Muon Colliders

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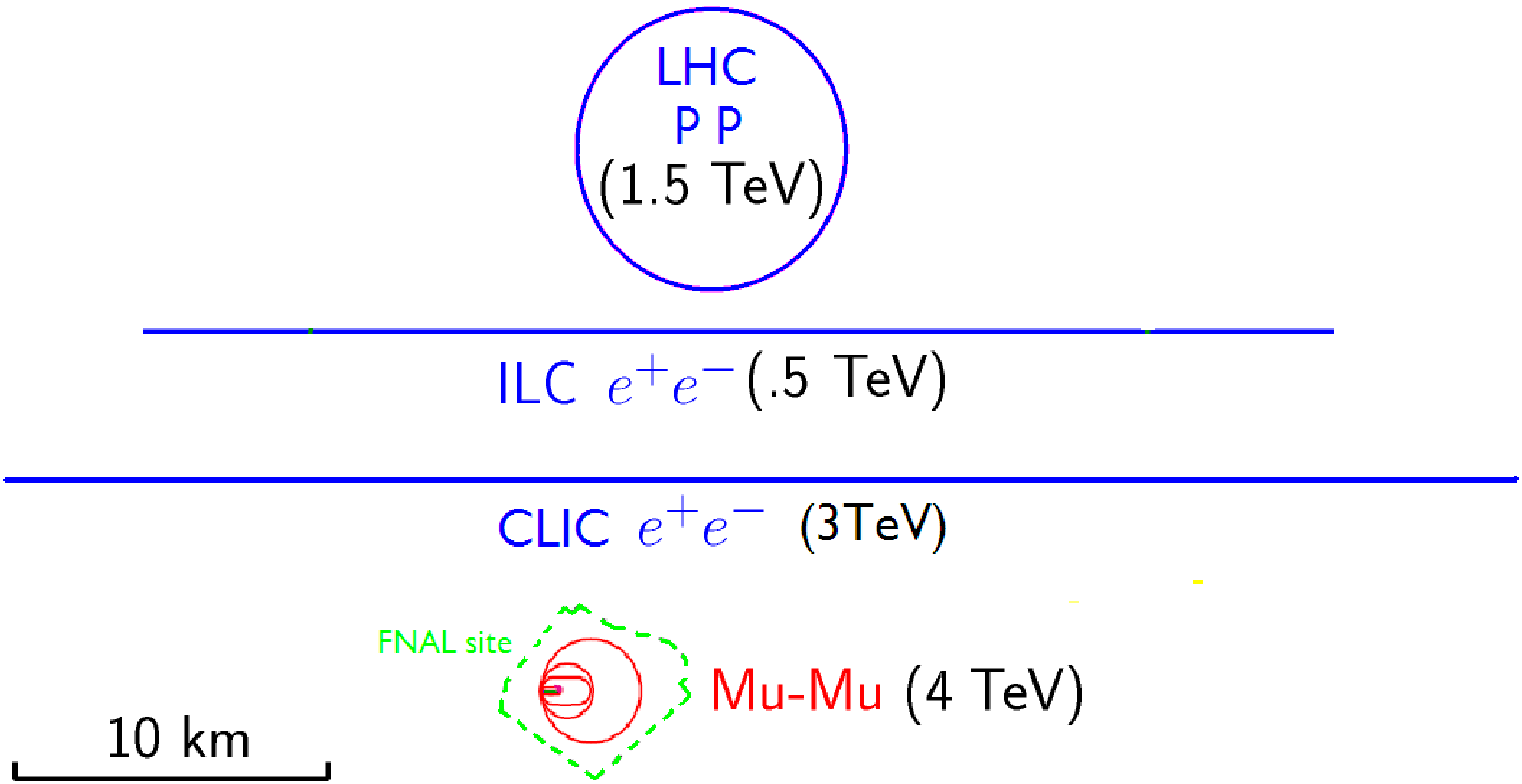
Telluride

6/27/11

- Why
- Subsystems
  - p driver
  - target and capture
  - phase rotation
  - cooling
  - acceleration
  - collider ring
- Performance
- Conclusion

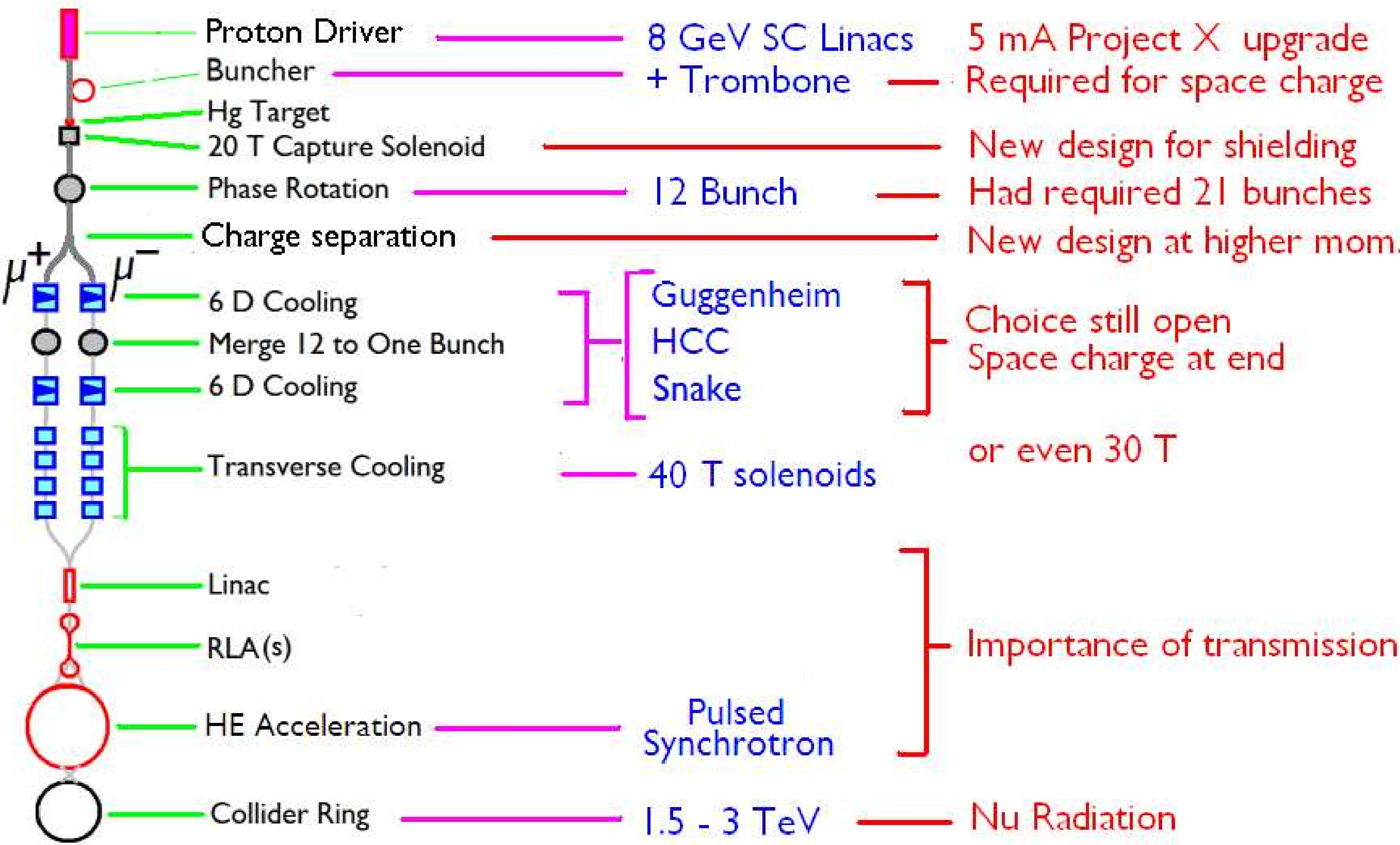
WHY CONSIDER A MUON COLLIDER

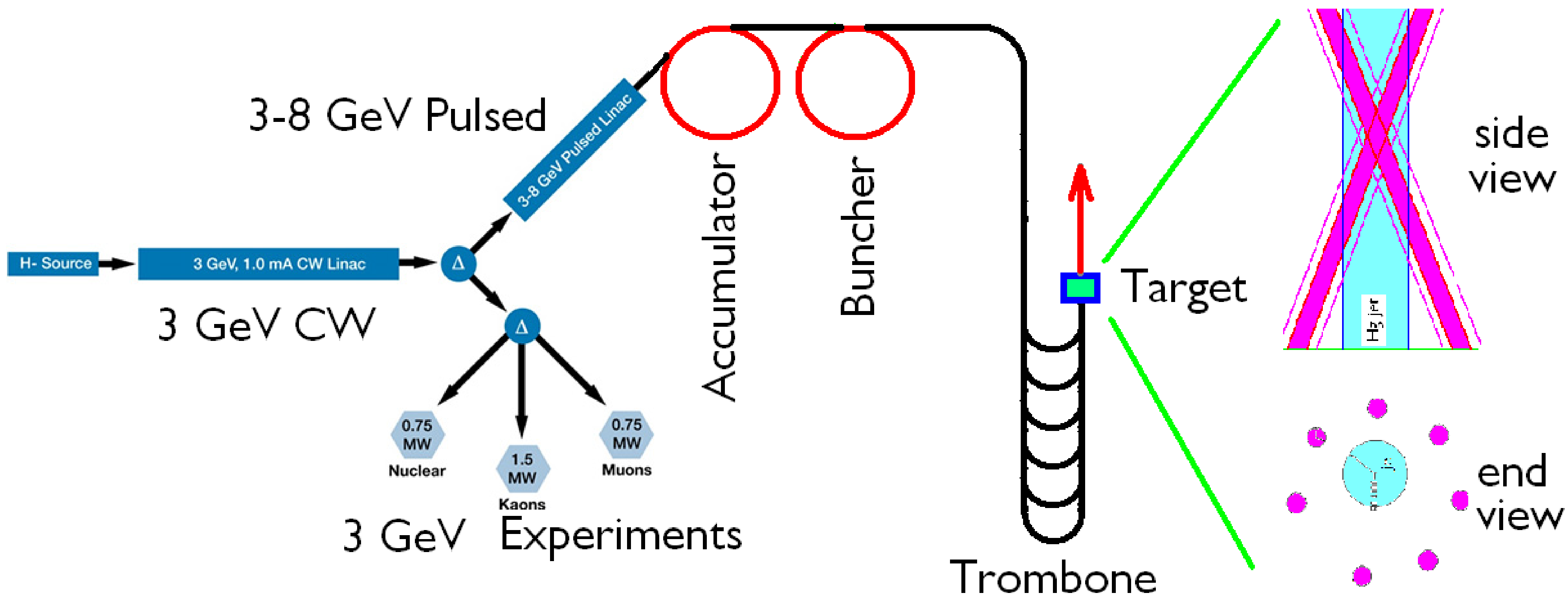
- LHC hints need for higher energy: $\geq$ 1.5 TeV ?
- 3 TeV CLIC uses $>$ 400 MW and is $\approx$ 50 km long



