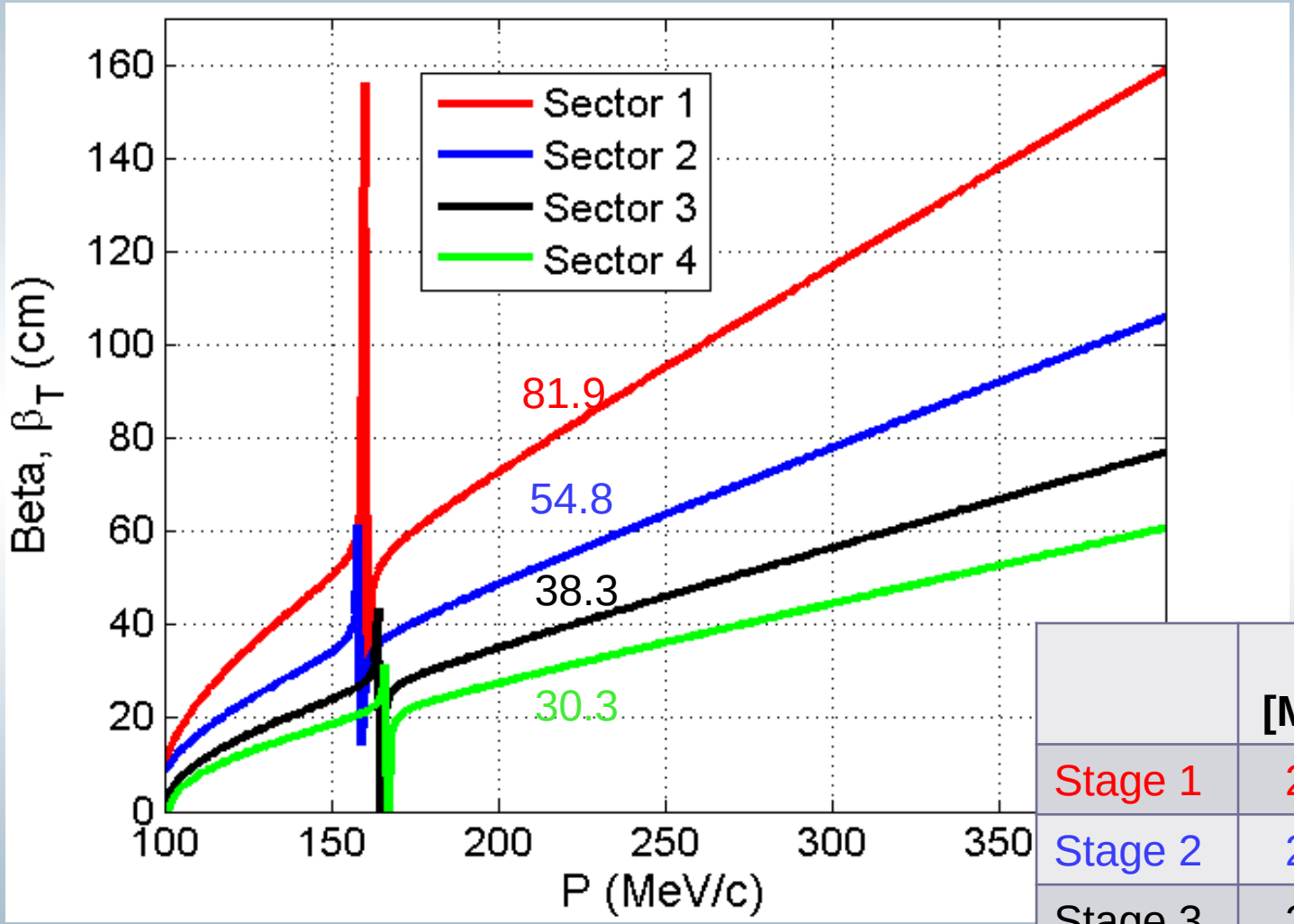
- Lattice parameters such as rf freq., cell length, focusing strength, absorber length, change along STAGES
- Keep emittance above equilibrium



Lattice Parameters

Parameters	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Coil tilt (deg.)	3.1	1.5	1.6	1.25
Current density (A/mm^2)	63.25	125.0	165.0	195.0
Max B on coil (T)	4.20	8.47	9.56	11.83
Max B on axis (T)	2.35	3.50	4.82	6.06
Trans. beta (cm)	81.9	54.8	38.3	30.3
Absorber angle (deg.)	40	44	100	110
Absorber type	LH_2	LH_2	LH_2	LH_2
Rf frequency (MHz)	**325**	**325**	650	650
RF phase (deg.)	14	15	20	16
RF gradient (MV/m	**22**	**22**	**28**	**30**
Ref. Momentum (MeV/c)	219	215	212	210
Cell length (m)	2.0	1.32	1.0	0.8
Hoop Stress (MPa)	110	460	410	490

Lattice Acceptance

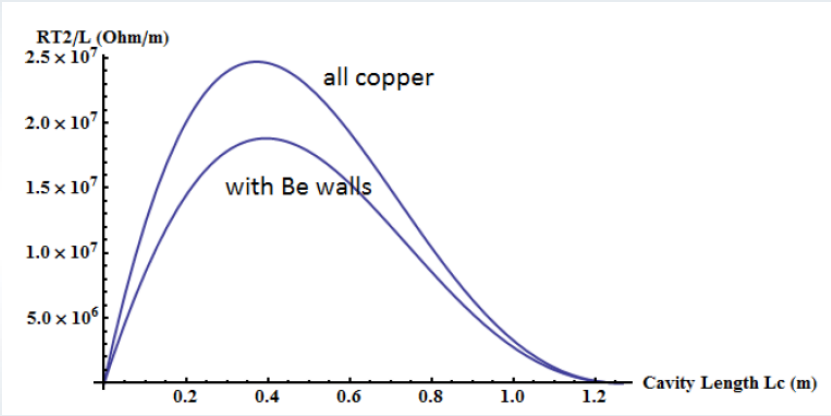


	P_z [MeV/c]	σ_{Pz} [MeV/c]
Stage 1	237.8	22.3
Stage 2	228.8	14.4
Stage 3	220.9	12.7
Stage 4	219.4	12.5

