On Cost of Future Colliders

and Options/Preemptive Measures

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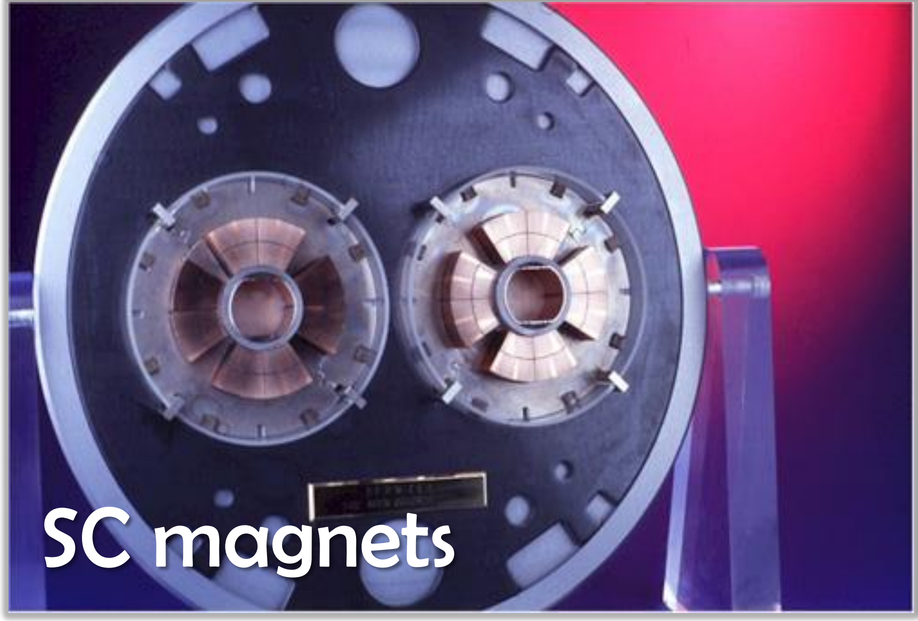
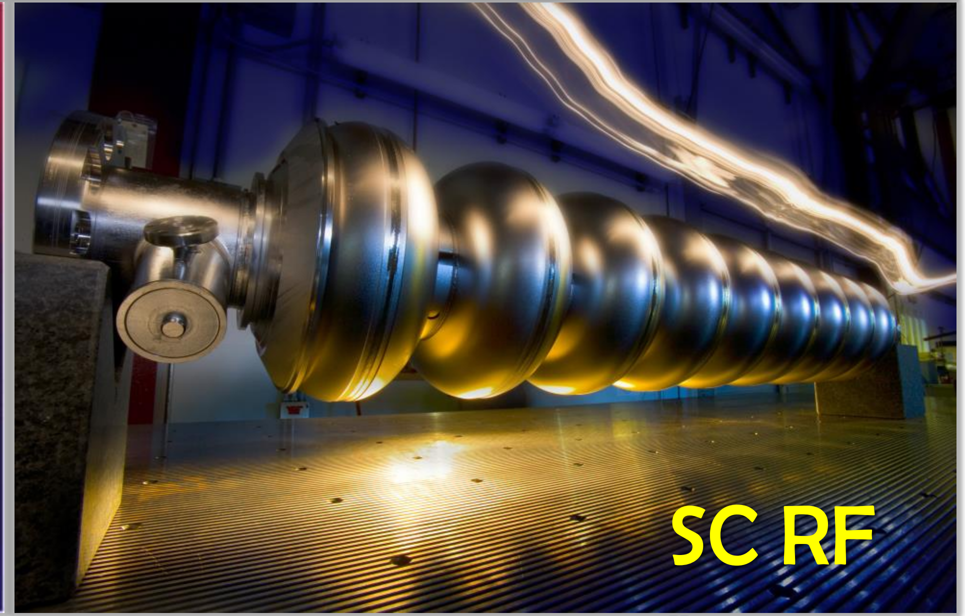
*FRA, LLC operates Fermilab under contract No. DE-AC02-07CH11359 with the U.S. DOE

Four “Feasible” Technologies


Normal Conducting Magnets


Normal Conducting RF


SC magnets


SC RF

… in addition to “traditional” technologies of tunneling, electric power and site infrastructures, etc …

Analysis:

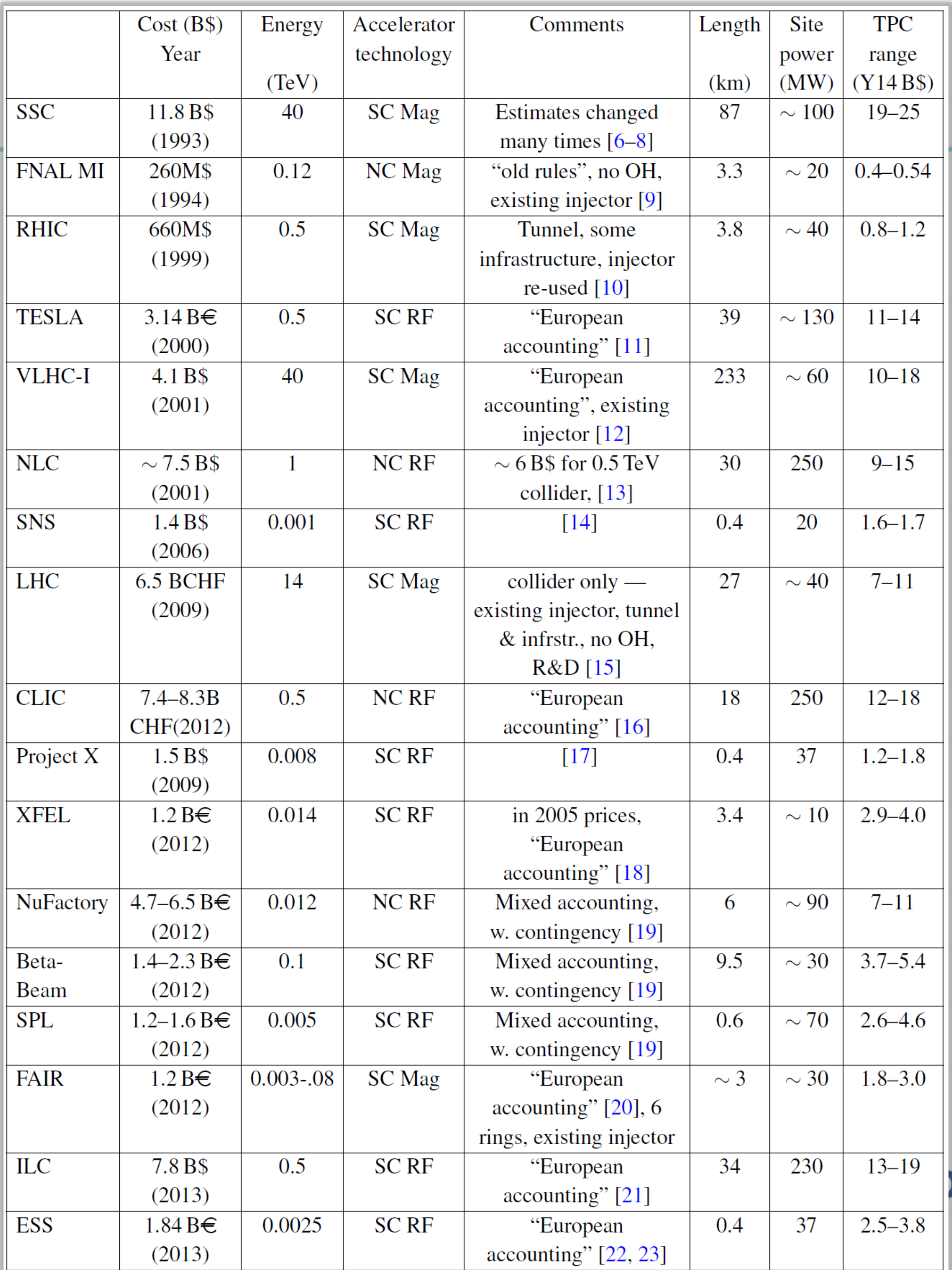
2014 JINST 9 T07002

17 "Data Points" - Costs of Big Accelerators:

