Muon Colliders

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- Parameters
- Compare with CLIC
- Compare with Hadron Colliders
- Costs using Shiltsev model
- Is this really plausible?
- Conclusion

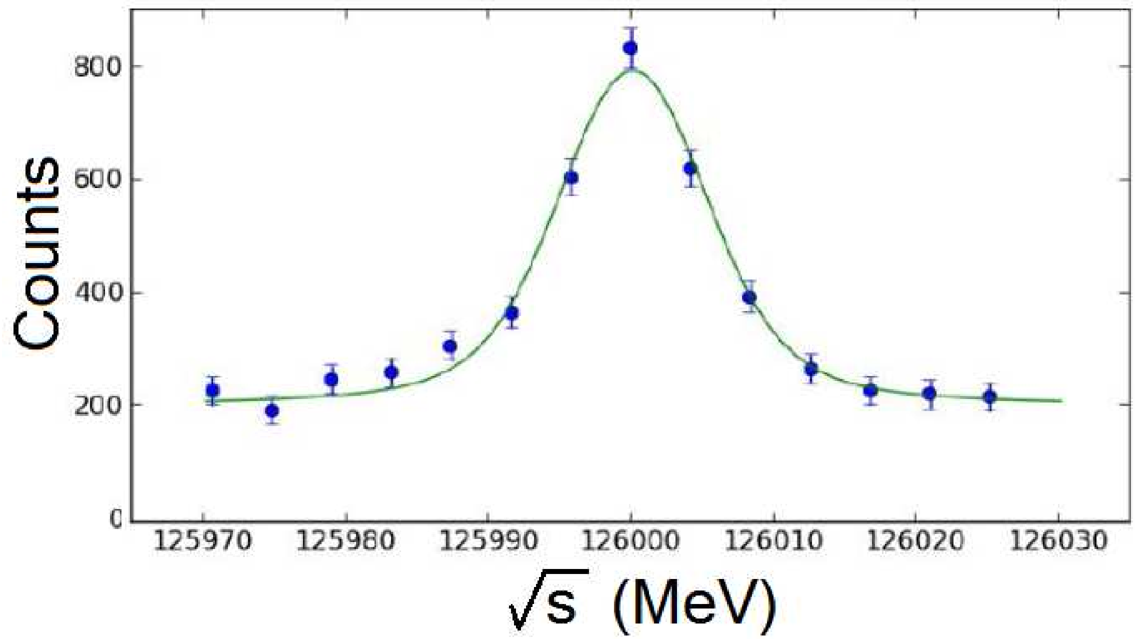
Muon Collider Rings

C of m Energy	0.126	1.5	3	6	TeV
Luminosity	0.008	1	4	12	10^{34} cm^{-2}sec^{-1}
Muons/bunch	4	2	2	2	10^{12}
Total muon Power	2.5	7.2	11.5	11.5	MW
Ring <bending field>	4.4	6.04	8.4	11.6	T
Ring circumference	0.3	2.6	4.5	6	km
β^* at IP $= \sigma_z$		10	5	2.5	mm
rms momentum spread	0.004	0.1	0.1	0.1	%
Depth		135	135	540	m
Repetition Rate	30	15	12	6	Hz
Proton Driver power	4	4	3.2	1.6	MW
Muon Trans Emittance	200	25	25	25	μm
Muon Long Emittance	1.5	72	72	72	mm

6 TeV case is a blind extrapolation from 1.5 and 3 TeV designs

Comment about Higgs Factory

- The Muon Higgs factory makes an order of magnitude fewer Higgs than a 120 GeV FCC ee
- But it alone could measure the Higgs width
- It is too challenging and expensive for this single result
- Only realistic as an add on to a HE Muon Collider



Neutrino Radiation for 6 TeV

$$R_B = 4.4\ 10^{-24} \frac{N_\mu\ f\ E^3\ t\ < B >}{D\ B}\ \mathrm{Sv}$$

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

For R=10 mrem & E=3 TeV: B_{min}=1.5 T & L_{max} = 28 cm

For other E: $\propto \frac{(N_\mu\ f\ E)\ E^2}{D} \propto \frac{P_{beam}\ E^2}{D}$

If $f \propto 1/E$ then $P_{beam} = \mathrm{constant}$

For 6 TeV and R constant: $D \propto E^2$ 135 $\rightarrow$ 540 m

Will geology allow this?

Wall Power Assumptions

- Proton Driver power consumption assumes a 20% efficiency
- A 15 MW resistive insert capture solenoid is included
- Static cryogenic power requirements are based on total lengths of cryogenic systems $\times$ MICE design estimates
- rf power requirements based on preliminary designs of rf systems
- Beam heating in Front End cooling did not including reductions from the proposed chicane system
- Dynamic heating at 20 K assumes ionization cooling with liquid hydrogen. With high pressure gas, it would be at a higher temperature, and thus less
- Beam heating of collider ring magnets assumes a tungsten liner

Wall Power for 1.5 TeV

	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
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	9.1	19.5				28.6
SC RF RCSs	12566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Service & Control		70					70
Totals	26777	94.6	52.5	18.0	21.7	8.8	216

for 3 TeV: 230 MW for 6 TeV: 270 MW

3 TeV $\mu^+\mu^-$ vs. e^+e^- (CLIC)

		$\mu^+\mu^-$	e^+e^-
Luminosity/IP (total)	10^{34} cm^{-2}s^{-1}	4	2
Luminosity/IP (1%)	10^{34} cm^{-2}s^{-1}	4	2
IPs = Detectors		2	1
β^* at IP $= \sigma_z$	mm	5	0.09
rms bunch height σ_y	μm	3	0.001
Total lepton Power	MW	11.5	28
Wall power	MW	216	570
Lepton power/Wall power	%	20.0	20.3
$N_{Det}\times$ L(tot)/Wall power	10^{34} cm^{-2}s^{-1}GW^{-1}	35	10
$N_{Det}\times$ L(1%)/Wall power	10^{34} cm^{-2}s^{-1}GW^{-1}	35	3.5