- Muon Colliders certainly smaller, & hopefully cheaper

Schematic & outline





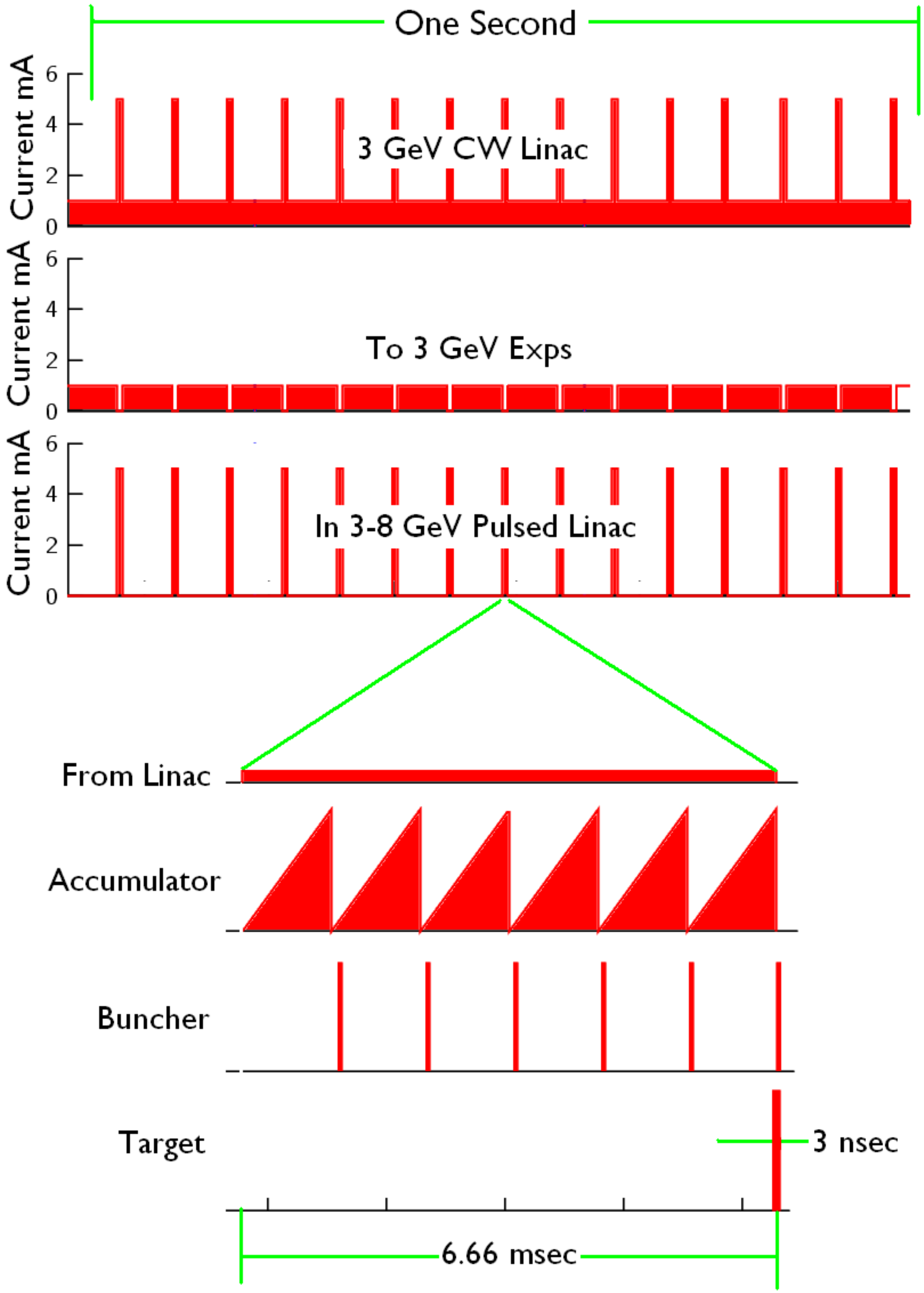
Task Force on Project X upgrades Gollwitzer

- Upgrade CW linac to 5 mA
- 3-8 GeV Pulsed Linac
- Accumulator, Buncher, and Trombone (Ankenbrandt)

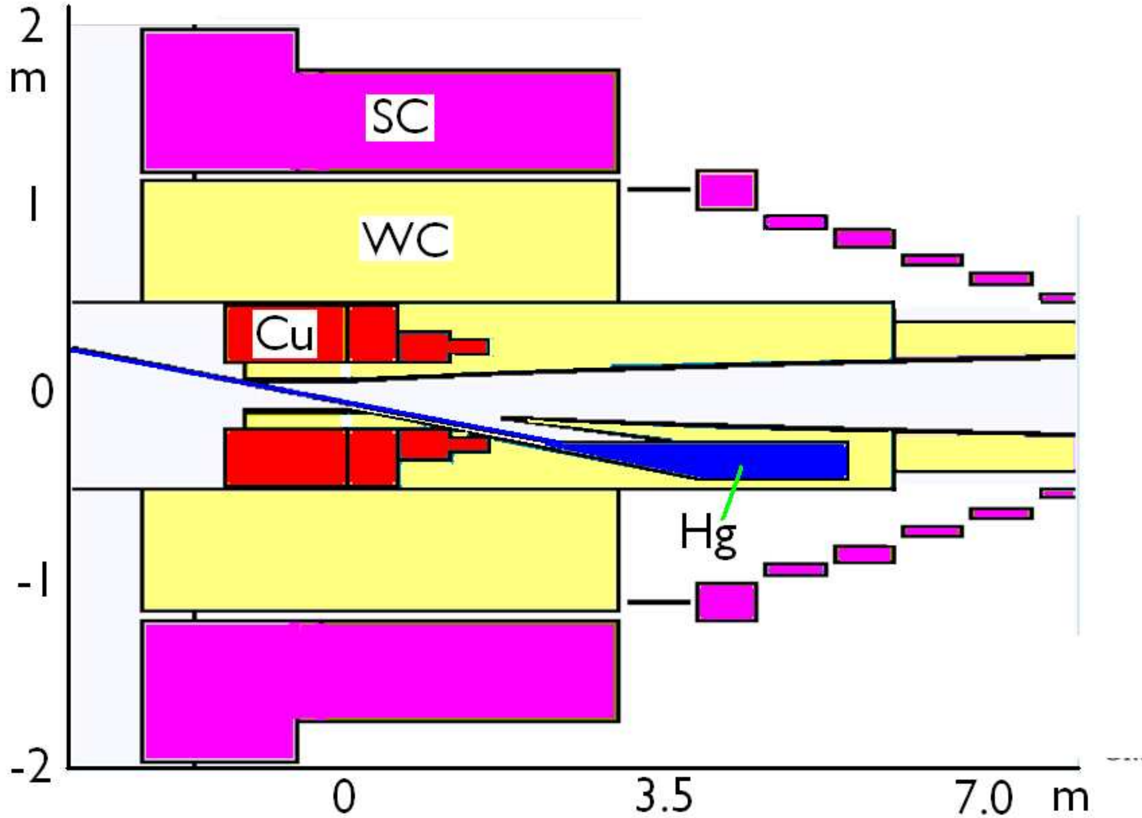
Note: this is my interpretation

Time structure

- 90% of time at 1 mA
  Switched at 3 Gev to Experiments
- 10% of time at 5 mA
  To 3-8 GeV Pulsed Linac
- Repetition as needed for Collider (15 Hz)
- Each 6.6 msec train accumulated into ≈ 6 bunches
- Bunched to rms 3 nsec
- Each bunch kicked to separate channels (trombone) with lengths to bring all to target at same time