- Actually built:
  - RHIC, MI, SNS, LHC
- Under construction:
  - XFEL, FAIR, ESS
- Not built but costed:
  - SSC, VLHC, NLC
  - ILC, TESLA, CLIC, Project-X, Beta-Beam, SPL, ν-Factory

Wide range :

- 4 orders in *E*nergy, >1 order in *P*ower, >2 orders in *L*ength
- Almost 2 orders in cost
  - (normalized to US TPC)



	Cost (B$) Year	Energy (TeV)	Accelerator technology	Comments	Length (km)	Site power (MW)	TPC range (Y14 B$)
SSC	11.8 B$ (1993)	40	SC Mag	Estimates changed many times [6–8]	87	~ 100	19–25
FNAL MI	260M$ (1994)	0.12	NC Mag	"old rules", no OH, existing injector [9]	3.3	~ 20	0.4–0.54
RHIC	660M$ (1999)	0.5	SC Mag	Tunnel, some infrastructure, injector re-used [10]	3.8	~ 40	0.8–1.2
TESLA	3.14 B€ (2000)	0.5	SC RF	"European accounting" [11]	39	~ 130	11–14
VLHC-I	4.1 B$ (2001)	40	SC Mag	"European accounting", existing injector [12]	233	~ 60	10–18
NLC	~ 7.5 B$ (2001)	1	NC RF	~ 6 B$ for 0.5 TeV collider, [13]	30	250	9–15
SNS	1.4 B$ (2006)	0.001	SC RF	[14]	0.4	20	1.6–1.7
LHC	6.5 BCHF (2009)	14	SC Mag	collider only — existing injector, tunnel & infrstr., no OH, R&D [15]	27	~ 40	7–11
CLIC	7.4–8.3B CHF(2012)	0.5	NC RF	"European accounting" [16]	18	250	12–18
Project X	1.5 B$ (2009)	0.008	SC RF	[17]	0.4	37	1.2–1.8
XFEL	1.2 B€ (2012)	0.014	SC RF	in 2005 prices, "European accounting" [18]	3.4	~ 10	2.9–4.0
NuFactory	4.7–6.5 B€ (2012)	0.012	NC RF	Mixed accounting, w. contingency [19]	6	~ 90	7–11
Beta-Beam	1.4–2.3 B€ (2012)	0.1	SC RF	Mixed accounting, w. contingency [19]	9.5	~ 30	3.7–5.4
SPL	1.2–1.6 B€ (2012)	0.005	SC RF	Mixed accounting, w. contingency [19]	0.6	~ 70	2.6–4.6
FAIR	1.2 B€ (2012)	0.003-.08	SC Mag	"European accounting" [20], 6 rings, existing injector	~ 3	~ 30	1.8–3.0
ILC	7.8 B$ (2013)	0.5	SC RF	"European accounting" [21]	34	230	13–19
ESS	1.84 B€ (2013)	0.0025	SC RF	"European accounting" [22, 23]	0.4	37	2.5–3.8

V.Shiltsev, A phenomenological cost model for high energy particle accelerators

! WARNING !

αβγ - Cost Estimate Model:

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

a) **±33% estimate, for a “green field” accelerators**

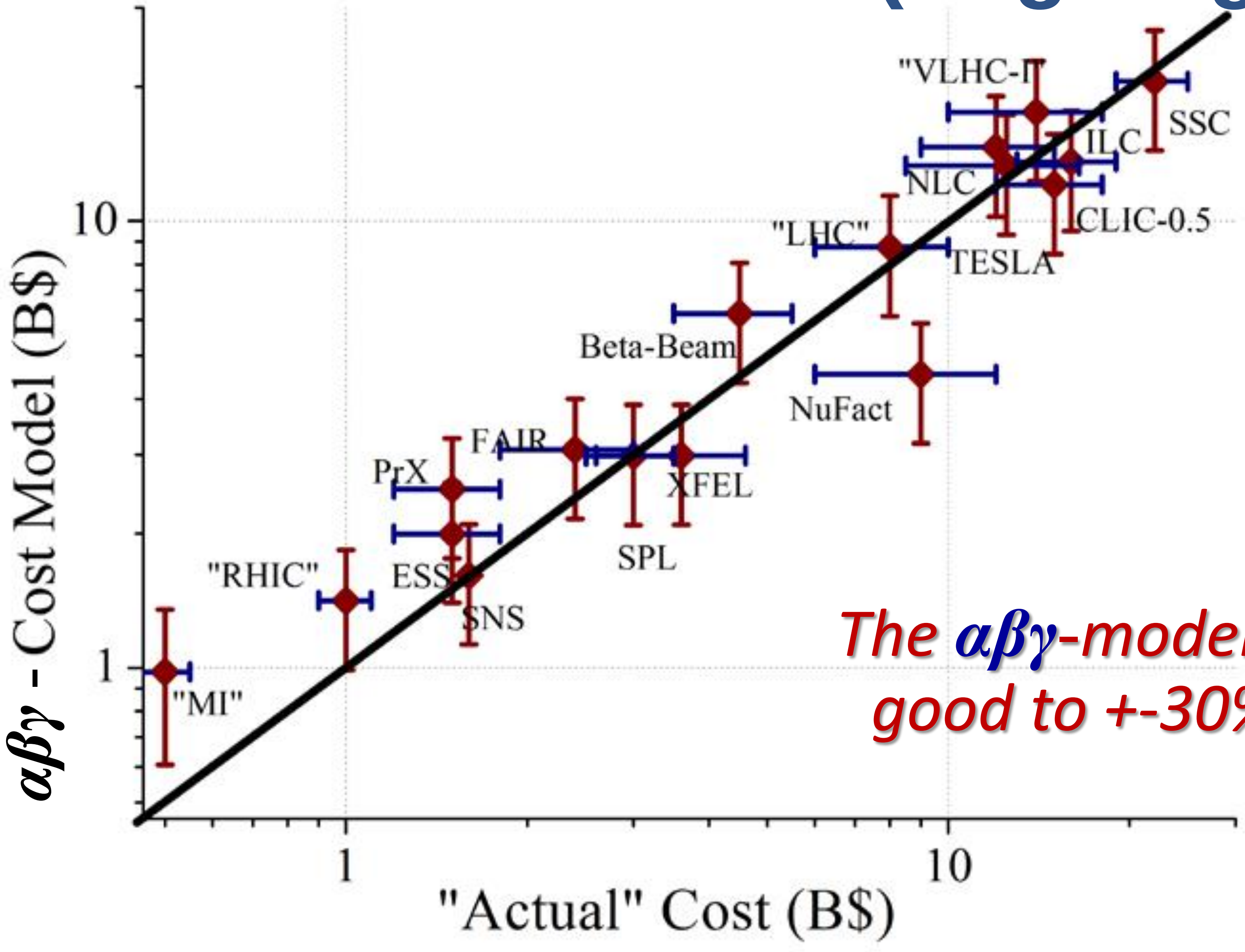
b) **“US-Accounting” = TPC !** (~ 2 × *European Accounting*)

c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **$\alpha \approx$ 2B$/sqrt(*L*/10 km)**
- **$\beta \approx$ 10B$/sqrt(*E*/TeV)** for SC/NC RF
- **$\beta \approx$ 2B$ /sqrt(*E*/TeV)** for SC magnets
- **$\beta \approx$ 1B$ /sqrt(*E*/TeV)** for NC magnets
- **$\gamma \approx$ 2B$/sqrt(*P*/100 MW)**

USE AT YOUR OWN RISK!