Choice of RF length

f_0=325 MHz, R_c=0.353 m			
β	0.6	0.85	1.0
L_c (m)	0.180	0.245	0.282
RT^2/L_c ($M\Omega/m$)	36.8 / 18.6	48.2 / 23.9	54.3 / 26.7
Power (MW)	4.56 / 8.71	4.77 / 9.22	4.89 / 9.52
f_0=650 MHz, R_c=0.177 m			
β	0.6	0.85	1.0
L_c (m)	0.090	0.122	0.141
RT^2/L_c ($M\Omega/m$)	52.0 / 26.3	68.1 / 33.8	76.8 / 37.7
Power (MW)	1.61 / 3.08	1.69 / 3.26	1.73 / 3.37
f_0=975 MHz, R_c=0.118 m			
β	0.6	0.85	1.0
L_c (m)	0.060	0.082	0.094
RT^2/L_c ($M\Omega/m$)	63.7 / 32.2	83.5 / 41.4	94.1 / 46.2
Power (MW)	0.88 / 1.68	0.92 / 1.78	0.94/ 1.83

$$\frac{RT^2}{L_c} = \frac{T^2\mu_0^2 c^2 L_c}{\pi J_1^2(2.405) R_c R_s (1 + R_c/L_c)},$$



- For P=200 MeV/c, β=0.88
- Length for 325 MHz is 25 cm,
- Length for 650 MHz is 13.5 cm

Tianhuan Luo, Tech. Note (2013)

Choice of rf gradient

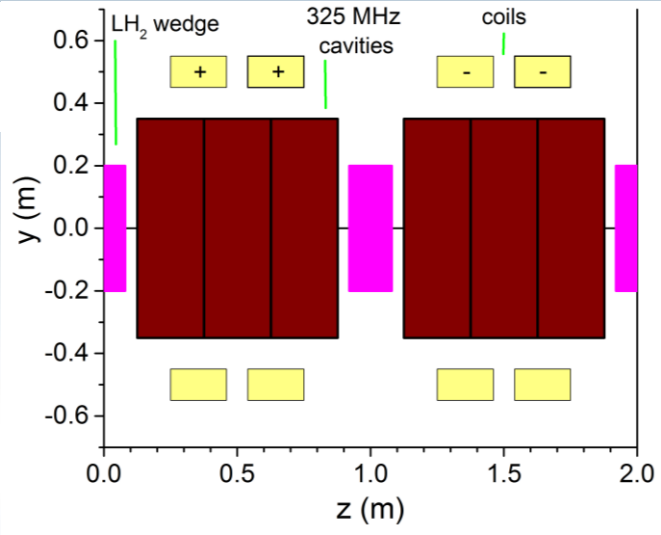
- Need consistent value for comparison
- Cavity lengths also matter
- Propose consistent values
  - consistent with 17 MV/m at 201.25 MHz

Freq. MHz	Length cm	Grad MV/m	ΔE $v = c$ MeV	ΔE 200 MeV/c MeV
325	30	22	5.51	5.23
650	15	31	3.88	3.68
975	10	38	3.17	3.01

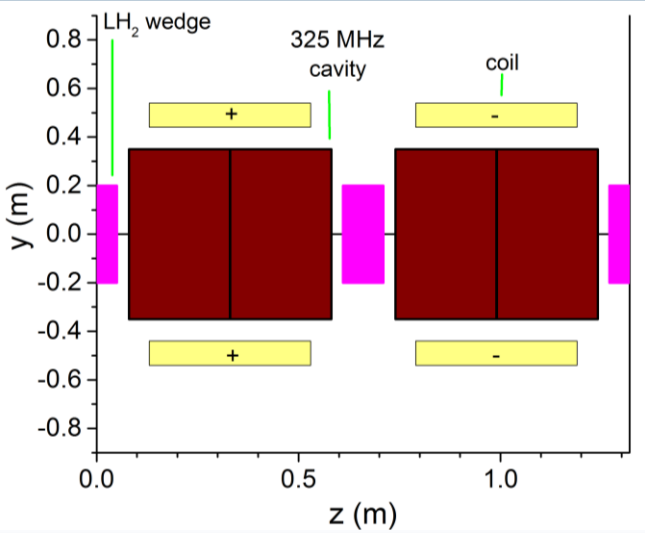
J. S. Berg, Vacuum RF Meeting Talk, Oct. 8, 2013

4-Stage System

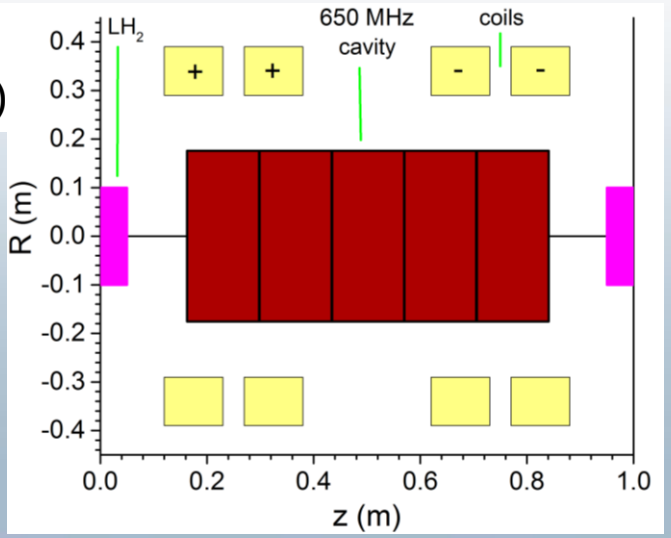
Stage 01
(66 cells)



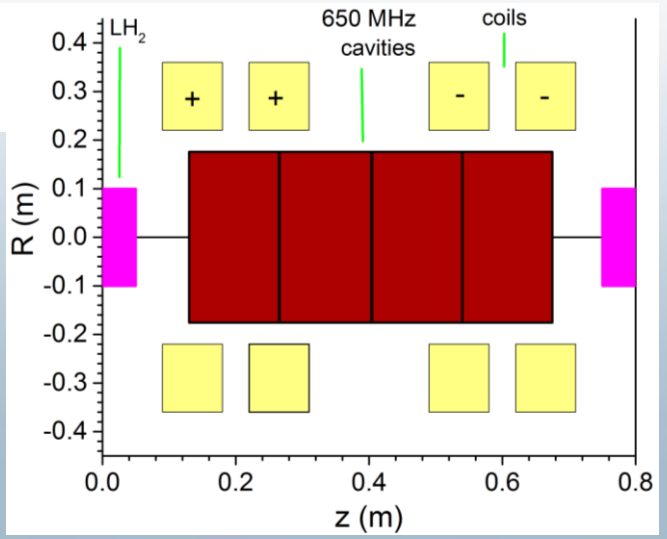
Stage 02
(130 cells)