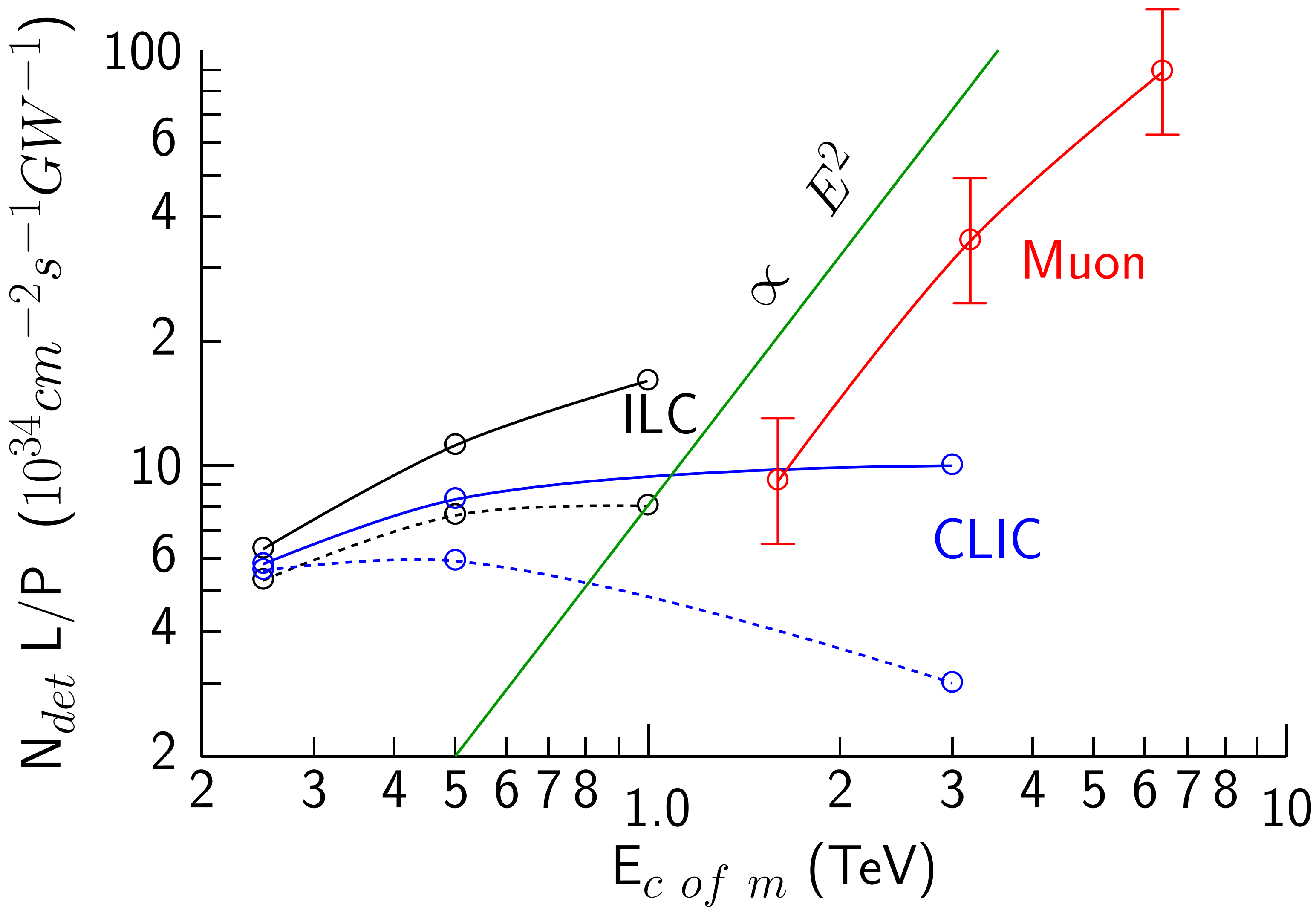
Comments

- Spot sizes and tolerances much easier than CLIC's
- $\mu^+\mu^-$luminosity/detector twice CLIC's (for dE/E $< 1\%$) $\times$ 2 detectors
- Wall power to Lepton Power efficiencies similar
- Lepton and Wall Power $\approx 1/3$ CLIC's

Muon advantage is because muons interact $\approx$ 1000 times, but electrons only once

Merit

$$Merit = \frac{Luminosity \times N_{detectors}}{Power_{wall}}$$



Comment on Merits

It has long been argued that a detailed study of 'New Physics' requires a lepton collider with appropriate energy, and from the above one can conclude that

- If 'New Physics' is below 2 TeV then ILC, CLIC or even PWF may be appropriate
- But if 'New Physics' $>$ 2 TeV then a Muon Collider appears to be the only way to achieve needed luminosity with reasonable wall power consumption.

- Plasma acceleration claims higher double the CLIC efficiency, but with the such loading, low emittance dilution will be a challenge.