Total Cost vs Model (Log-Log)

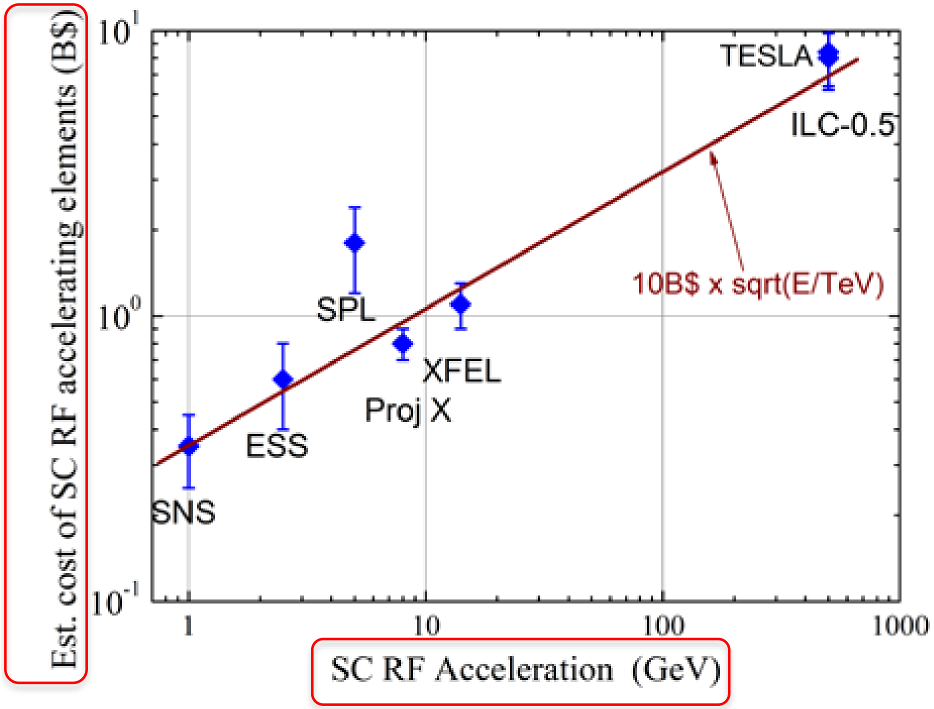


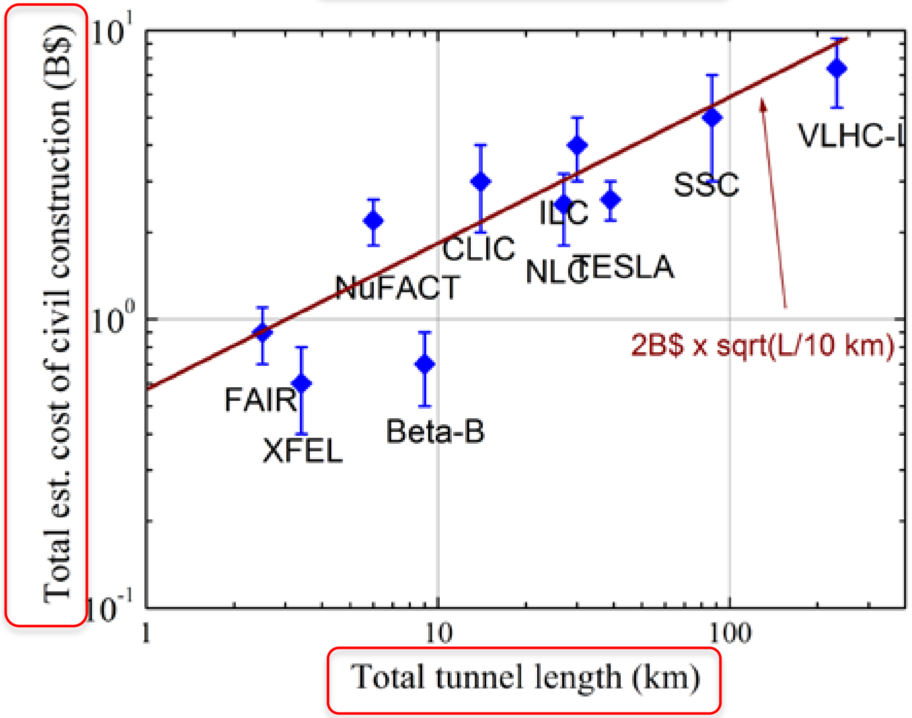
The *αβγ*-model is good to +-30%

Illustrations

Comment:

Sqrt-functions are quite accurate over wide range because such dependence well approximates the *"initial cost" – effect* :





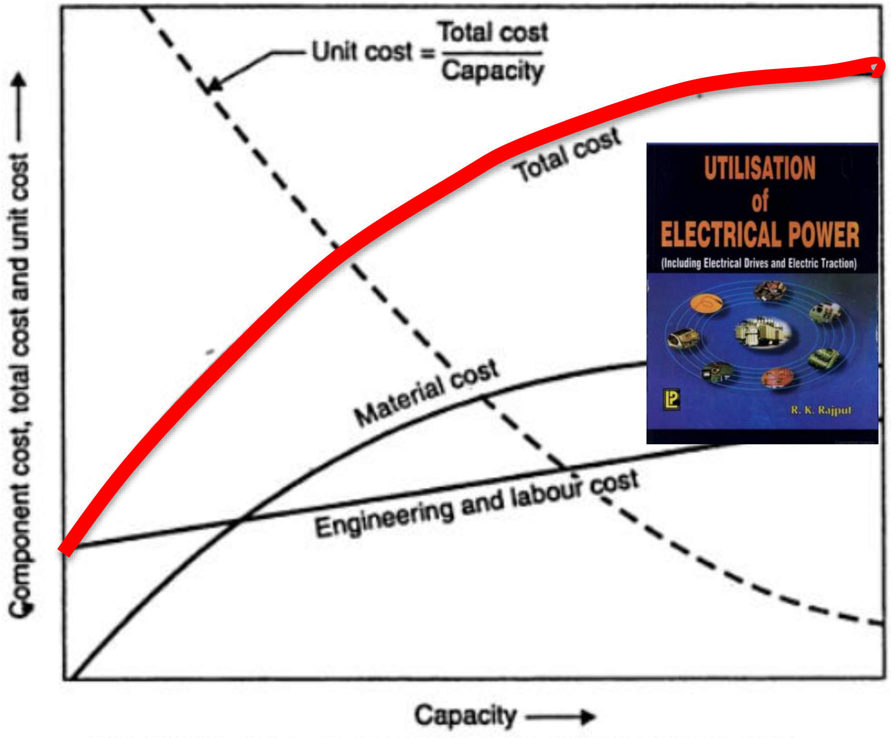


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

Take LHC as an Example:

- ***αβγ* – Model:**
  - 40 km of tunnels
  - 14 TeV c.o.m SC magnets
  - ~150 MW of site power

$$2\sqrt{40/10} = 4$$

$$2\sqrt{14} = 7.5$$

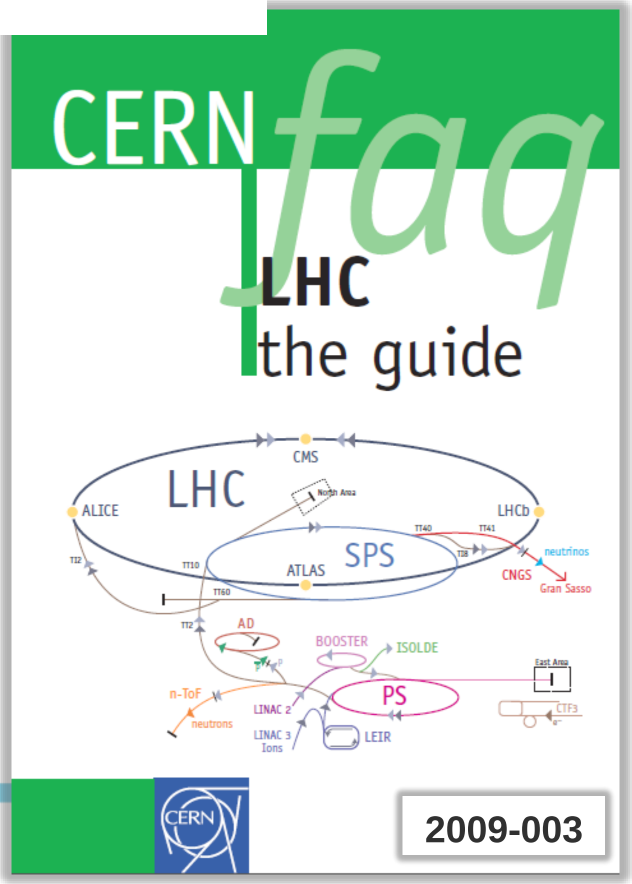
$$2\sqrt{150/100} = 2.5$$

TOTAL PROJECT COST : **14B$ ± 4.5B$**

- **CERN LHC Factbook (2009):**
  - 6.5 BCHF, incl. **5 BCHF** for accelerator (European Accounting)
  - x 2 to US TPC → **10 BCHF=10B$**
  - Cost of existing injector complex ~30-40% **3-4 B$**

TPC : **~13-14B$**

(of which CERN paid 10 over ~8 yrs)



Important Note: Two out of Three Factors in the Model are Independent from Our R&D Efforts – Tunneling, Power Infrastructure

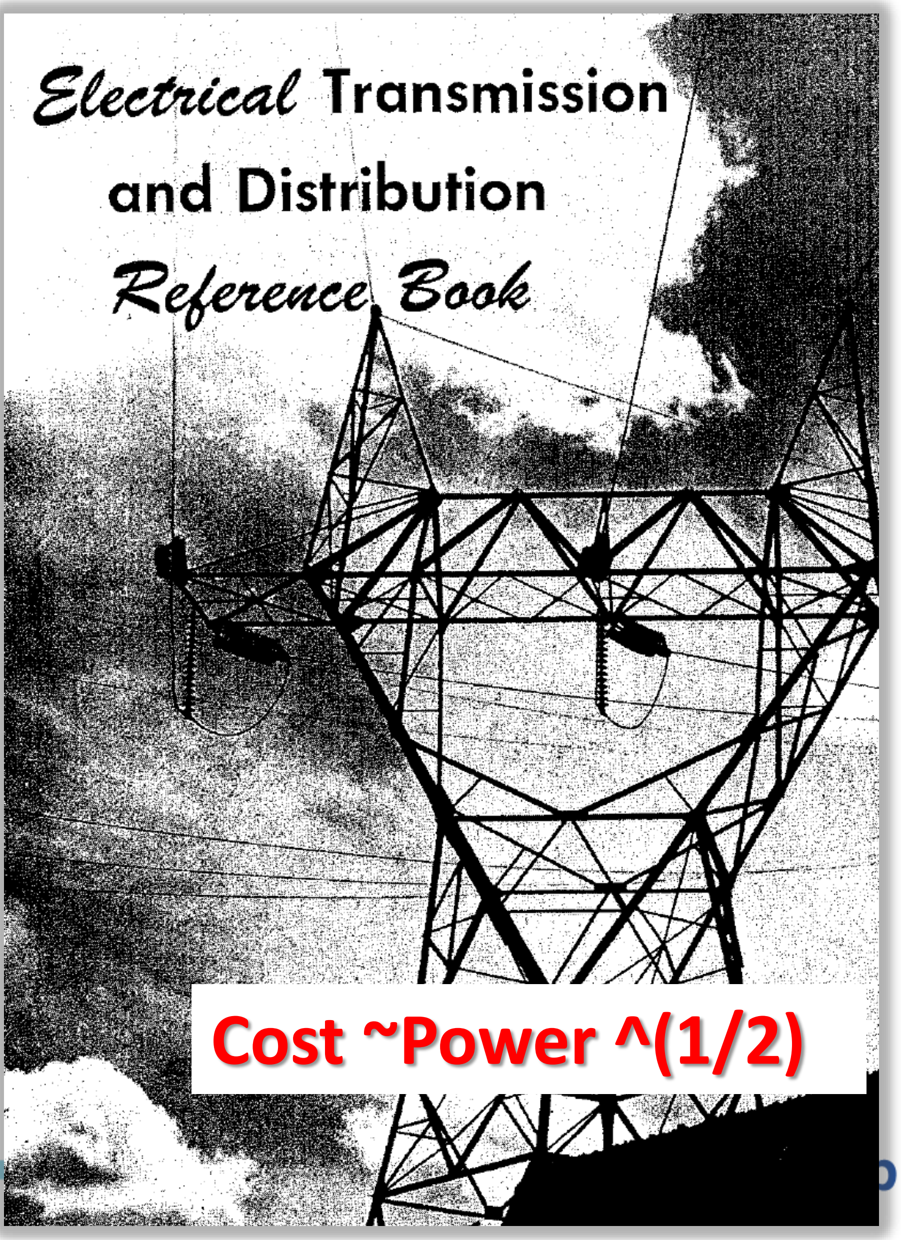
Do not expect Cost ~ $(L \times D^2)$ = meter^3 !