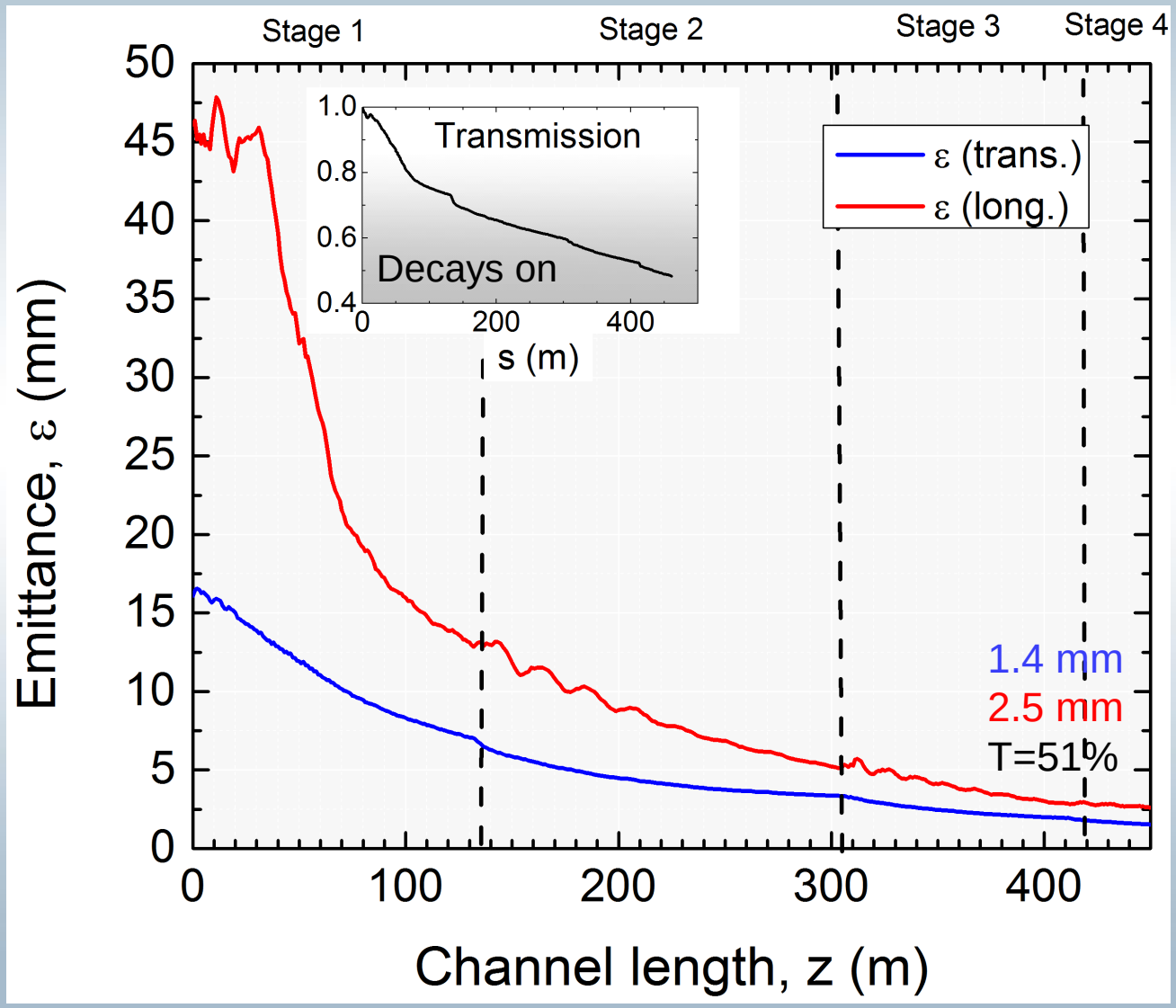
Stage 03
(107 cells)



Stage 04
(68 cells)