Compare with hadron colliders

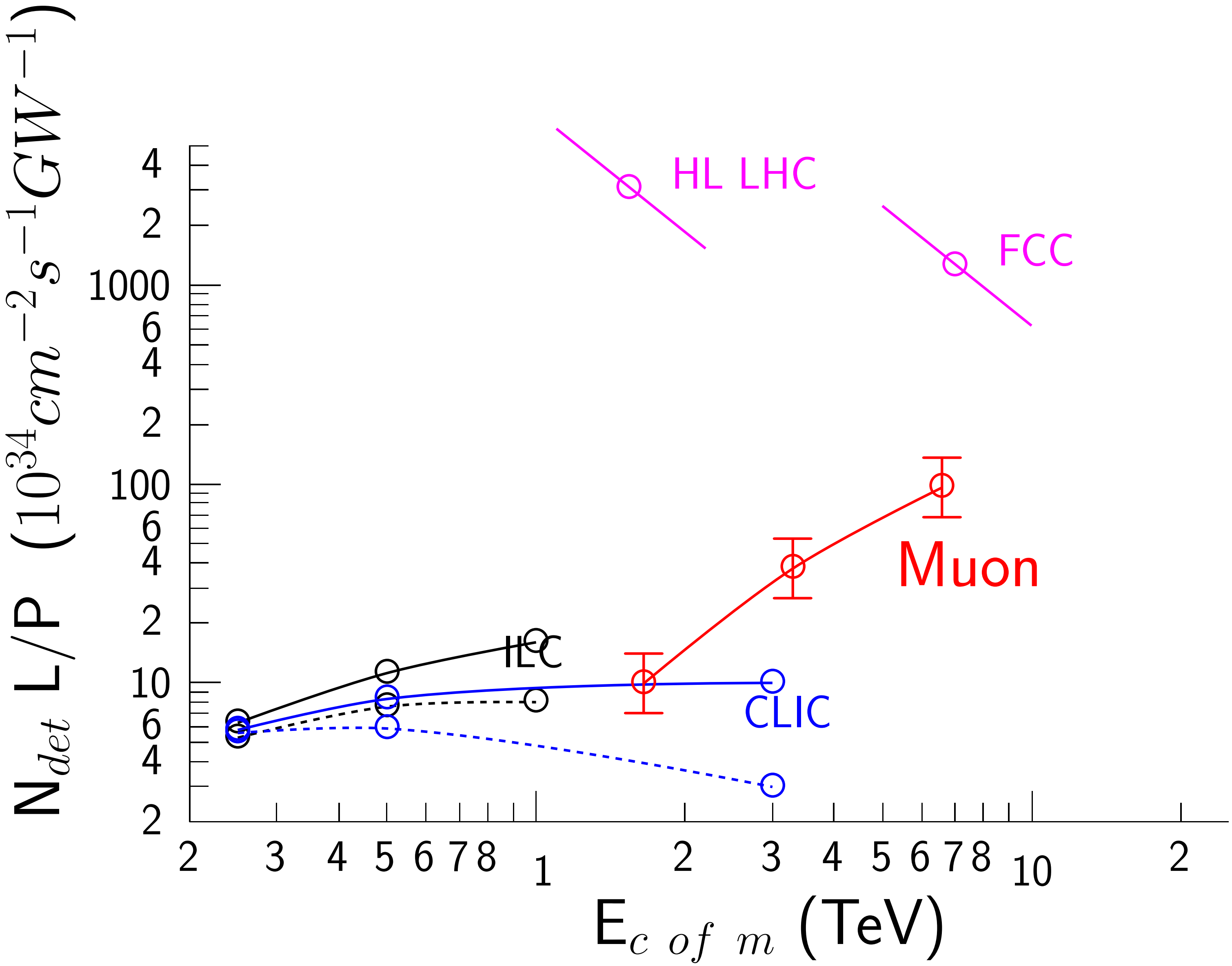
If n_{parton} is effective number of partons in a proton, then

$$E_{(parton-parton)} = \frac{E_{(p)}}{n_{(parton)}}$$

$$Lum_{(parton-parton)} = Lum_{(p-p)} \times n^2_{(parton)}$$

In reality it is more complicated. Luminosities are spread over a range of n_{parton} with dependencies (structure functions) that depend on the parton. When n_{parton} is higher the lumiosity rises as n^2_{parton} and the energy falls, and visa-versa.

Compare with hadron colliders



Comments

- The effective luminosity of HL LHC is $\approx$ 250 times that of CLIC
  LHC for discovery CLIC for details

- But FCC hh is only $\approx$ 12 times a 6 TeV Muon Collider
- And the gap is closing

A muon collider is becoming a

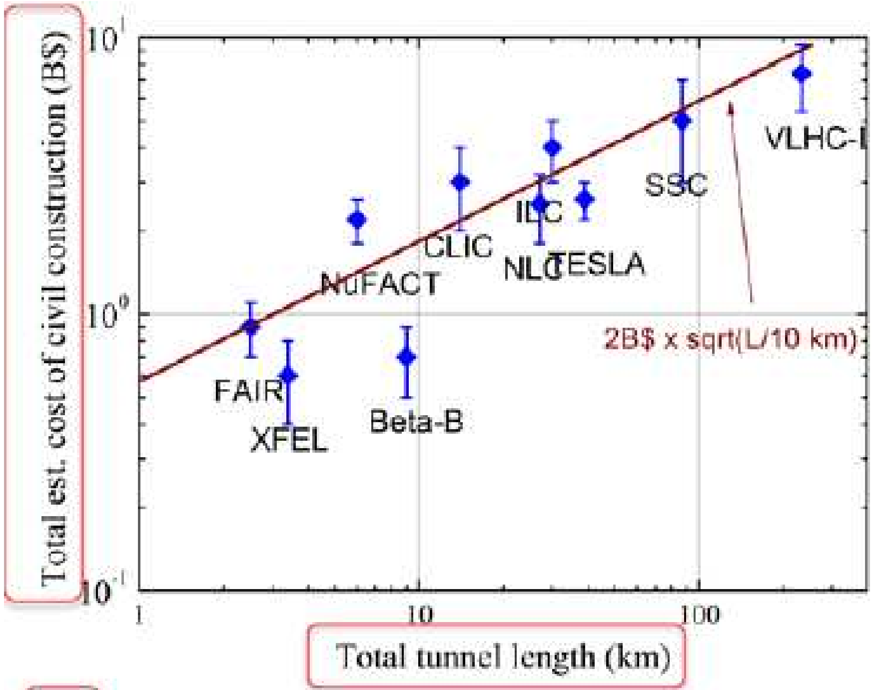
'Discovery Machine'