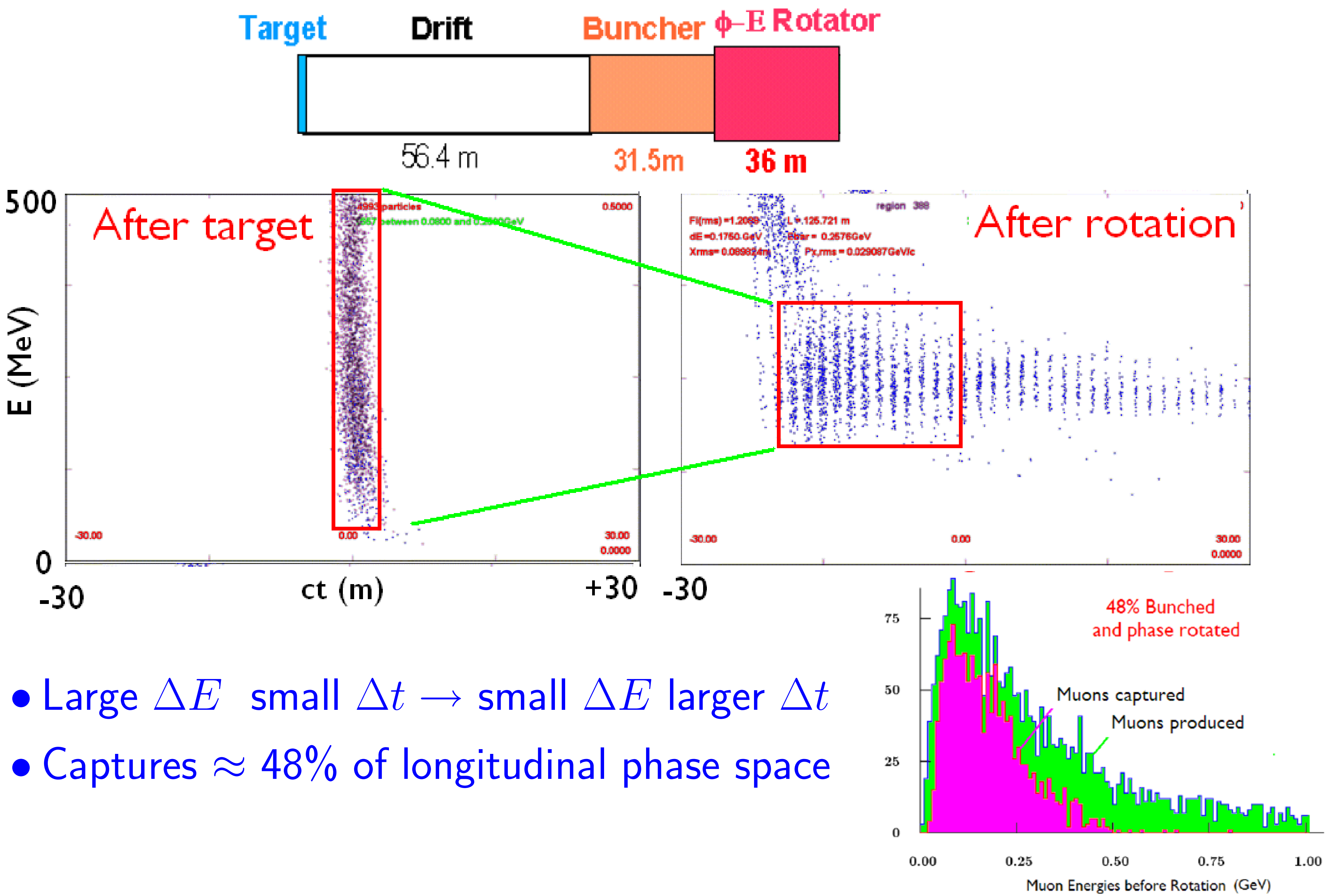


Target Collection: 20 T Hybrid solenoid



- Copper coil gives 6 T
- Super-conducting solenoid give 14 T, tapering to 3 T
- Tungsten Carbide in water shielding for 4 MW 8 GeV beam
  Cu coil uses 15 MW SC coil OD is 4 m
- Captures $p_\perp \leq 240$ MeV/c: $\approx$ 80% of transverse phase space

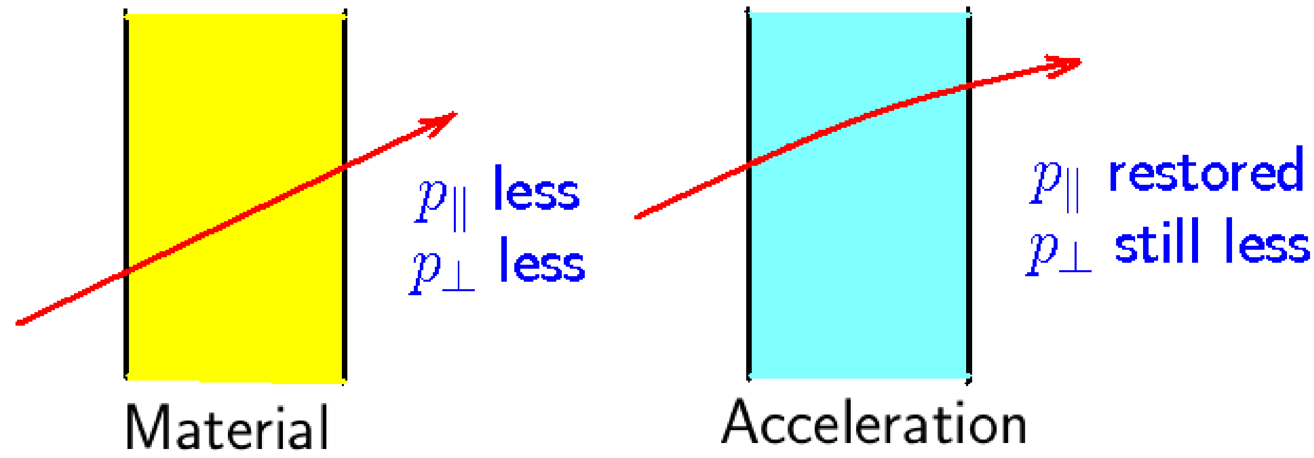
Phase Rotation David Neuffer



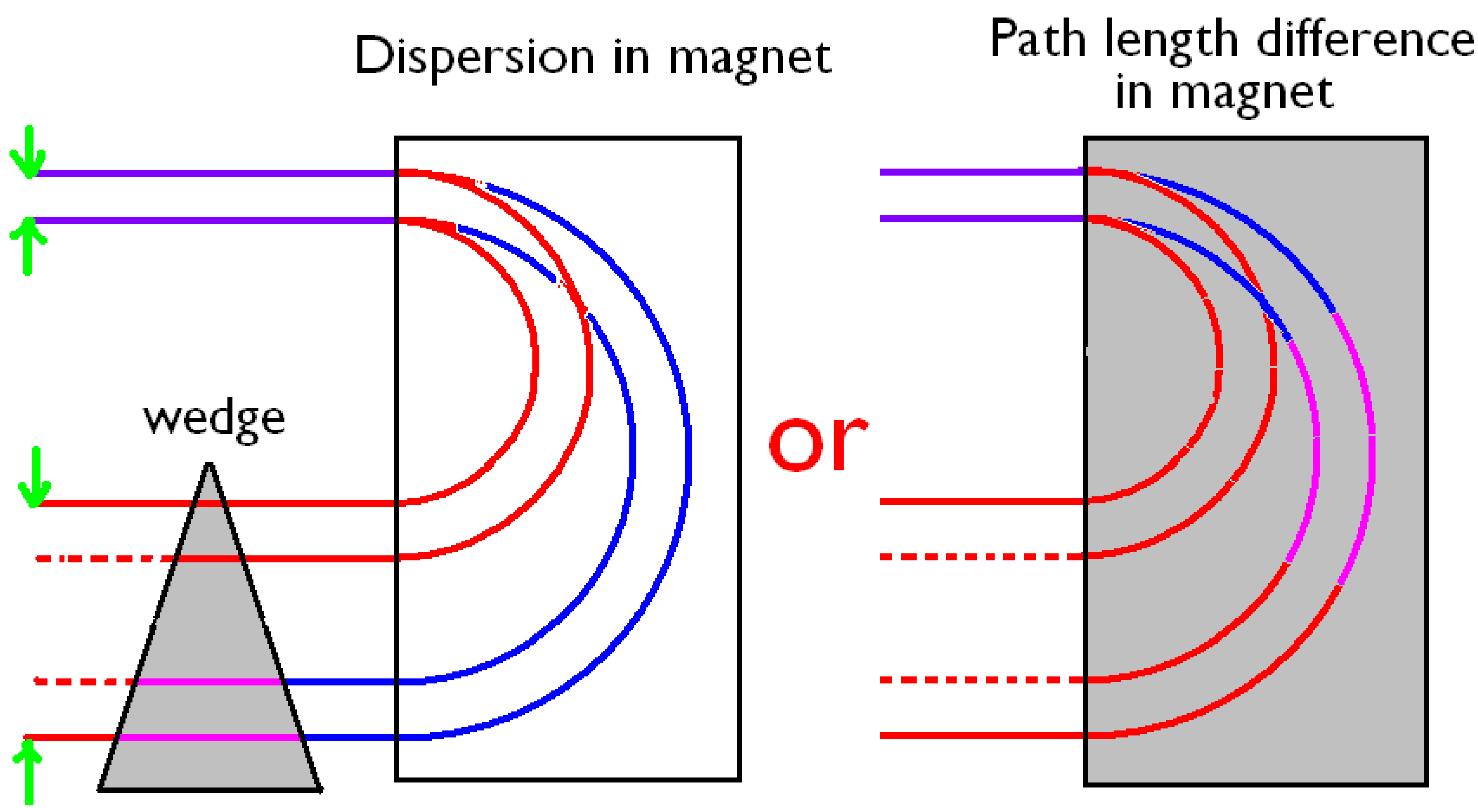
- Large ΔE small $\Delta t \rightarrow$ small ΔE larger Δt
- Captures $\approx$ 48% of longitudinal phase space