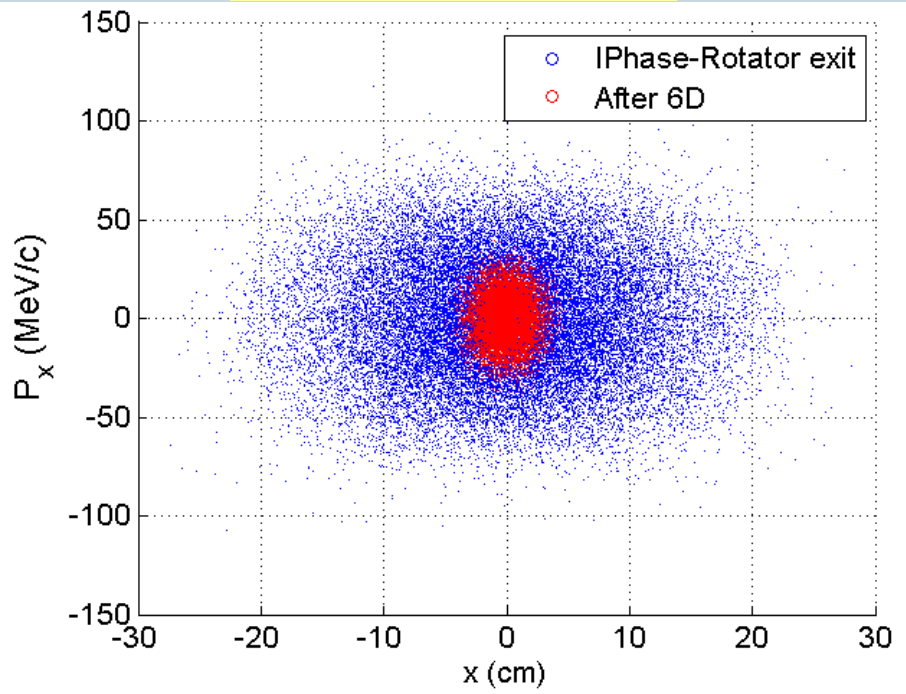


Lattice performance

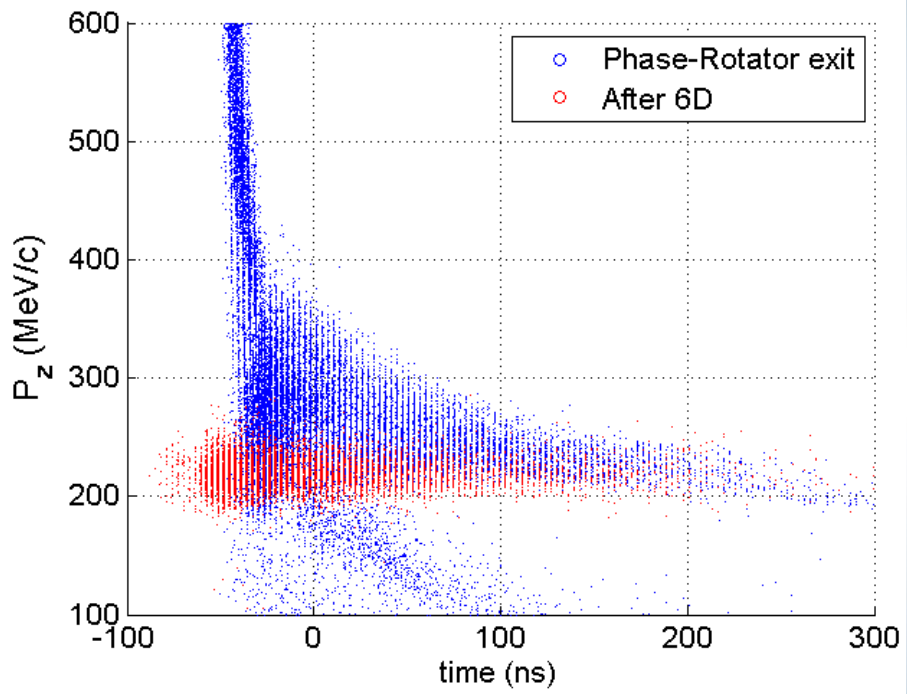


Beam before & after Cooling

Transverse cooling

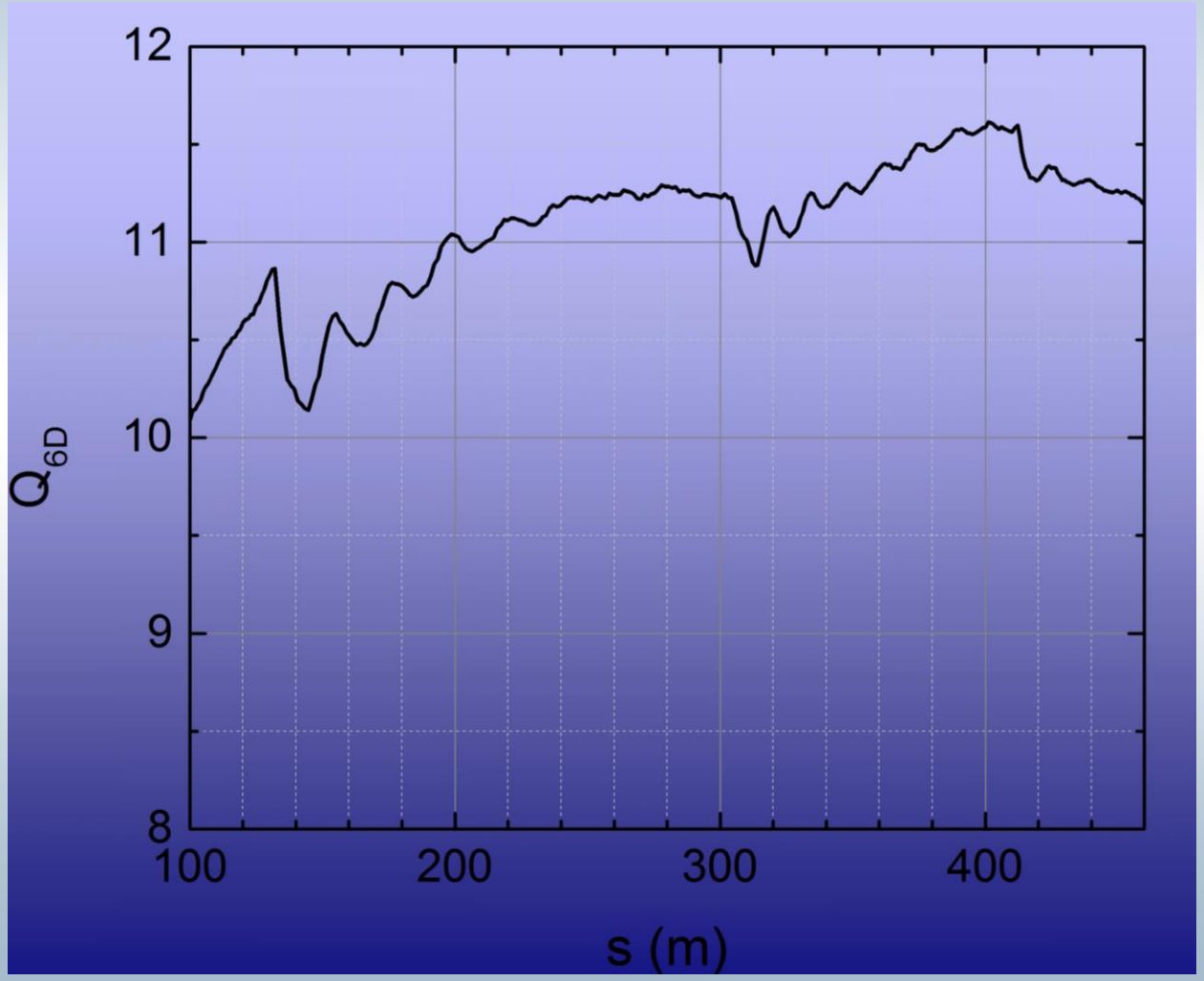


Longitudinal cooling

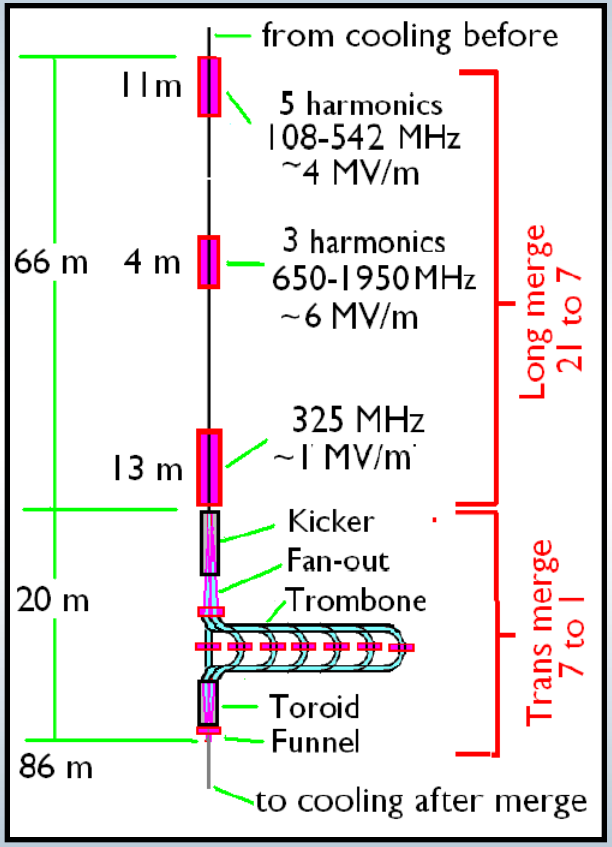


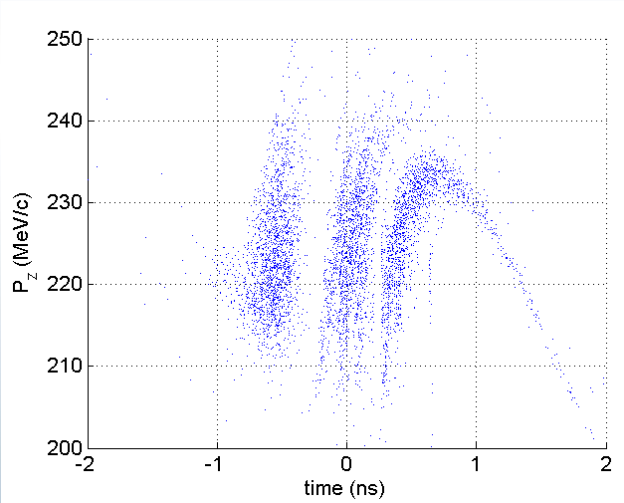
- Average momentum before: 262 MeV/c
- Average momentum after 6D: 219 MeV/c