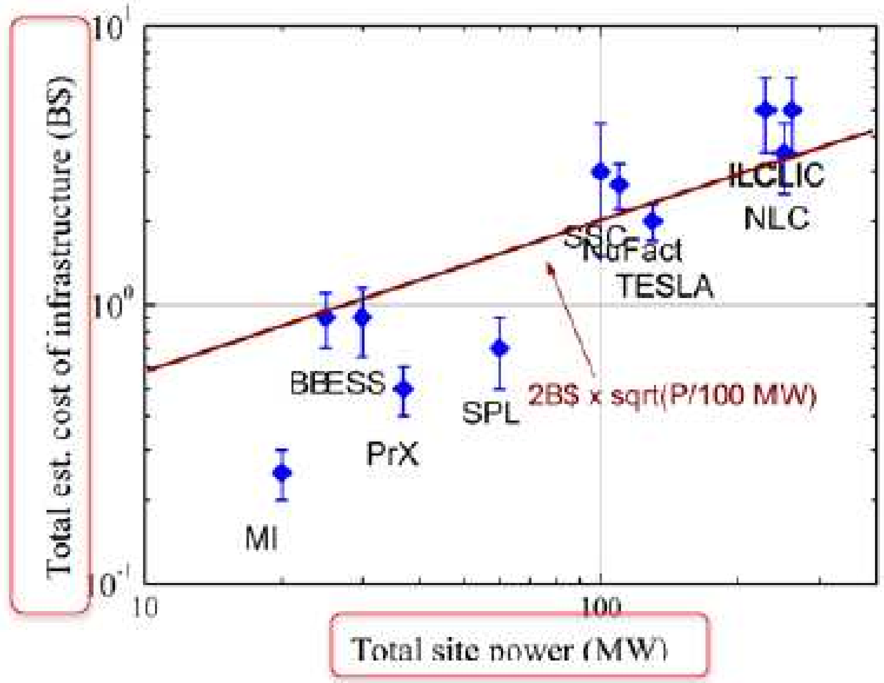
Shiltsev Cost Model Input

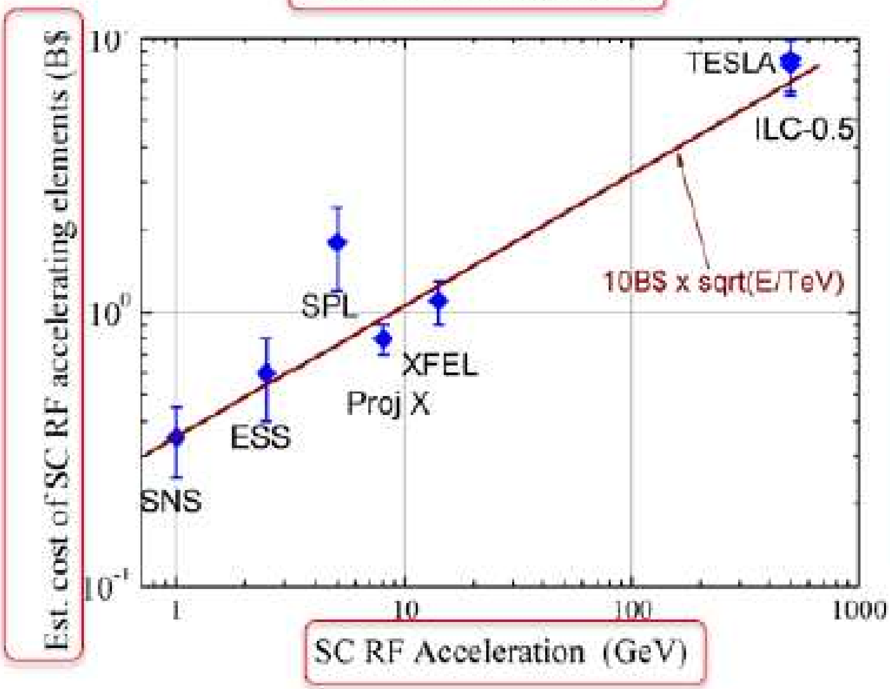
- Look at cost data from:
  - Built RHIC, MI, SNS, LHC
  - Under Construction: XFEL, FAIR, ESS
  - Other: SSC, VLHC, NLC,ILC, TESLA, CLIC, Proj-X, Beta-beam, SPL,ν-factory

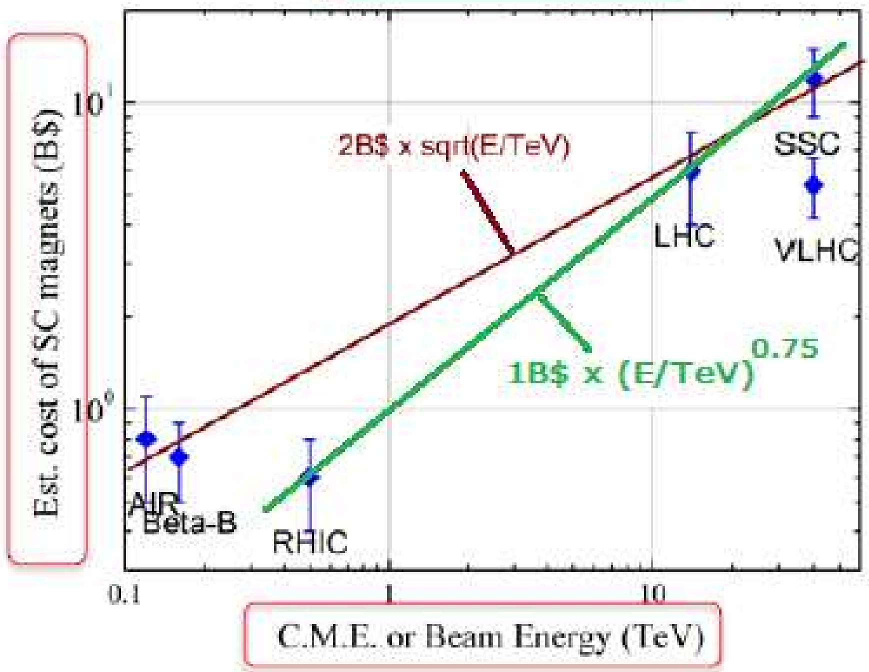
- Plot and fit:
  - Civil Construction vs. sum of lengths
  - SC rf vs. Energy
  - Infrastructure vs. Wall power consumption

Shiltsev; JINST 9 T07002 (2014)


Total est. cost of civil construction (B$)
Total tunnel length (km)
2B$ x sqrt(L/10 km)
FAIR
XFEL
Beta-B
NuFACT
CLIC
ILC
NLC
TESLA
SSC
VLHC-I


Total est. cost of infrastructure (B$)
Total site power (MW)
2B$ x sqrt(P/100 MW)
MI
BB
ESS
PrX
SPL
SSC
NuFact
TESLA
ILC
CLIC
NLC


Est. cost of SC RF accelerating elements (B$
SC RF Acceleration (GeV)
10B$ x sqrt(E/TeV)
SNS
ESS
SPL
Proj X
XFEL
TESLA
ILC-0.5


Est. cost of SC magnets (B$)
C.M.E. or Beam Energy (TeV)
2B$ x sqrt(E/TeV)
1B$ x (E/TeV)
0.75
AIR
Beta-B
RHIC
LHC
SSC
VLHC

Shiltsev Parametric Cost Model

For linear machines

$$Cost \approx 2\sqrt{\frac{L}{10km}} + 10\sqrt{\frac{E}{1TeV}} + \sqrt{\frac{P}{100MW}}$$