Data on 270 tunnels world wide

Tunnelling and Underground Space Technology

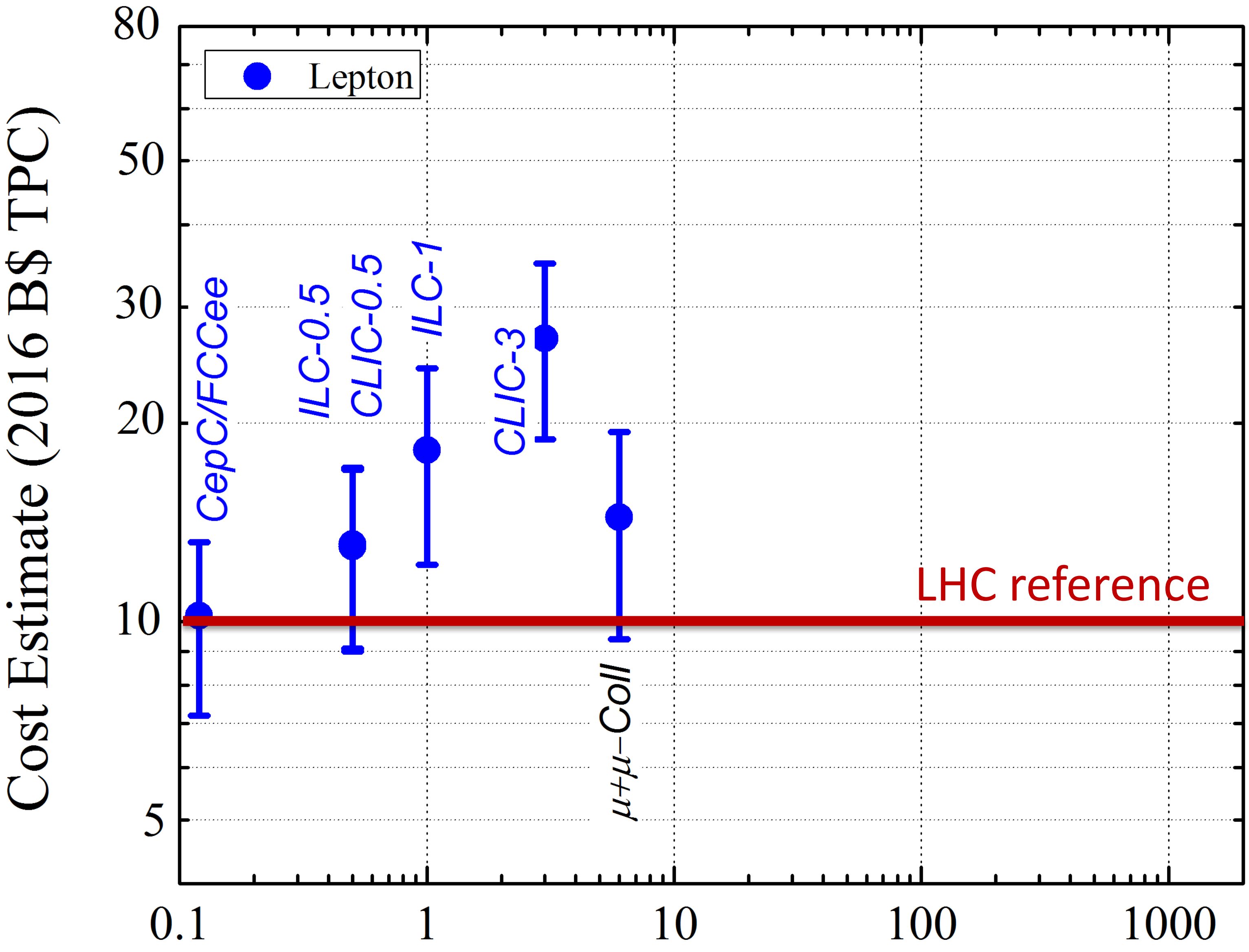
Tunnelling and Underground Space Technology 33 (2013) 22–33

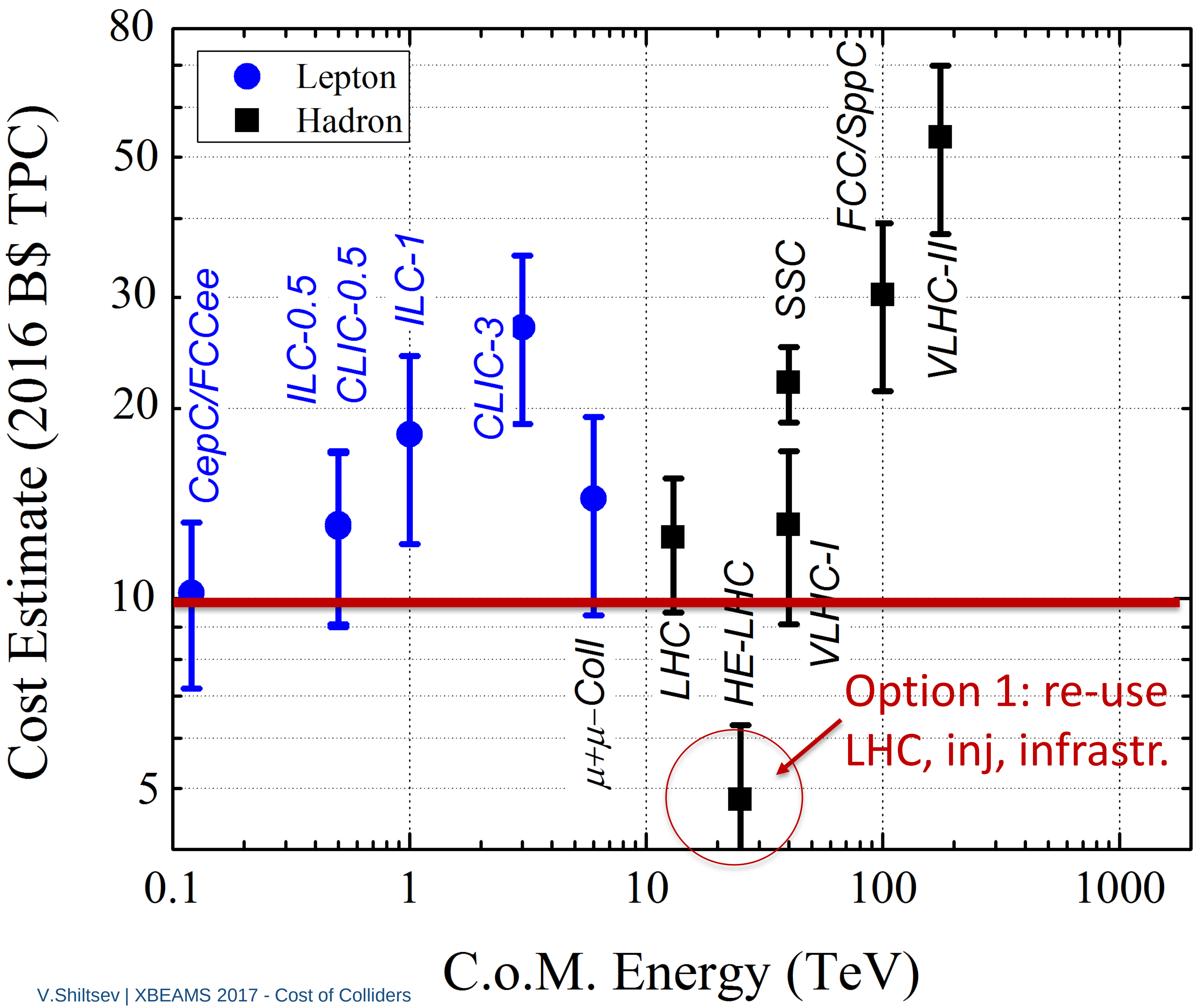
Cost ~ L^(0.4-1) D^(0.6-1.5)



Electrical Transmission and Distribution Reference Book

Cost ~Power ^(1/2)