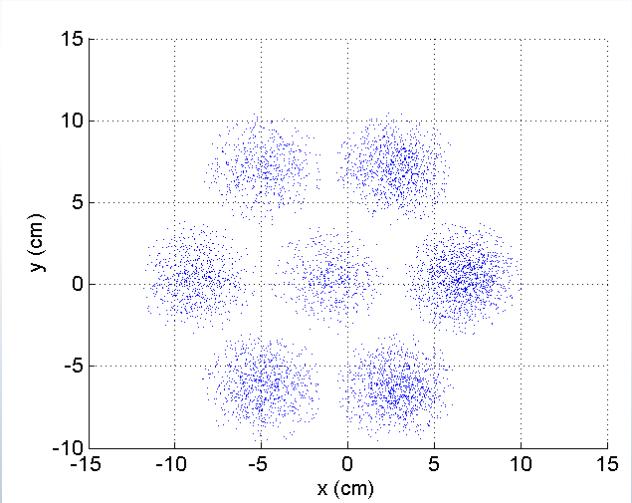
6D Quality Factor



Bunch Merger





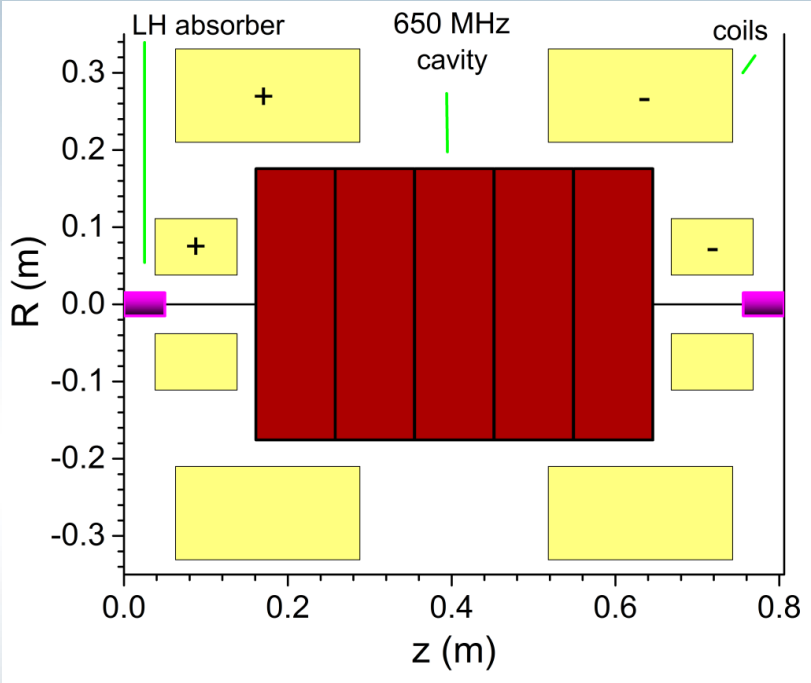


- More details: See R. Palmer and Y. Bao Talks

Post-Merge

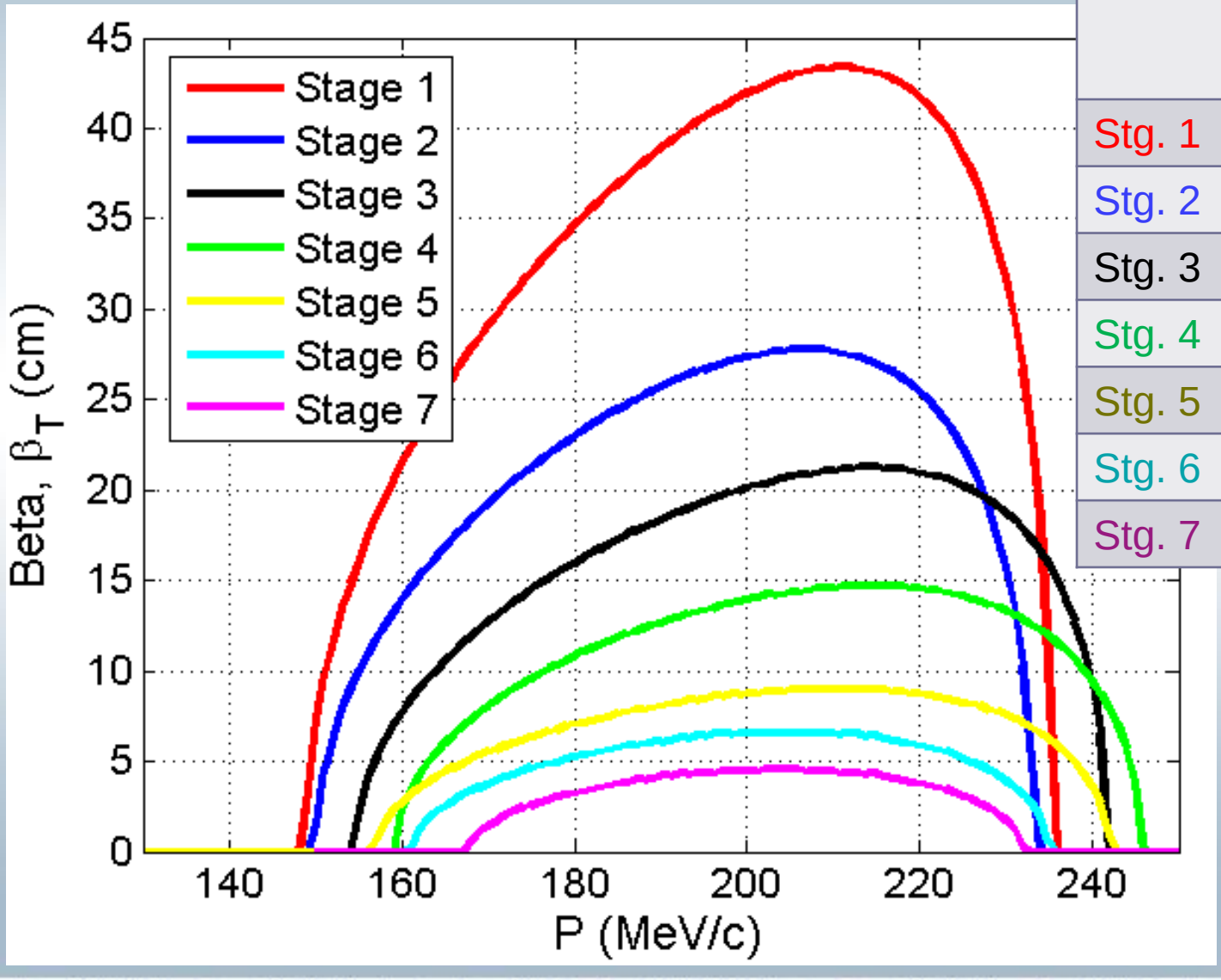
Parameters	**Stg. 1**	**Stg. 2**	**Stg. 3**	**Stg. 4**	**Stg. 5**	**Stg. 6**	**Stg. 7**
Coil tilt (deg.)	1.1	1.3	1.2	1.2	1.1	0.7	0.8
Current density (A/mm^2)	69.8	90.0	127.0	124.0	239.4	185.0	198.0
Max B on coil (T)	6.87	8.43	12.71	9.40	12.90	13.75	14.10
Max B on axis (T)	2.65	3.70	5.04	6.12	8.78	10.65	12.60
Trans. beta (cm)	42.01	27.42	20.17	13.97	8.78	6.42	4.56
Wedge angle (deg.)	100	100	100	110	110	130	140
Absorber type	LH_2	LH_2	LH_2	LH_2	LH_2	LH_2	LH_2
Rf frequency (MHz)	**325**	**325**	325	325	650	650	650
RF phase (deg.)	41	41	41	47	50	46	46
RF gradient (MV/m	**17.5**	**18.5**	**21.0**	**20.5**	**27**	**28.5**	**26**
Ref. Momentum (MeV/c)	204	204	204	204	204	204	204
Cell length (m)	2.75	2.00	1.50	1.27	0.806	0.806	0.806
Hoop Stress (MPa)	360	370	600	240	320	285	260