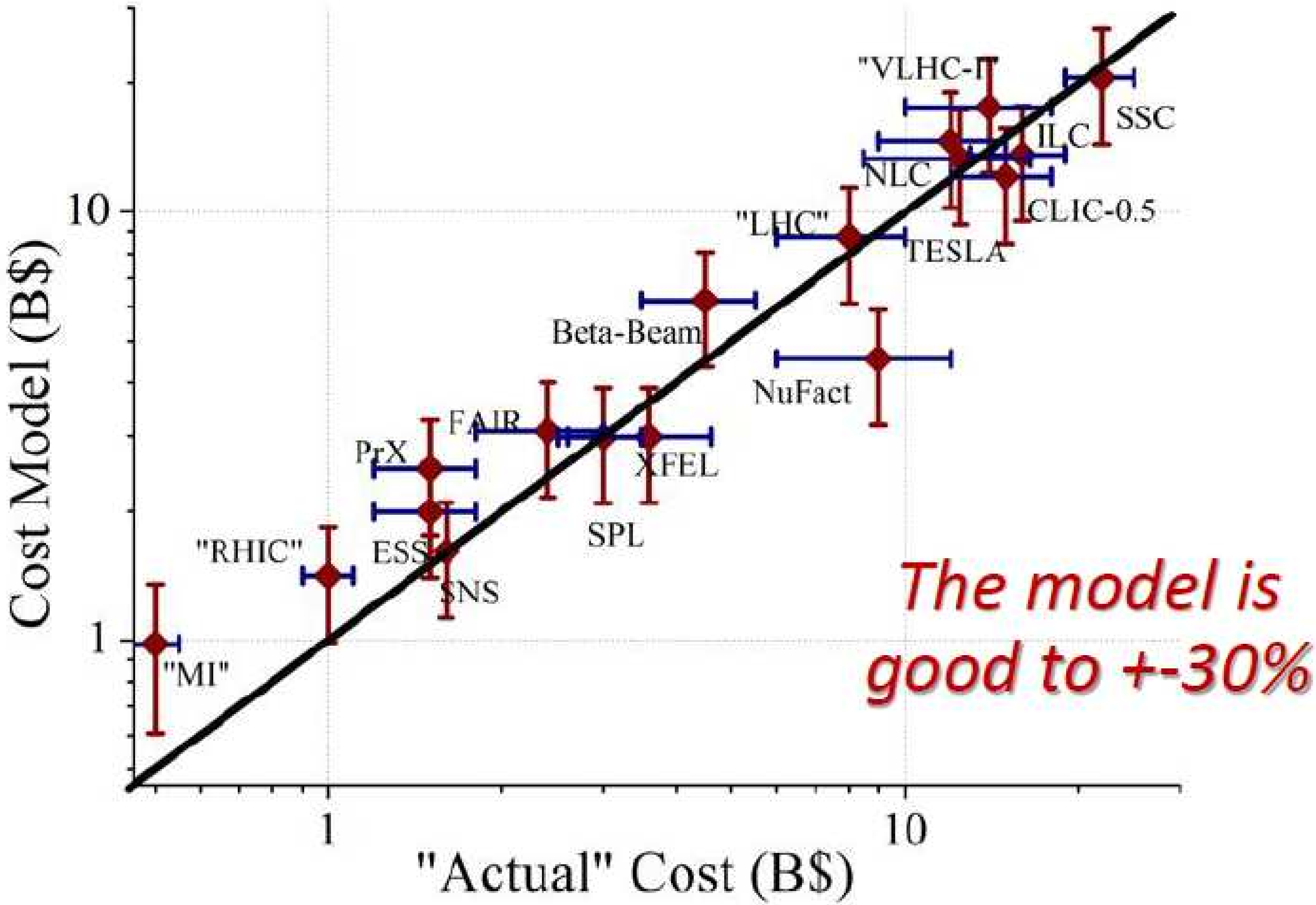
For Circular machines:

$$Cost \approx 2\sqrt{\frac{L}{10km}} + 2\sqrt{\frac{E}{1TeV}} + \sqrt{\frac{P}{100MW}}$$

My version for circular giving more weight to RHIC and LHC:

$$Cost \approx 2\sqrt{\frac{L}{10km}} + \left(\frac{E}{1TeV}\right)^{0.75} + \sqrt{\frac{P}{100MW}}$$

Shiltev Comparisons



Cost of 100 TeV hh Collider

For "conventional" SC dipoles (8.4 T)

- Ring circumference 200 km
- Injector lengths: $27 + 5 = 32$ km
- SC Magnets for 2 x 50 TeV
- Wall Power 200 MW

$$Cost \approx \; 2\sqrt{\frac{L}{10km}} + \left(\frac{E}{1TeV}\right)^{0.75} + \sqrt{\frac{P}{100MW}}$$

$$Cost \approx 2\sqrt{232/10} + (100/1)^{0.75} + 2\sqrt{200/100}$$

$$= \quad 9.6 \quad + \quad 31.6 \quad + \quad 2.8 \quad = \quad \mathbf{44\ B\$}$$

Cost of 6 T Muon Collider

- Length of all components $\approx$ 20 Km
- Total acceleration $\approx$ 300 GeV
- Momentum in collider ring $\approx$ 3 TeV
- Momentum in accelerators $\approx$ 4 TeV
- Wall Power $\approx$ 270 MW
- For p Driver $\approx$ 1 B$/MW ???

L rf mag power Driver

$$Cost \approx 2\sqrt{\frac{20}{10}} + 10\sqrt{\frac{0.3}{1}} + \left(\frac{7}{1}\right)^{0.75} + 2\sqrt{\frac{270}{100}} + \quad 4$$

$$= \ 2.8 \ + \ 5.5 \ + \ 4.3 \ + \ 1.6 \ + \ 4 \ = \ \mathbf{18\ B\$}$$

Comment on $\mu^+\mu^-$ vs. p-p

- Luminosity of a 6 TeV Muon Collider is approaching that of a Hadron Collider
- Its Cost should be less

- Both are VERY expensive
- We are NOT talking about the short term

Is a Muon Collider plausible?

- I am not asking for Baseline selection
- I am not asking for end-end simulation
- This is a more academic question
- It is a much more modest question

- Do we have plausible approaches for required systems ?