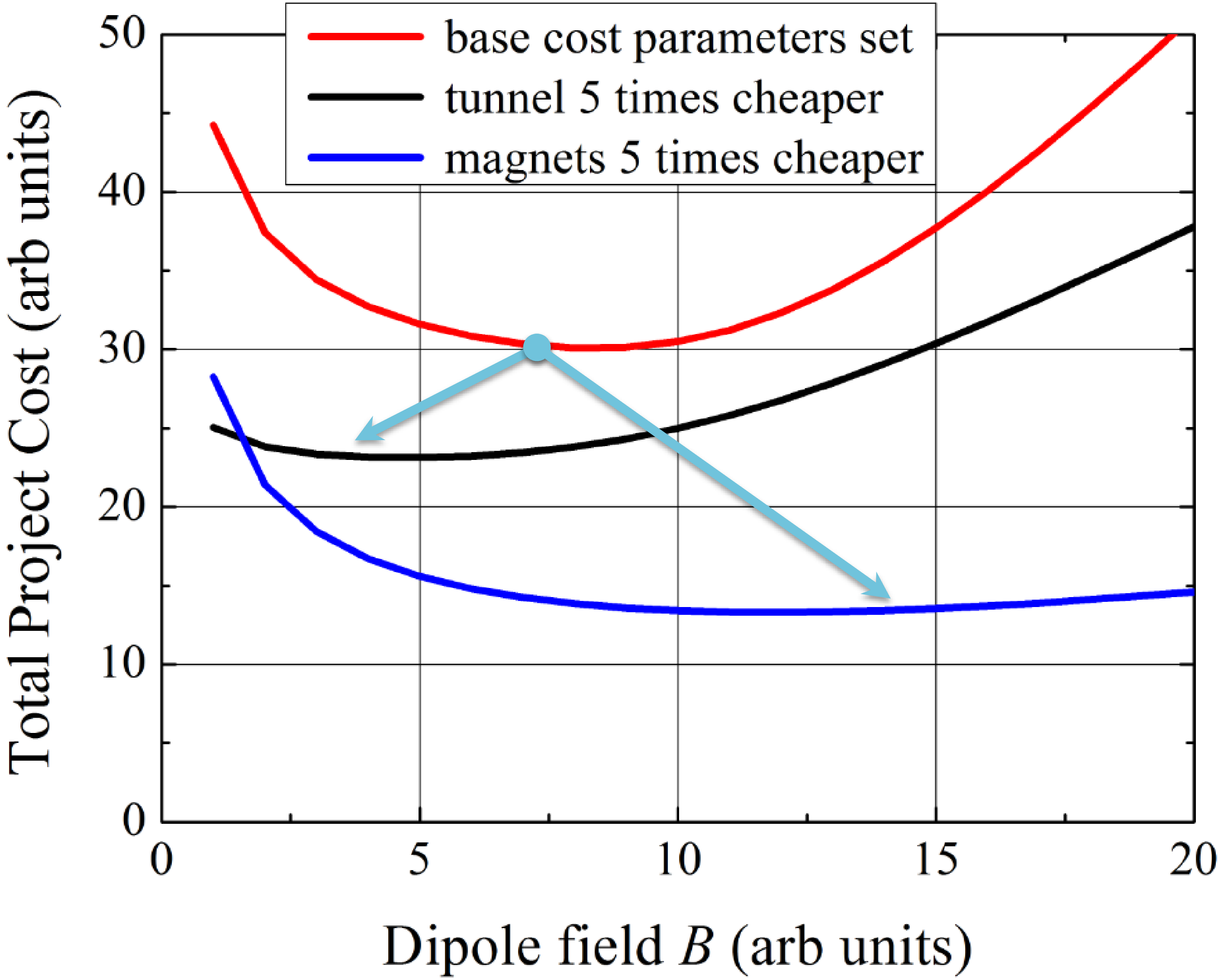

Cost Estimate (2016 B$ TPC)
80
50
30
20
10
5
0.1
1
10
100
1000
C.o.M. Energy (TeV)
● Lepton
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
μ+μ–Coll
LHC reference



Option 1: re-use LHC, inj, infrastr.

Option 2 : Develop Technology to Lower Cost

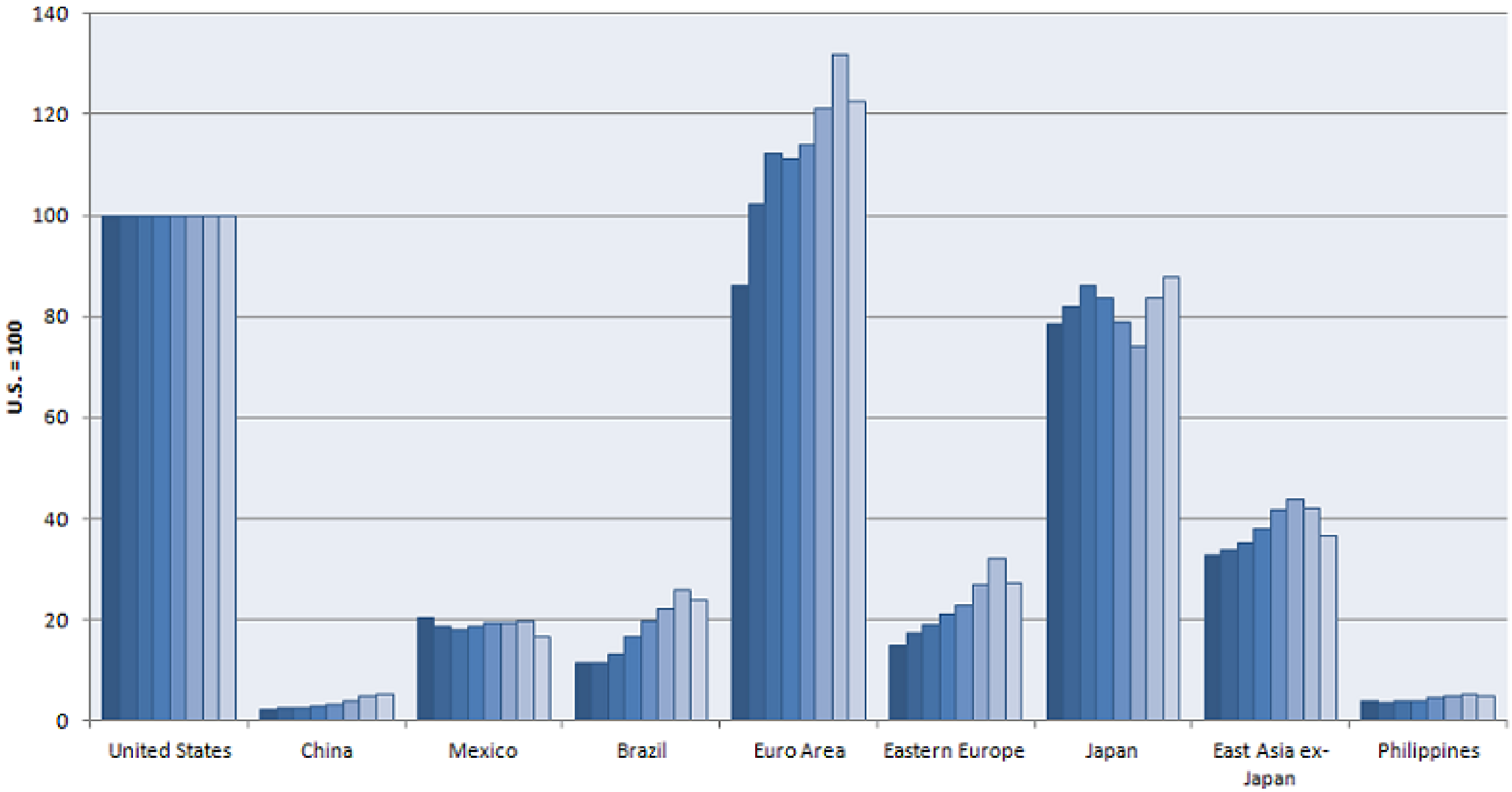
100 TeV *pp* : Qualitative Cost Dependencies



* for illustration purposes only

Option 3: *“Move to China !”*

Average hourly compensation costs of manufacturing employees, selected economies and regions, 2002-2009



Note: For a description of the economic groups, see the technical notes at www.bls.gov/ilc/ichcctn.pdf, Table 2.
Source: U.S. Bureau of Labor Statistics, International Labor Comparisons.