Stages 5-7



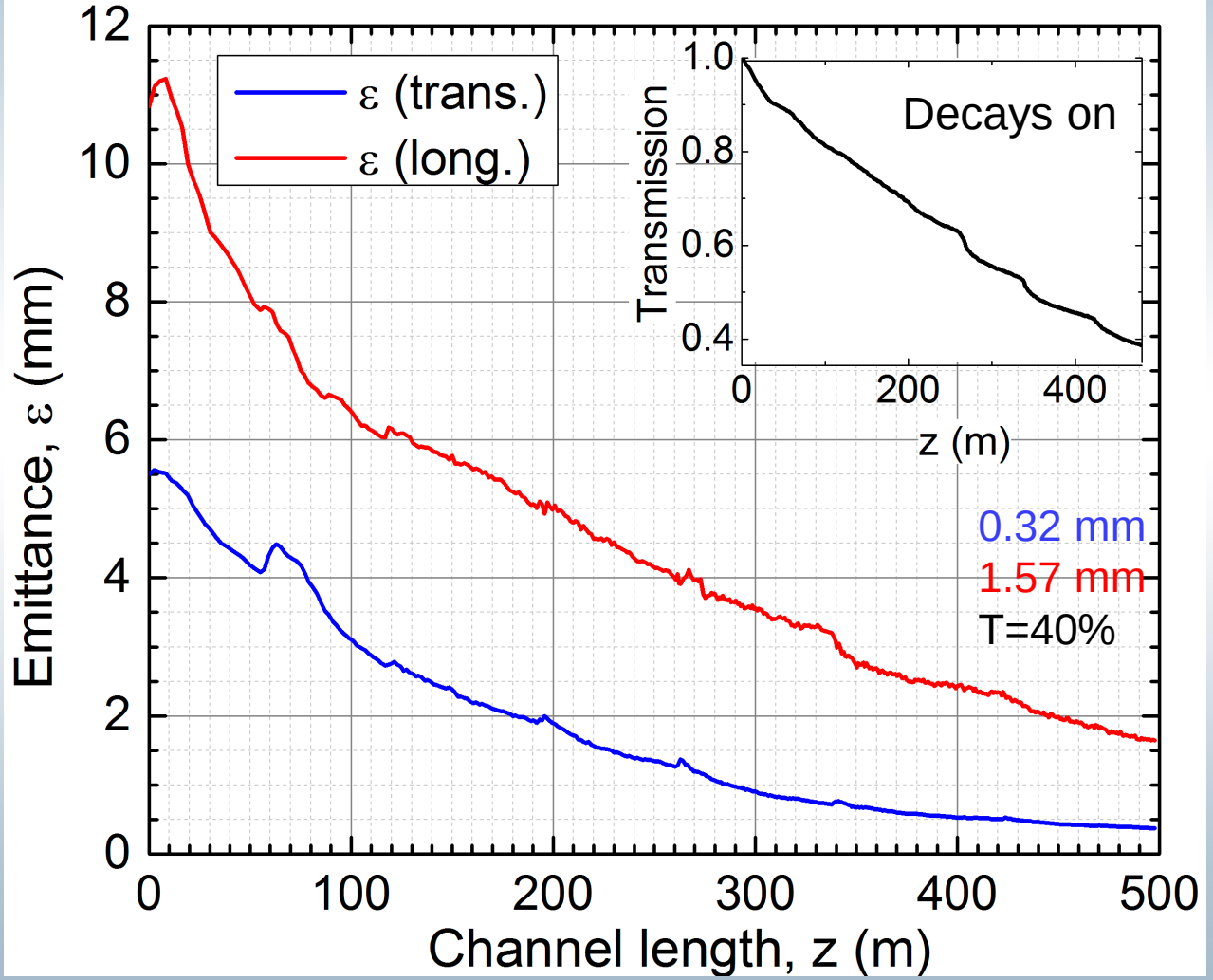
- While Stages 1 to 3 are similar to the pre-merge, the last stages have different structure
- Offers the less possible hoop stress <320 MPa!