Ionization Cooling

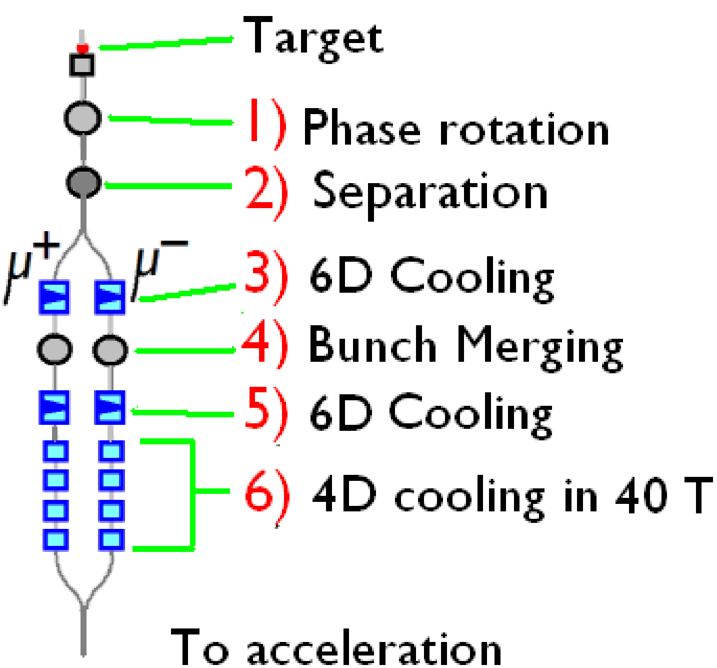
Transverse
(4D)

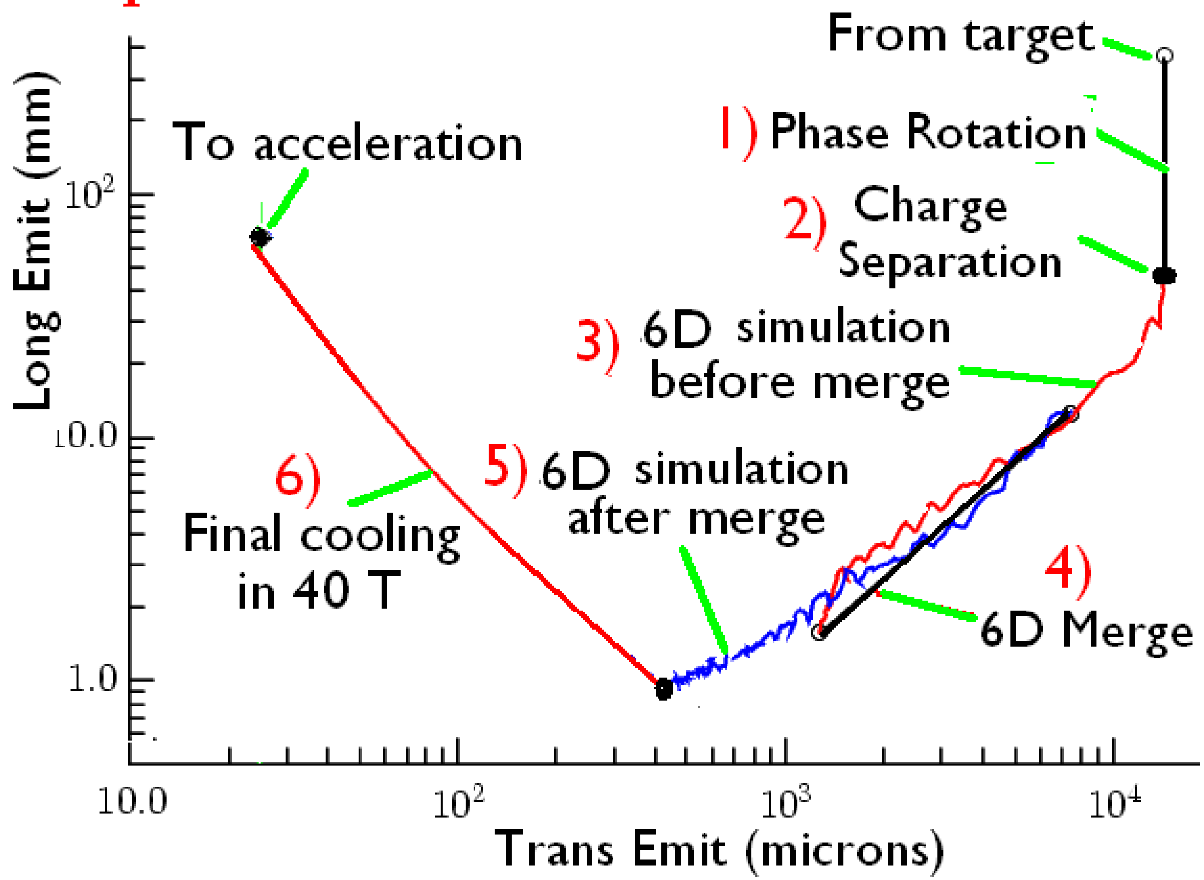


Longitudinal
(6D)



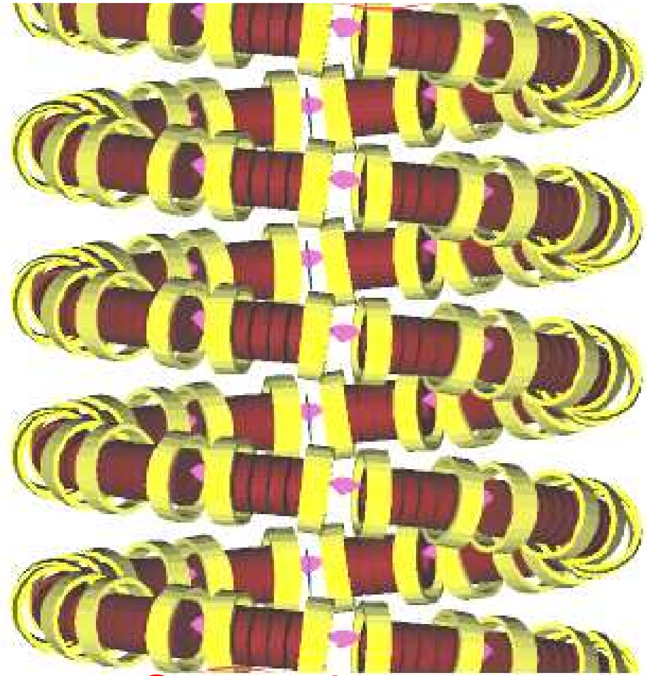
Ionization Cooling Sequence



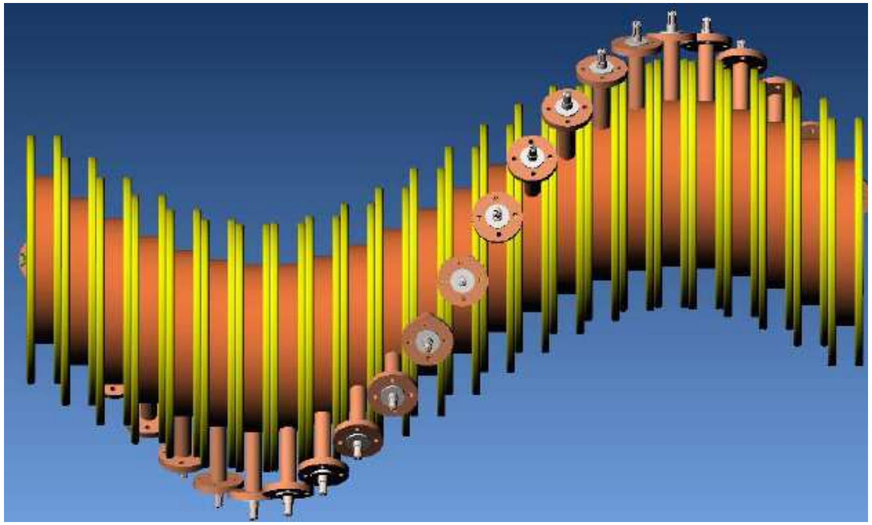


- The simulations plotted did NOT include space charge
- 6D cooling is best done at $\approx$ 200 MeV/c
  Longitudinal cooling more than needed is then possible
- To get to low emittance use highest field (40T?) and Low energy
  At low energy long emittance grows, but this now acceptable