My Answers

Proton Driver	yes	(Many options)
4 MW Hg Target	yes	(Hg jet)
Front End	yes	(Recent progress)
6D Cooling	yes	(hybrid 6D ?)
Merge	yes	(Bao simulation)
Final Cooling	No	
Acceleration	yes	(Linac + RLA ?)
Collider rings	yes	(1.5 & 3 TeV)
Machine Detector Interface	yes	(With timing)

Why NO for Final Cooling?

Problem #1

No design of matching between 40 T Solenoids

- Simulation of sequence of cooling in solenoids ok
  did not achieve required emittance
  did not achieve required transmission

- Requires serious study including workshop(s)
- Look at alternatives: potato slicer, PIC
- This an academic challenge, not IBS like

Problem #2

We require vacuum rf in magnetic fields for re-acceleration in Final Cooling because it cannot use gas

If gas used, then cooling in 40 T field is in LiH, and for cooling:

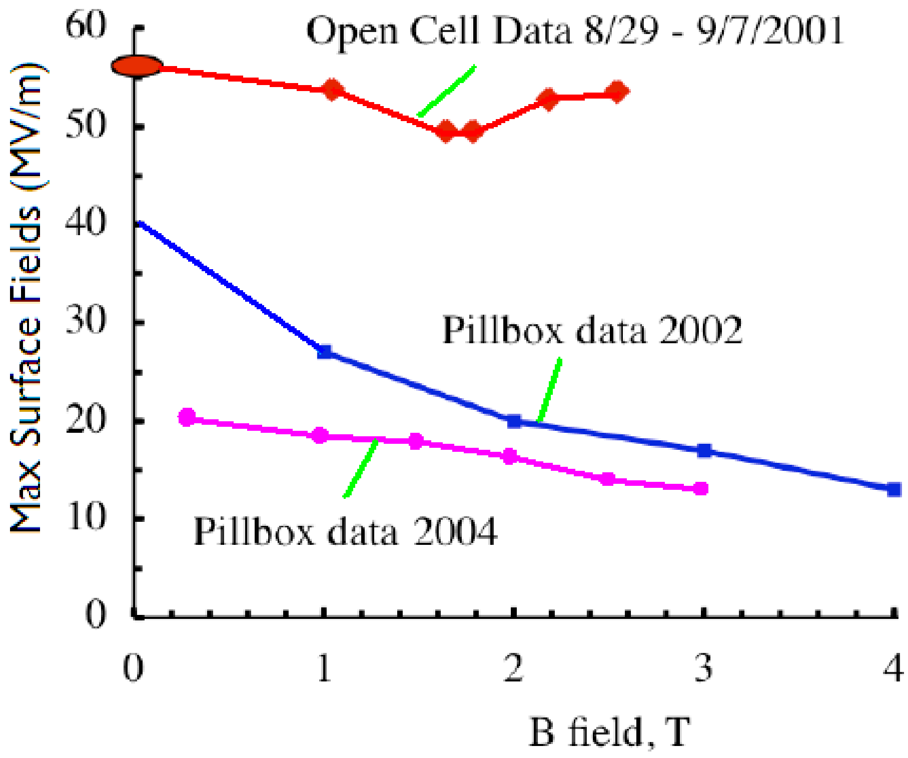
$$\epsilon \approx \ 2\epsilon_o$$

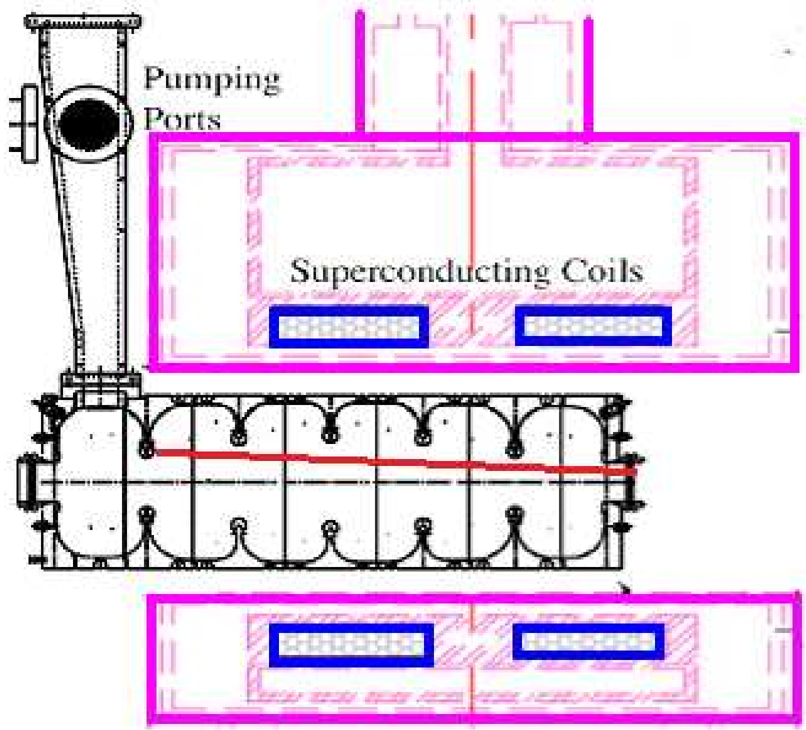
Then in re-acceleration, eg at 4T in the gas:

$$\epsilon \ = \ 2 \, \frac{4}{40} \, \frac{C_{LiH}}{C_{H_2}} \epsilon_o \approx \frac{\epsilon_o}{3}$$

which is heating, and far exceeds the cooling in the LiH and 40 T over the rf is impractical