Lattice Acceptance



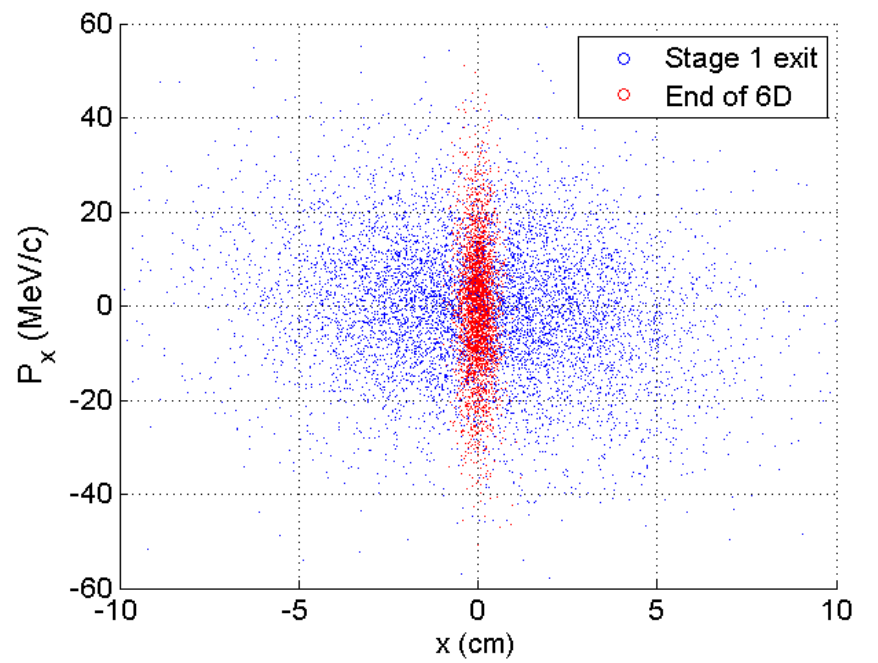
	P_z [MeV/c]	σ_{Pz} [MeV/c]
Stg. 1	219.3	13.9
Stg. 2	212.6	13.9
Stg. 3	216.6	14.3
Stg. 4	214.0	13.1
Stg. 5	211.5	12.6
Stg. 6	207.6	10.8
Stg. 7	207.6	8.6

Lattice performance (7-Stages)