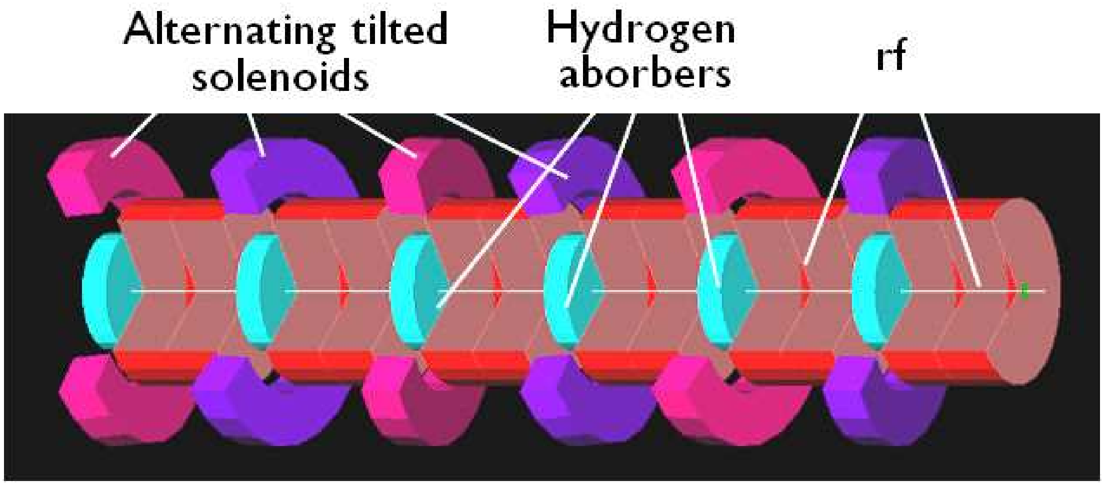
3 candidate 6D cooling lattices



Guggenheim



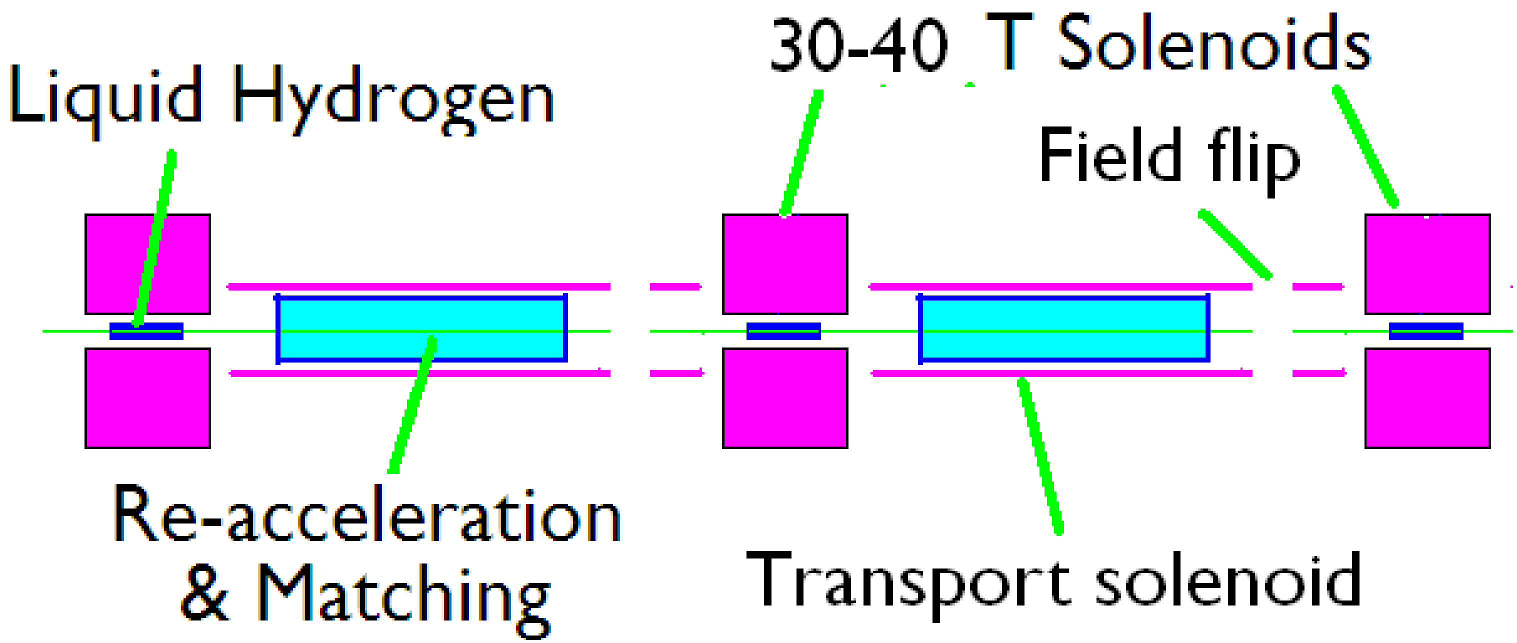
Helical Cooling Channel



Snake

- Alan Bross will explain
- All simulated   All have problems/limitations

Only one candidate for Final cooling to $\epsilon_\perp = 25\ \mu$ m



- 13 stages
- Cooling in hydrogen simmulated for all
- Matching and re-acceleration simulated only for last 2 stages
  Without space charge simulations look ok
- Circa 40 T HTS in resistive outsert under construction (PBL/BNL SBIR funded)

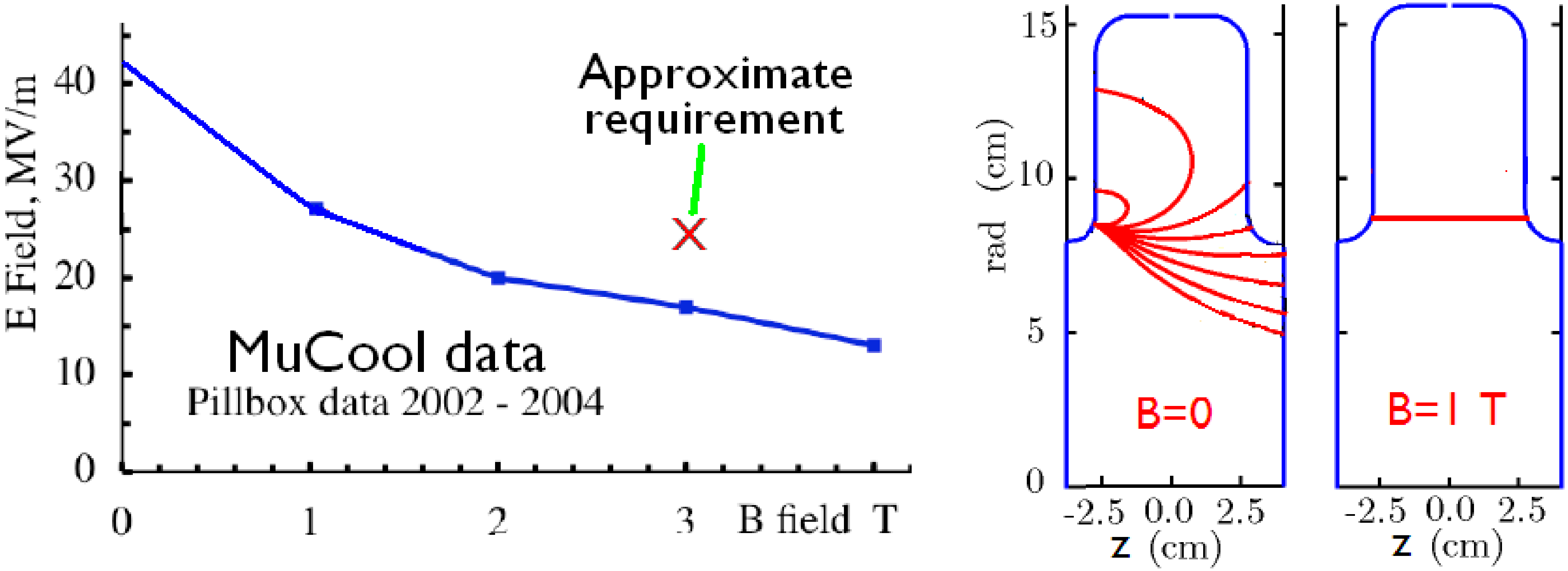
Space charge Problems

- From approximate analytic calculations:
  - Transverse space charge in final cooling
    requires stronger transport solenoids may be ok
    (Fields $\approx$ 3 T on Vacuum rf gas cannot be used)
  - Longitudinal space charge in final cooling
    requires more rf may be ok

  - Transverse space charge in last 6D
    is not a problem
  - Longitudinal space charge in last 6D
    appears to be severe & hard to fix

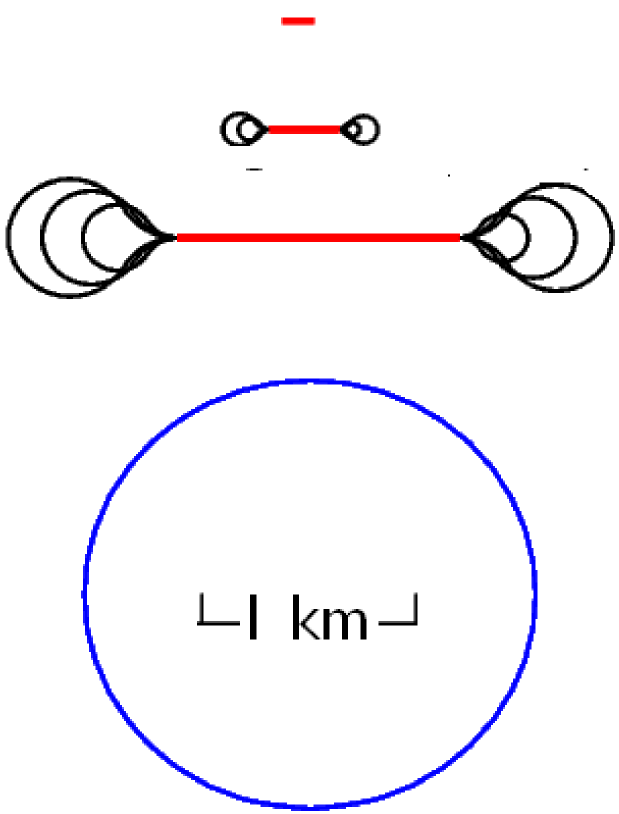
- Simulations starting in collaboration with U of Maryland

Technical challenge: rf breakdown in magnetic fields



- Theory and simulations of effect
- Fixes under study:
  - Magnetic Insulation Tried but not sufficient
  - High pressure gas Works, but not yet with beam & not for Final
  - Beryllium surfaces Some evidence, but definitive tests soon

Acceleration with improved transmission (Berg, Palmer)