Vac rf Breakdown in magnets



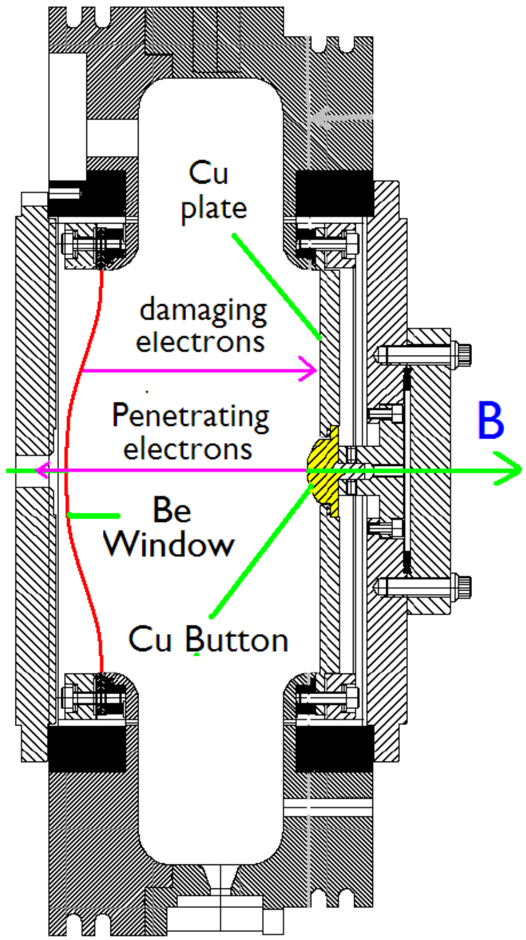


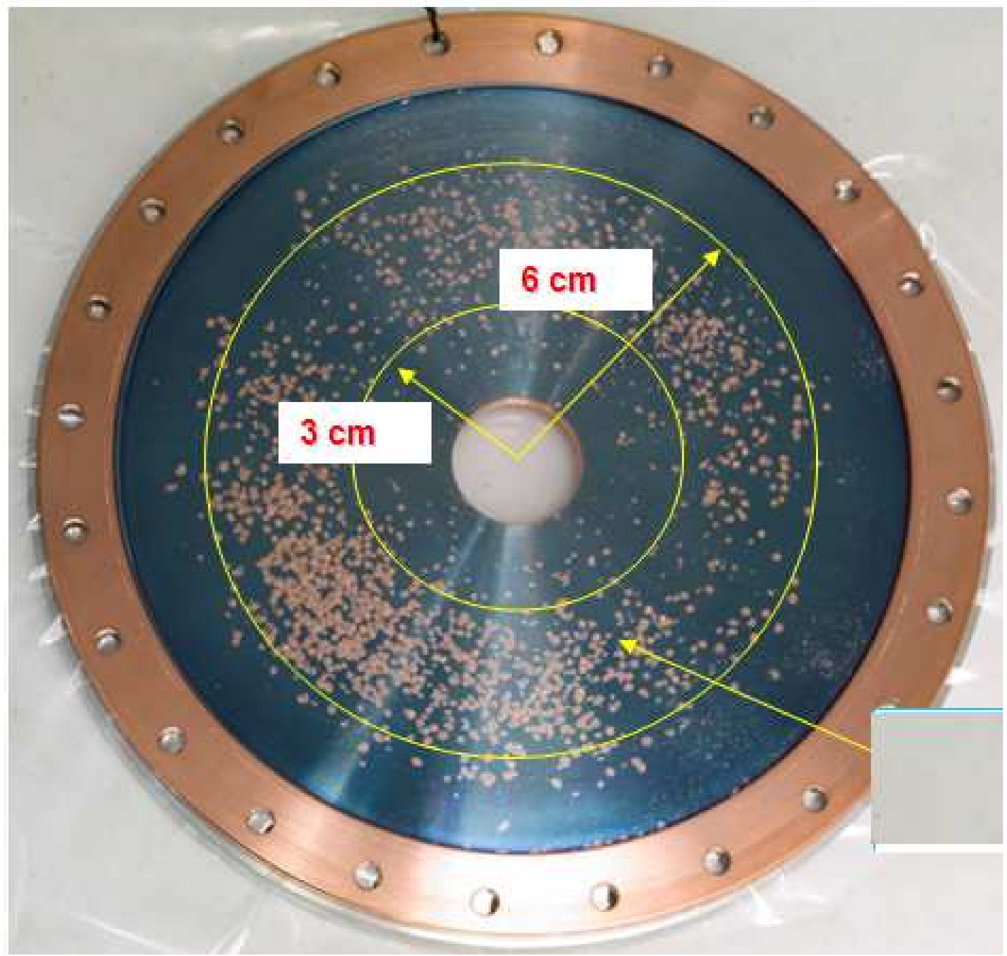
- Strictly: Breakdown is not the problem
- But damage in open cavity made a hole in the Ti window
- Damage & Life are the problem

Probable Solution

- We have theoretical expectation that Beryllium cavity walls will fix this
  - Because Be is light, pulse heating from focused electrons is less
  - Damage from fatigue in hard brittle Be also less
- And we have experimental evidence that Beryllium cavity walls will fix this
  - We have seen extensive damage on Copper
  - We have seen copper splashes on Be surfaces
  - We have seen copper dust
  - But probably no damage on Be
  - And no Be dust