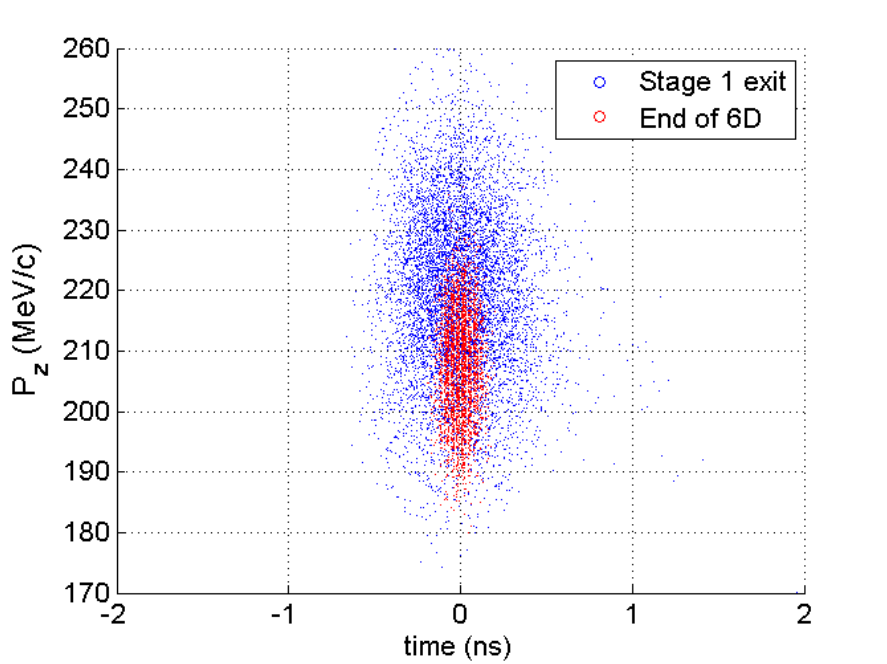


Beam before & after Cooling

Transverse cooling

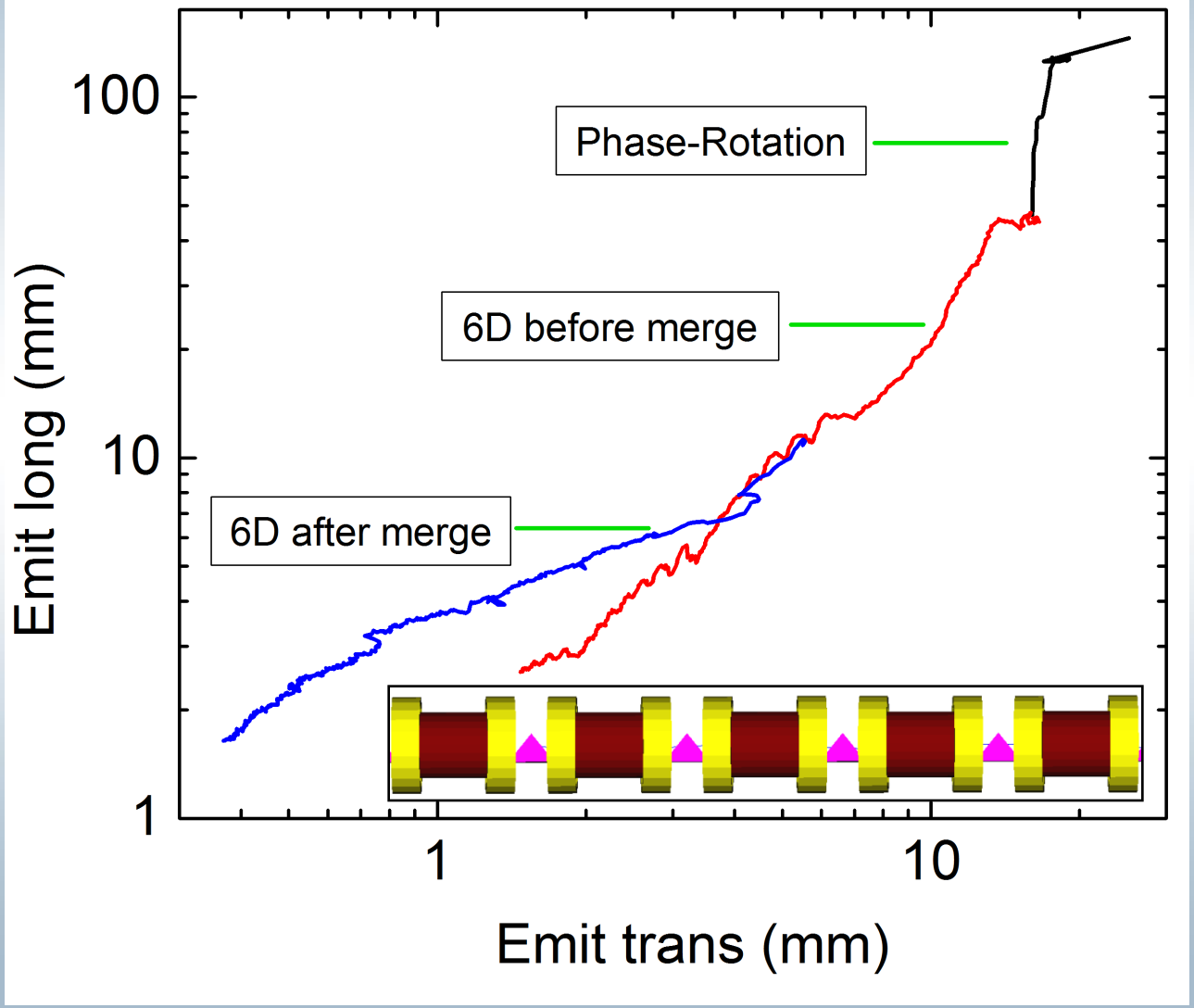


Longitudinal cooling

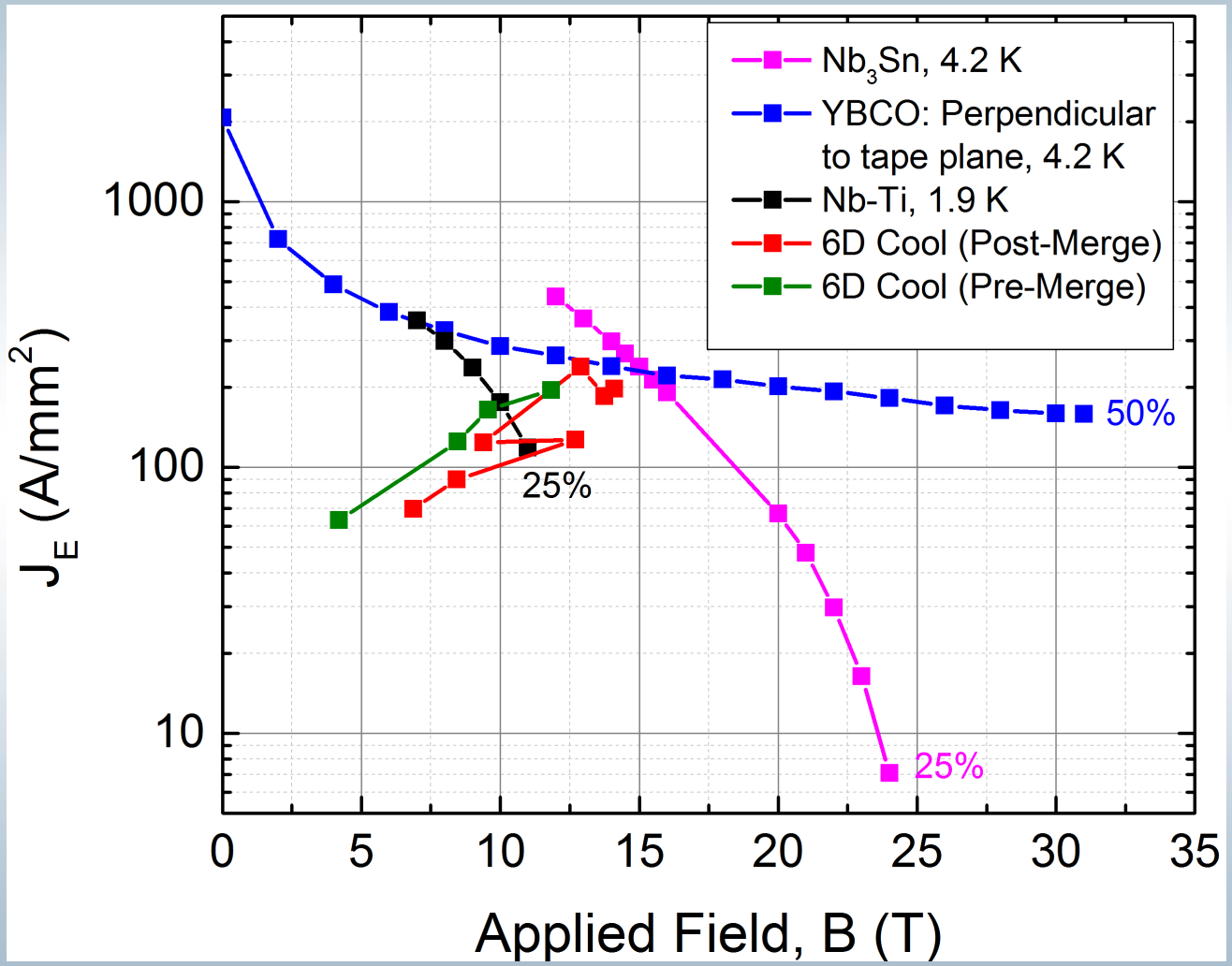


- Average momentum before: 224 MeV/c
- Average momentum after 6D: 207 MeV/c

Overall performance



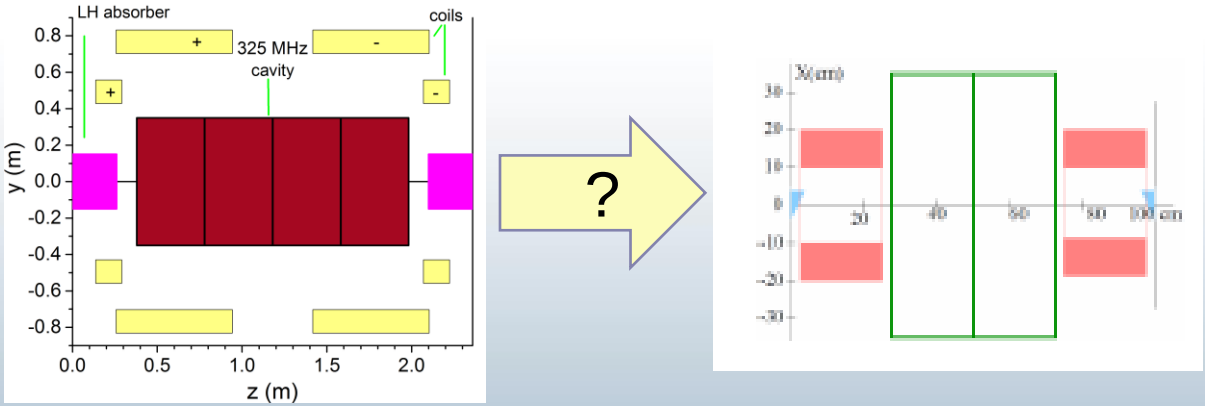
Magnet Technology



- Maximum field on coil is 14.1 T

Next Steps

- For the remaining two months:
  - Do a second pass of all stages and re-optimize.
  - Can we improve performance? Can we make the channel shorter?
  - Stages 5 to 7 may need some “engineering” re-optimization.



- Any other thoughts?

Summary

- A complete 6D cooling scheme was presented
- We tracked a real distribution from the target and delivered for the first time a “front-to-end” simulation.
- High statistics: 50,000 particles
- Rectilinear channel with two frequencies (325, 650 MHz)
- Max. field on coil 14.1 T which is within Nd_3Sn technology
- Max. hoop stress ~ 600 MPa
- RF gradients are within Scott’s criteria
- 4 stages at the pre-merger and 7 stages at the post-merger