1) .4-1.5 Linac L(linac)= 68 m

2) 1.5-12.5 RLA n=4.5 L(linac)= 306 m

3) 12.5-100 RLA n=6.5 L(linac)= 1250 m

No FFAG

4) 100-400 RCS n=23

5) 400-750 RCS n=27

Both in TeVatron tunnel circ(ring)= 6283 m

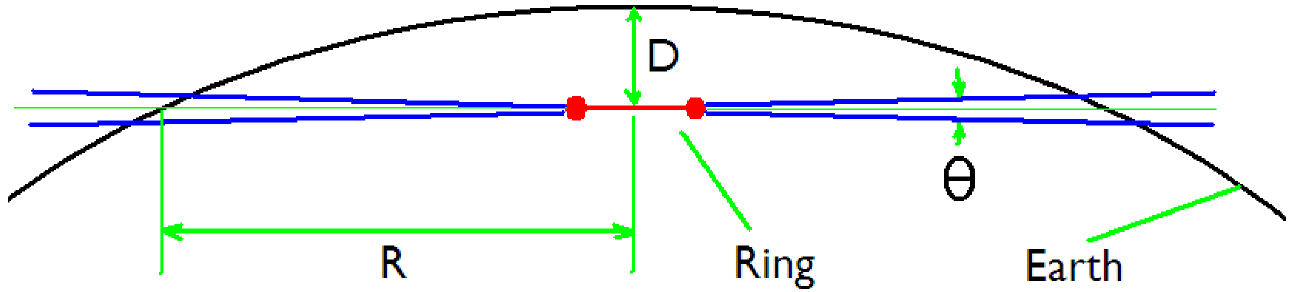
both RCS pulsed at 15 Hz

- Transmission 65.2 %
- Better transmission reduces space charge in cooling and p driver

MC Ring Parameters (Y Alexahin)

C of m Energy	1.5	3	TeV
Luminosity	1	2 (4)	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	0.087	0.087	
Muons/bunch	2	2	10^{12}
Total muon Power	7.2	11.5	MW
Ring $<$bending field$>$	6.04	8.4	T
Ring circumference	2.6	4.5	km
β^* at IP $= \sigma_z$	10	10 (5)	mm
rms momentum spread	0.1	0.1	%
RF frequency	805	805	MHz
RF Voltage	20	230	MV
Repetition Rate	15	12 (15)	Hz
Proton Driver power	4	3.2 (4)	MW
Muon Trans Emittance	25	25	pi mm mrad
Muon Long Emittance	72,000	72,000	pi mm mrad

Neutrino Radiation



$$R_B \ = \ 4.4 \ 10^{-24} \ \frac{N_\mu \ f \ E^3 \ t \ \ < B >}{D \ B} \quad \mathrm{Sv} \qquad \text{from regions of uniform B}$$

$$R_L \ = \ 6.7 \ 10^{-24} \ \frac{N_\mu \ f \ E^3 \ t \ \ < B > \ \ L}{D} \quad \mathrm{Sv} \qquad \text{from straight sections}$$

For $R_B = R_L$ $=$ $\boxed{\text{10\% Fed limit}}$ $=$ 0.1 mSv (10 mRad)

E TeV	B(min) T	L(max) m
1.5	0.25	2.4
3.0	1.5	0.28

But final focus is a special case because divergence is so large

- I do not think the current designs meet these criteria

What can we do ?

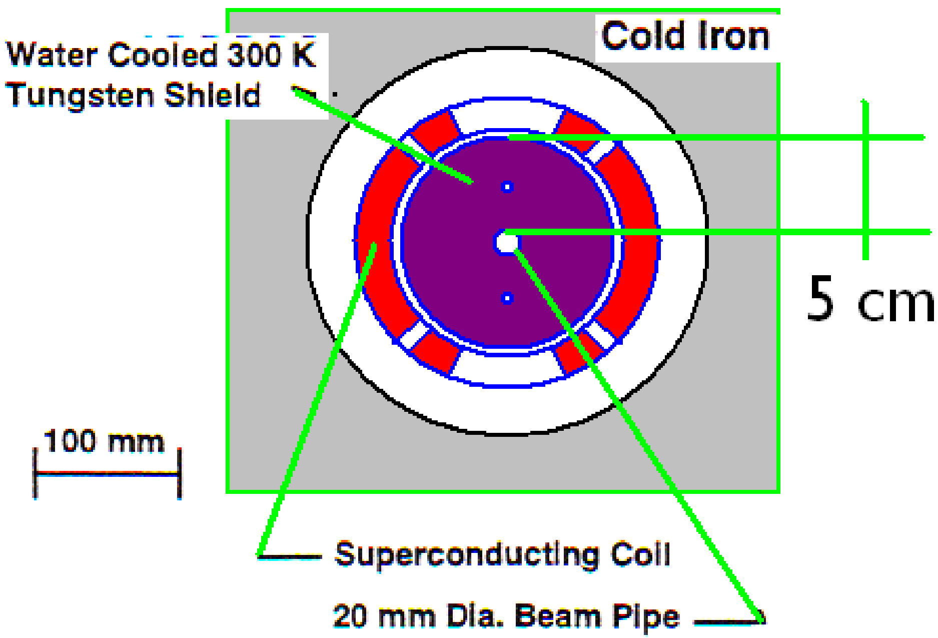
- Decide to allow a higher fraction of Federal limits ?
- Buy local hot spots ?
- Make all quadrupoles have some bending (combined function)
- Add low bending fields over rf and other transport
- Place ring deeper

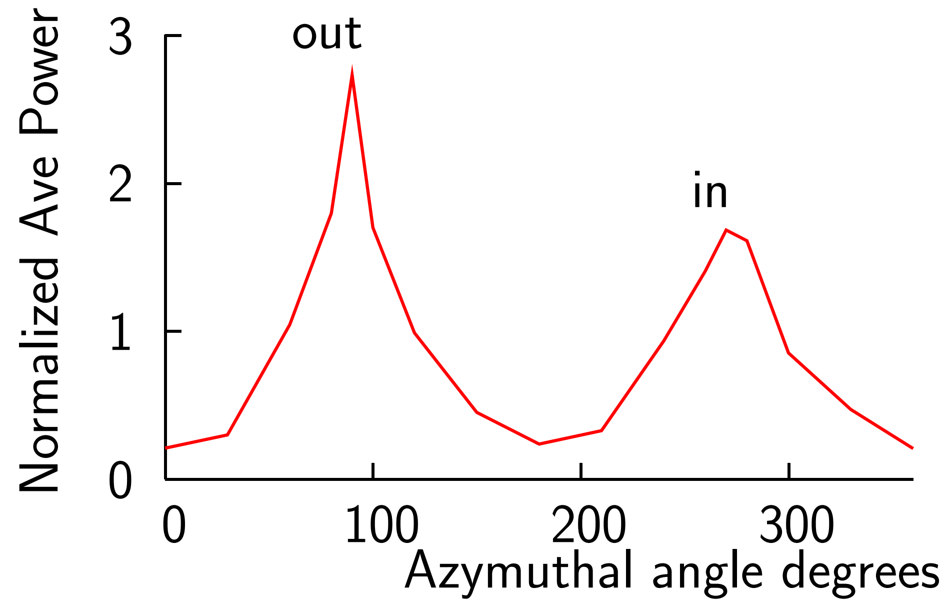
- Scrape muon beam
  At 1.1 sigma: 89% of luminosity, radiation/luminosity $= 0.61$
- Extract beam before all have decayed
  At 1.1 tau: 89% of luminosity, radiation/luminosity $= 0.79$

If for 3 TeV repetition rate rate 12 $\longrightarrow$ 15 (like 1.5 TeV)
Plus scraping at 1.1 sigma and extract at 1.1 τ
Then Luminosity the same, but $\boxed{\text{radiation} \times 0.48}$

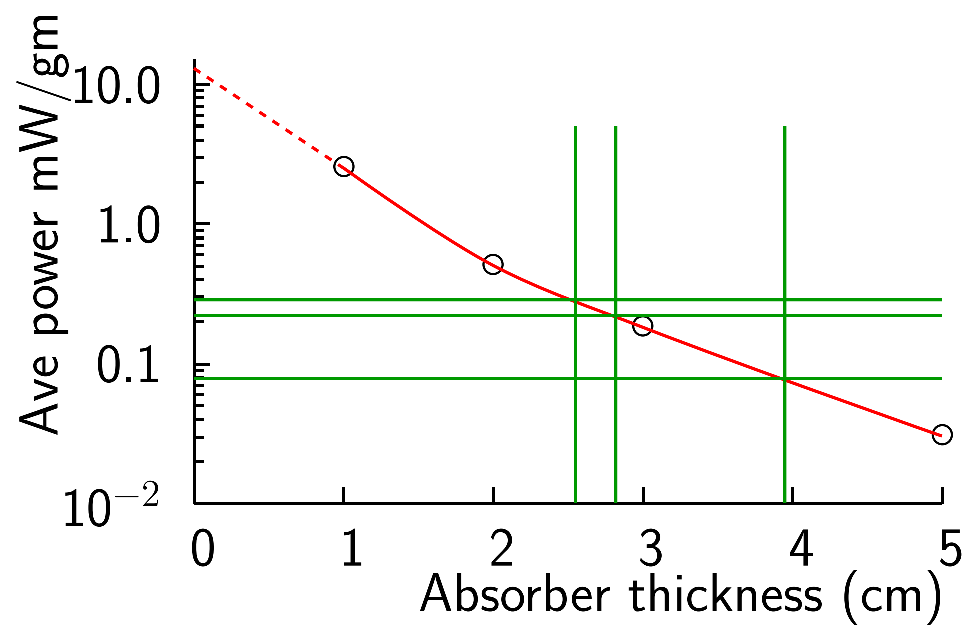
Heat load from Decay in Ring 2.4 MW to electrons