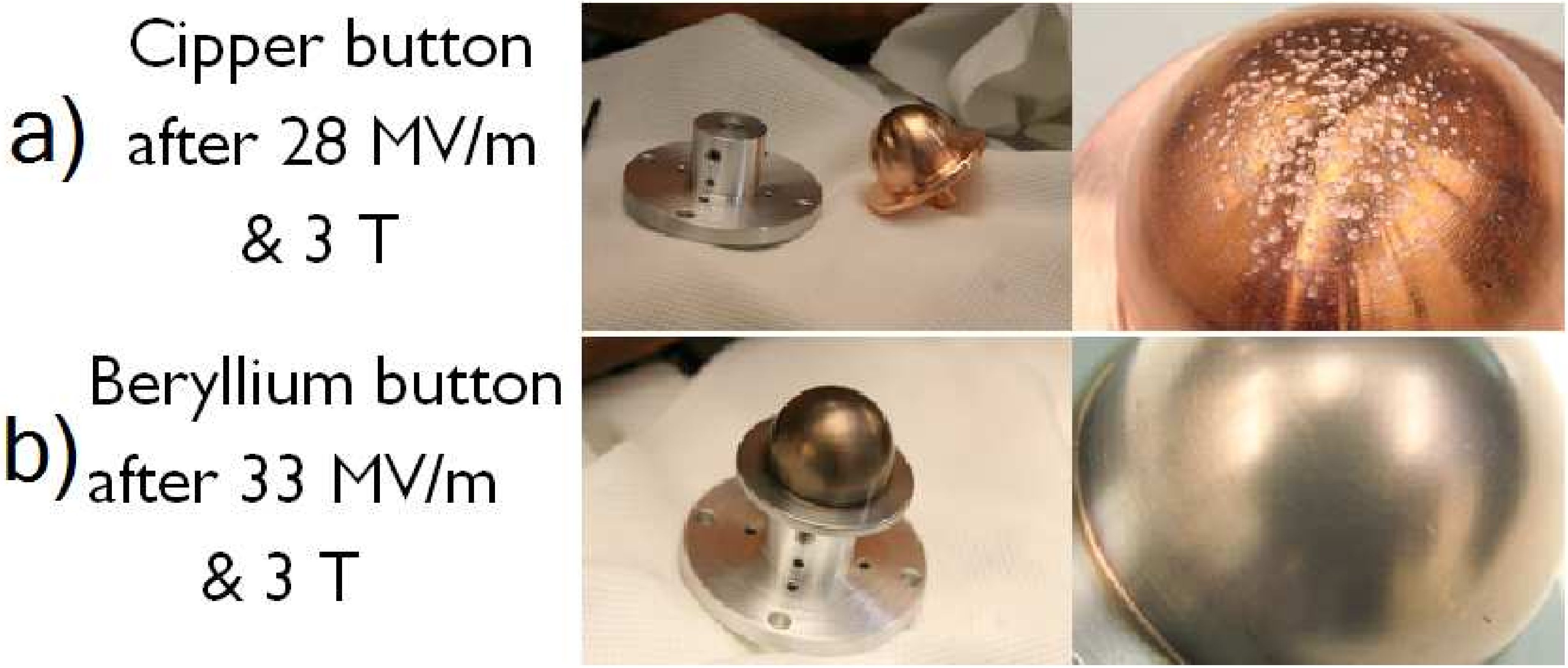
Damage Observation I





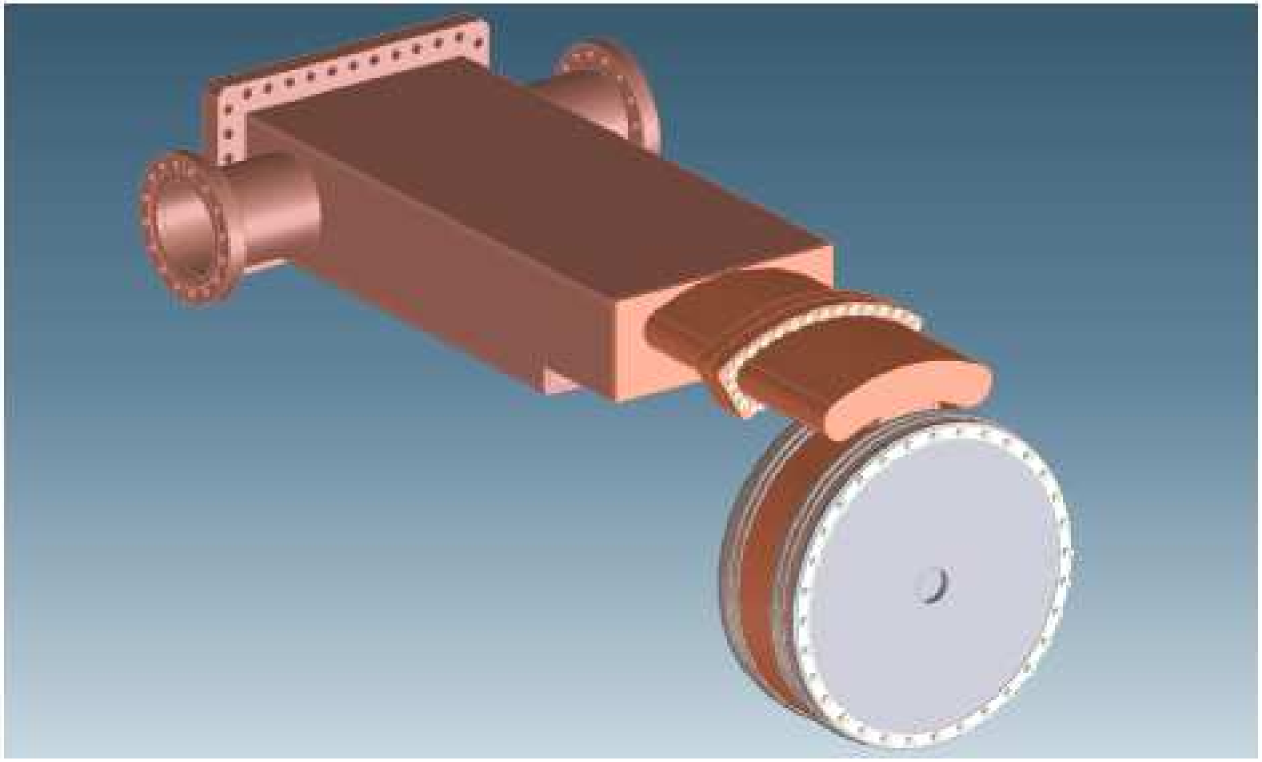
- Damage on copper
- None on Be opposite even with slightly higher fields

Damage Observation II



- Negligible damage on Be Button
- No Be dust observed
- Tiny pits probably there before experiment

Demonstration of Fix



- We have beautiful SLAC built Modular Cavity
- Need 50 k$ for Be end plates
- MTA is still running for MICE
- We should be able to test with Be walls

Conclusion I

- A Muon Collider is the only lepton collider with useful luminosity above ≈ 2 TeV
- A 6 TeV Muon Collider has a luminosity approaching the parton luminosity of a 100 TeV p-p Collider at the same parton energies
- And its cost appears significantly less
- Both are VERY expensive and not likely any time soon

This is a VISION thing

- Study of both $\mu^+\mu^-$ and p-p is appropriate
- Knowing if a 6 TeV $\mu^+\mu^-$ is plausible is IMPORTANT
- Knowing will increase the chance of NuStorm

Conclusion II

- There are two potential Show-Stoppers for $\mu^+\mu^-$:
  1. Final Cooling Design
  2. Vacuum rf in magnetic fields
- The efforts to address these are not large
- Much less than previous MAP IBS efforts
- They should be given high priority

Yes this is just my view