As in 98 Study of 4 TeV

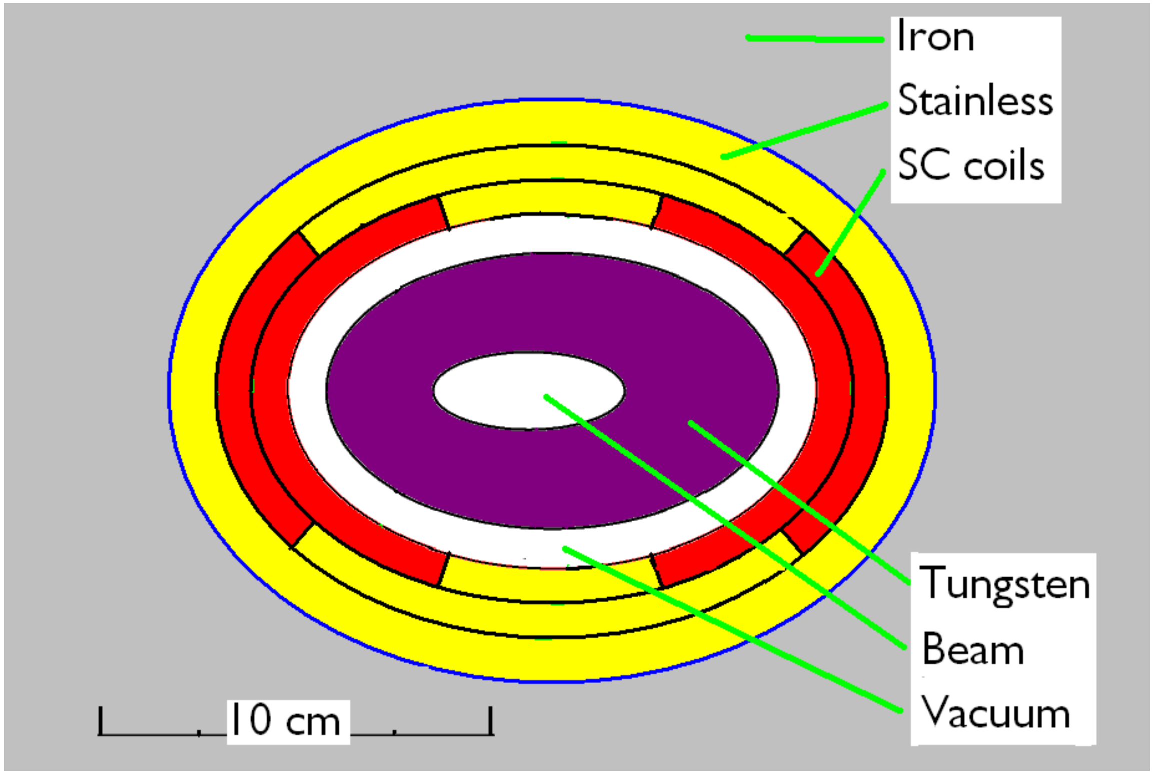




- Attenuation 0.2%
- Cryo eff=.27 %
- Cryo wall power 1.8 MW
- Better than needed
- Especially up & down

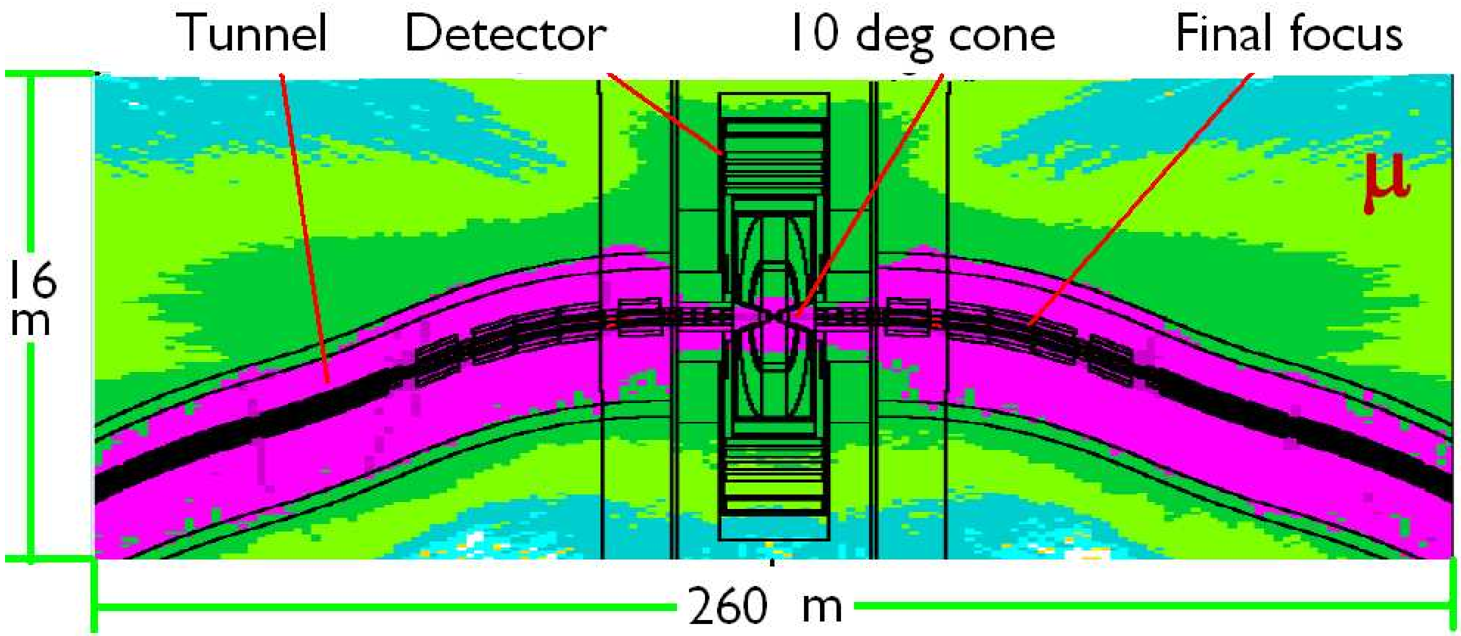


- Current Open mid-plane geometries not acceptable
- First shot at minimum shield pipe
- Design for 10 MW cryo wall power



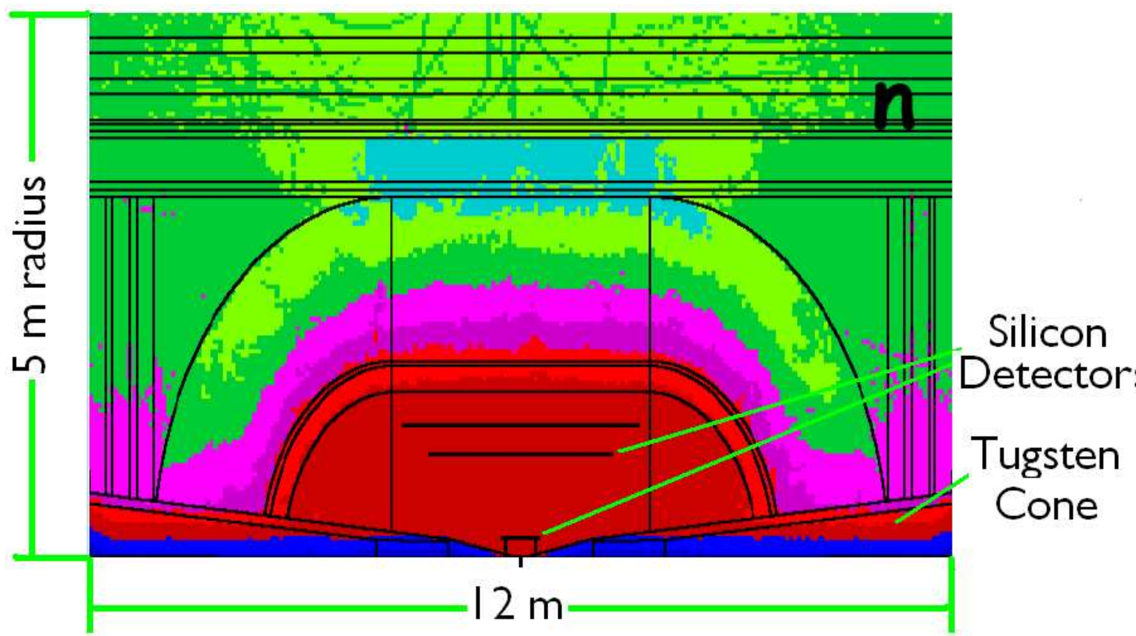
- Tungsten cross section less than half 98 Study & larger beam

Detector Shielding



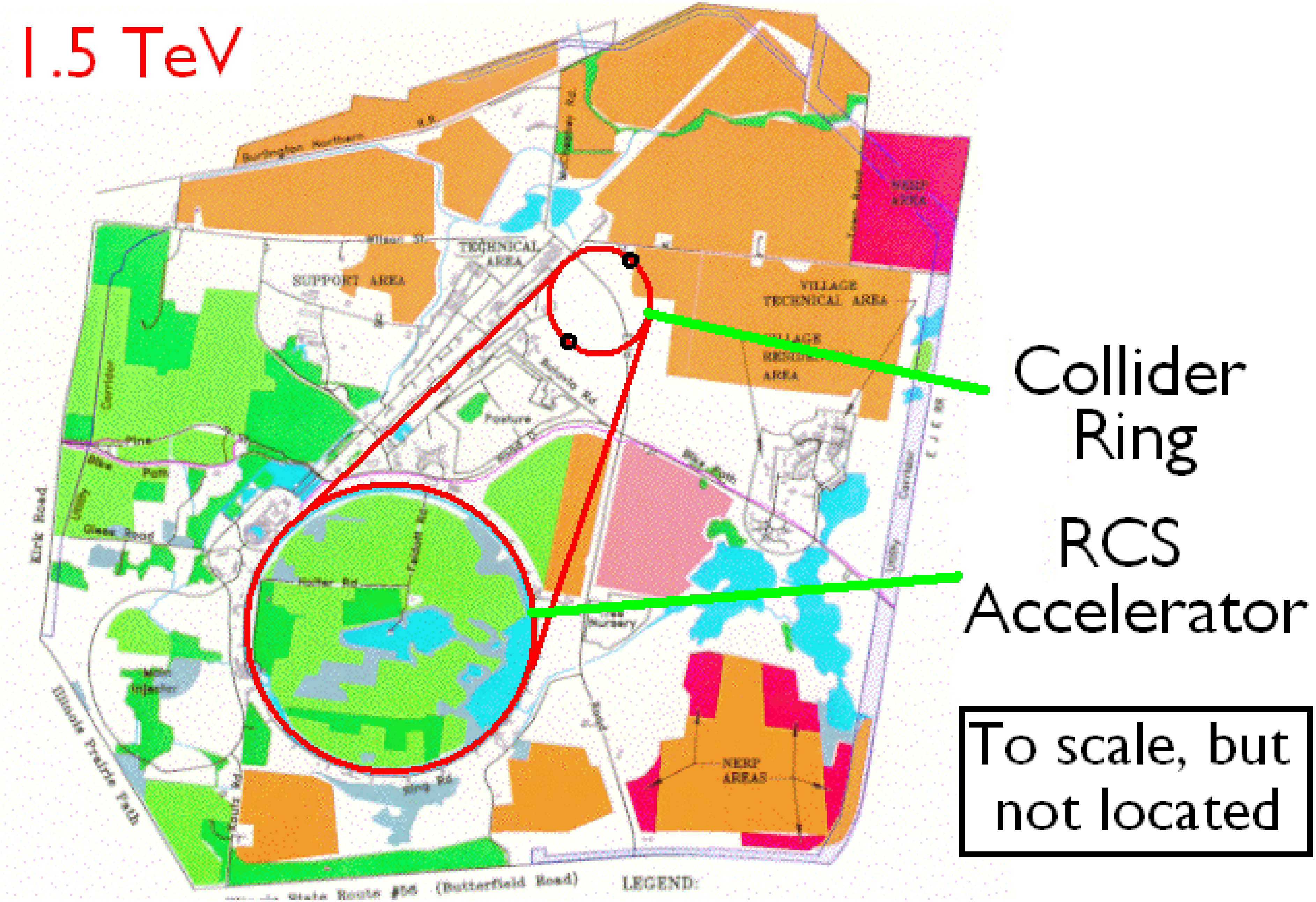
Fluence at first silicon tracker 10% of LHC at $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$

More in MDI Mokhov talk

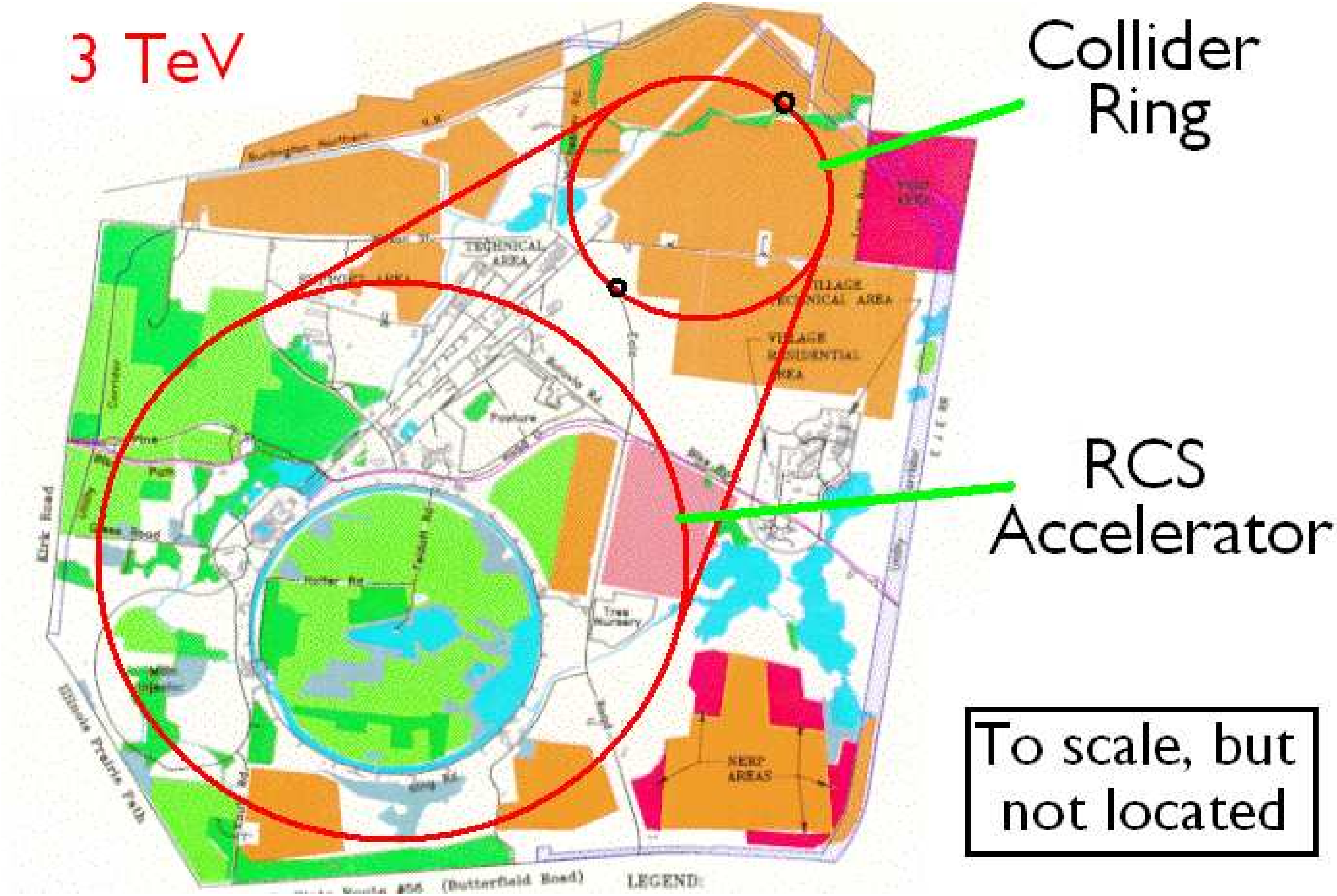


Layout at FNAL

1.5 TeV



Layout at FNAL



New estimates of Transmission

From new acceleration design (not and cooling simulations

	transmission	cumulative	mu/p	mu/pulse
After rotation			0.334	
Momenta 226 $\pm$ 100 MeV/c	0.654	1.0	0.219	
Best 21 bunches	0.7	0.7	0.153	$2{\times}27.7\ 10^{12}$
Charge separation	0.85	0.59	0.129	$23.5{\times}2\ 10^{12}$
6D Cooling before merge	0.468	0.28	0.061	$11.0\ {\times}2\ 10^{12}$
Merge	0.88	0.25	0.055	$9.7\ {\times}2\ 10^{12}$
6D Cooling after merge	0.48	0.12	0.026	$4.7\ {\times}2\ 10^{12}$
50 T Cooling	0.7	0.08	0.018	$3.3\ {\times}2\ 10^{12}$
RTRF low energy acceleration	0.84	0.067	0.015	$2.7\ {\times}2\ 10^{12}$
SCRF Acceleration	0.73	0.049	0.011	$2.0\ {\times}2\ 10^{12}$

- Assuming initial production from 8 GeV and MARS 15:
  For 2 10^{12} muons 187 10^{12} protons/bunch needed
- Proton power $15 \times 1.87\ 10^{14} \times 8\ 10^{9} \times 1.6\ 10^{-19} = \boxed{3.6\ \mathrm{MW}}$
- Still just under 4 MW specified

First estimation of Wall Power

	Len	Static	Dynamic	—	—	—	Tot
		4^o	rf	PS	4^o	20^o	
	m	MW	MW	MW	MW	MW	MW
p Driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merge	222	0.6	7.2		6.8	6.1	20.7
Merge	115	0.2	1.4				1.6
6D cooling after merge	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC RF acceleration	104	0.1	4.1				4.2
SC RF linac	140	0.1	3.4				3.5
SC RF RLAs	10400	570	19.5				28.6
SC RF RCSs	12566	790	11.8				23.1
Collider ring	2600	2.3		3.0	10		5.3
Totals	26777	4445	24.6	52.5	18.0	21.7	146.8

Similar calculations give for 3 TeV Wall power $=$ 159 MW

$\approx$ $\boxed{\text{1/3 of 3 TeV CLIC}}$, $\boxed{\text{2/3 of 0.5 TeV ILC}}$

Compare with CLIC

	$\mu^+\mu^-$	$\mu^+\mu^-$		e^+e^-CLIC
C of m Energy	1.5	3	TeV	3
Luminosity	1	2 - 4	10^{34} cm^{2}sec^{-1}	$2^{(1)}$
Ring <bending field>	6	8.4	T	-
Accelerator diam/length	2	4	km	48
rms bunch height	6	4	μm	0.001
Proton Driver power	4.	3.2	MW	-
Wall power	147	159	MW	415

- 3 TeV luminosity comparable or above CLIC's (for dE/E $<$ 1%)
- 3 TeV accelerator is much smaller than CLIC's
- Spot sizes and tolerances much larger than CLIC's
- 3 TeV Wall power $\approx$ 1/3 CLIC's

- But less developed
  Muon Accelerator Program (MAP) $\rightarrow$ Feasibility Study $\approx$2013

Conclusion

- Much simulation progress this year
  - new capture magnet design, shorter phase rotation, charge separation & merge designs, 6D cooling simulations, sequence of acceleration with better transmission, design of tungsten shield pipe Detector background studies
- Performance
  - Luminosities equal or greater than CLIC's
  - Estimate of wall power $\approx 1/3$ of CLIC (2/3 of ILC !)
- Possible worst problems
  - Space charge in late 6D cooling — Simulations started
  - rf breakdown in magnetic fields — Solutions being tested
  - Ring design with Neutrino radiation criterion — Ideas to help