SSRF
China

- **432 m**
- **3.5 GeV**
- **1.2B RMB**

2007

Spring-8
Japan

- **1436 m**
- **8 GeV**
- **11 BY**

1997

Diamond
UK

- **562 m**
- **3 GeV**
- **383 M £**

2007

NSLSII
USA

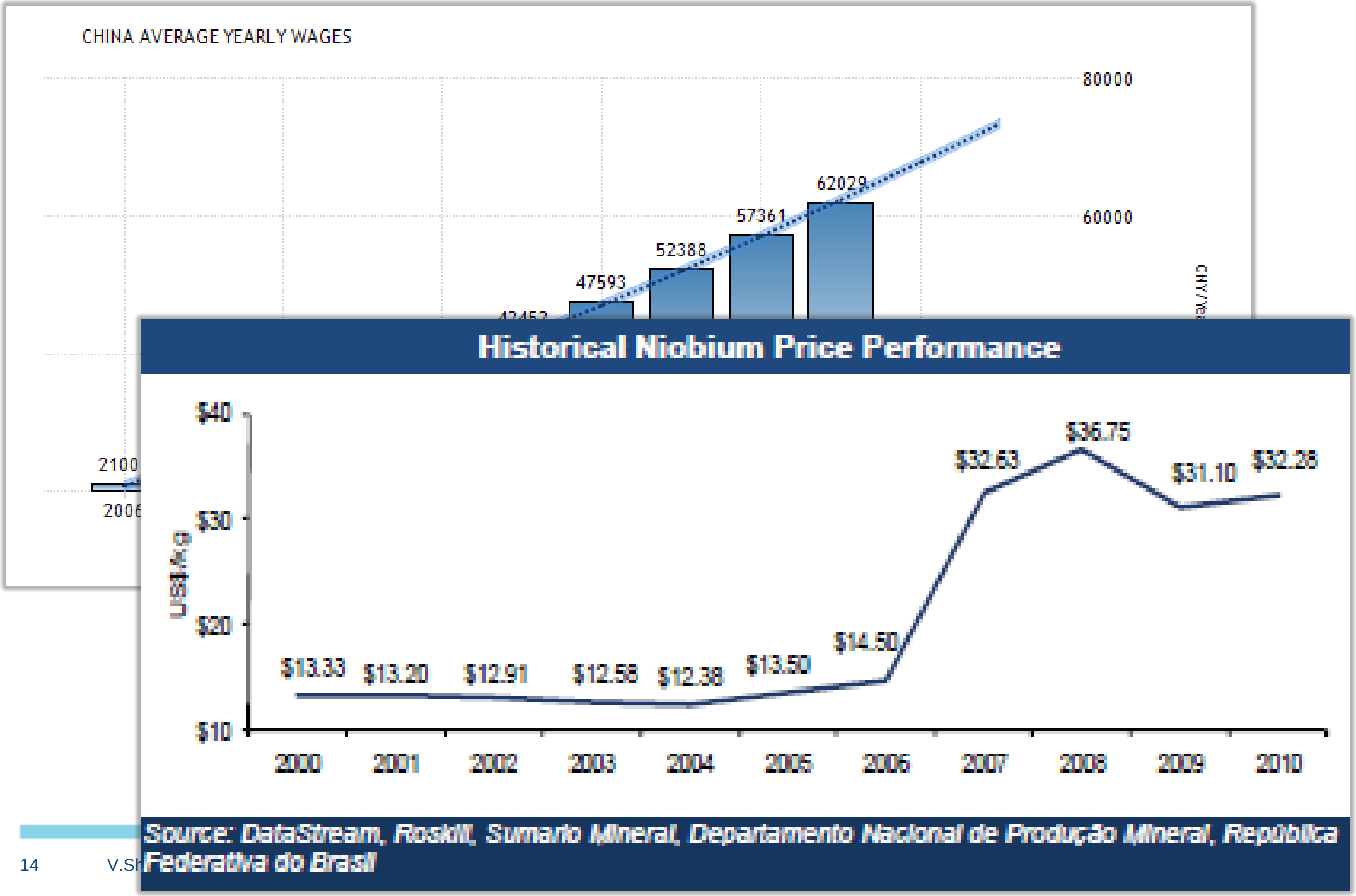
- **792 m**
- **3 GeV**
- **912 M$**

2015

Account infl'n, convert to USD and scale to sqrt(1 km):

350 M$*** ***772 M$ ***1040 M$*** ***1024 M$***

“Move to China !” - Caveats



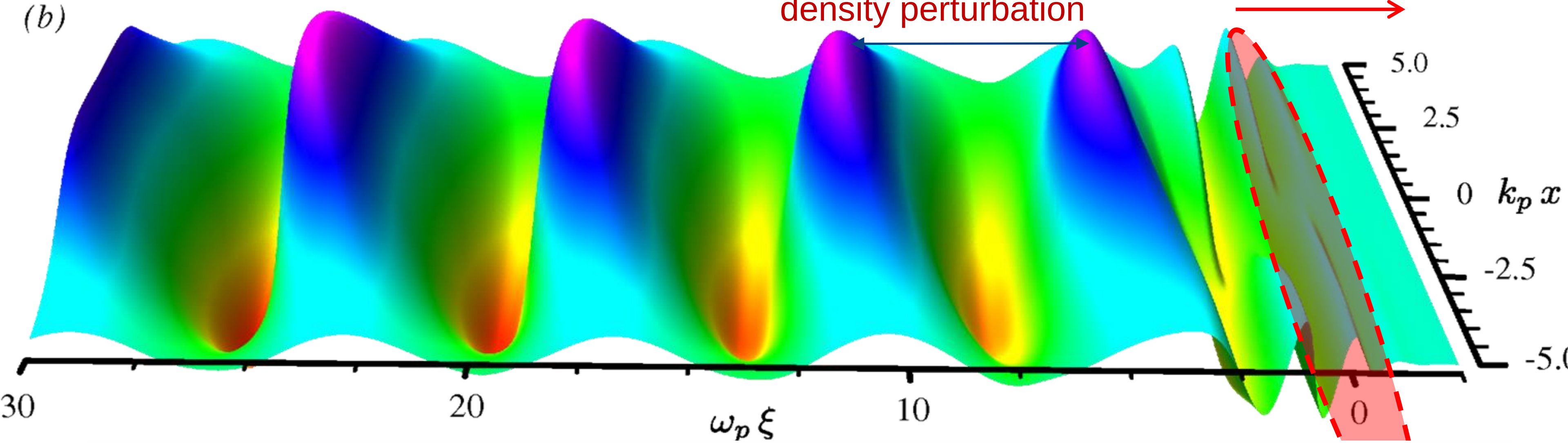
CHINA AVERAGE YEARLY WAGES

Historical Niobium Price Performance

Source: DataStream, Roskill, Sumario Mineral, Departamento Nacional de Produção Mineral, República Federativa do Brasil

Option 4: New Technology- Plasma

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



Plasma wave: electron density perturbation

Laser/beam pulse ~ λ_p/c

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:

Short intense e-/e+/p bunch

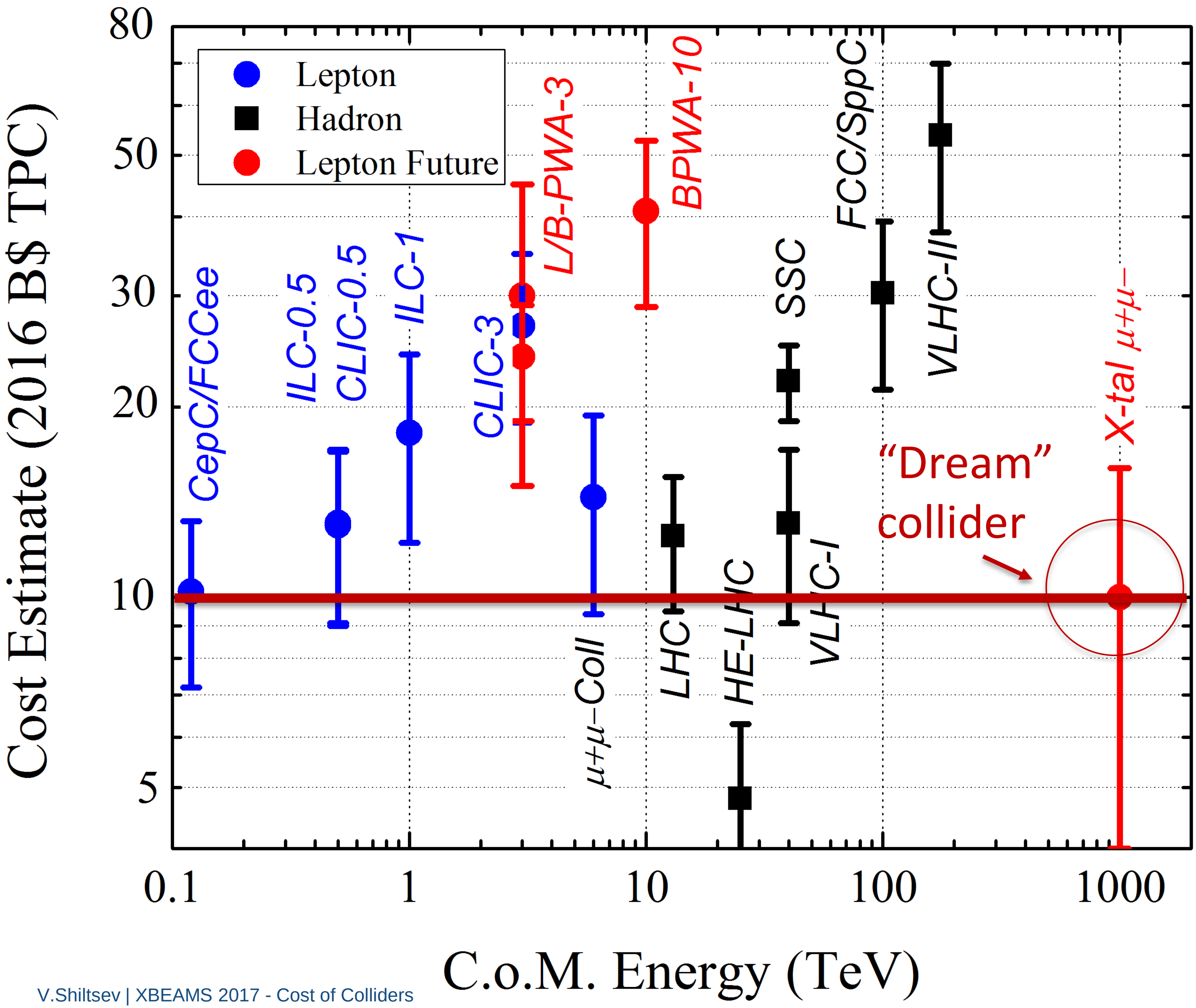
Few 10^{16}cm^{-3}, **6 GV/m** over 0.3m

Option B:

Short intense laser pulse

~10^{18}cm^{-3}, **50 GV/m** over 0.1m

First looks into “Plasma-Collider”: **staging kills ! <E>~2 GV/m,ε**



Lepton
Hadron
Lepton Future
Cost Estimate (2016 B$ TPC)
C.o.M. Energy (TeV)
80
50
30
20
10
5
0.1
1
10
100
1000
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
L/B-PWA-3
BPWA-10
μ+μ–Coll
LHC
HE-LHC
SSC
VLHC-I
FCC/SppC
VLHC-II
X-tal μ+μ–
“Dream” collider

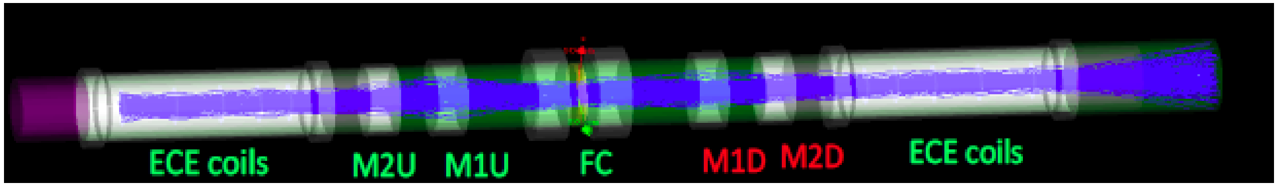
Option 5: *μ+μ- Collider*

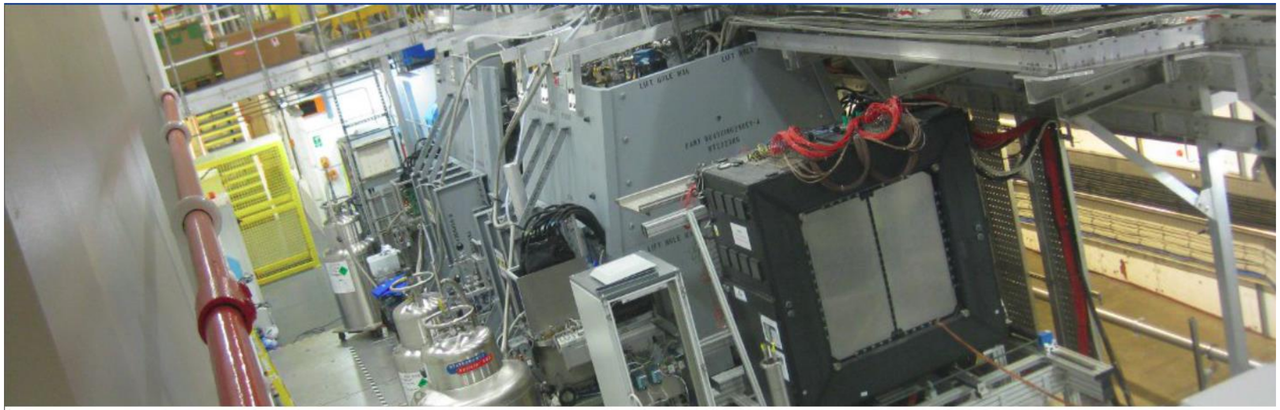
x5-10 more E_{cm} for same E_{beam}

- **Muons are particles for the far-future anyway**
  - The only option for a 1000 TeV collider
  - As convincingly shown Monday
- **There are opportunities even now:**
  - Even with fully traditional technology MC shows much more economical design options than any e+e-, approaching LHC in terms of Energy/$$ and facility power/Energy
  - MICE shows that muon cooling works
  - Great savings for labs having either proton complex or big tunnels
  - Novel approaches, like shown Mon, can offer further gains… need R&D
- **The past tells us that we were much more successful in improving performance than the energy**

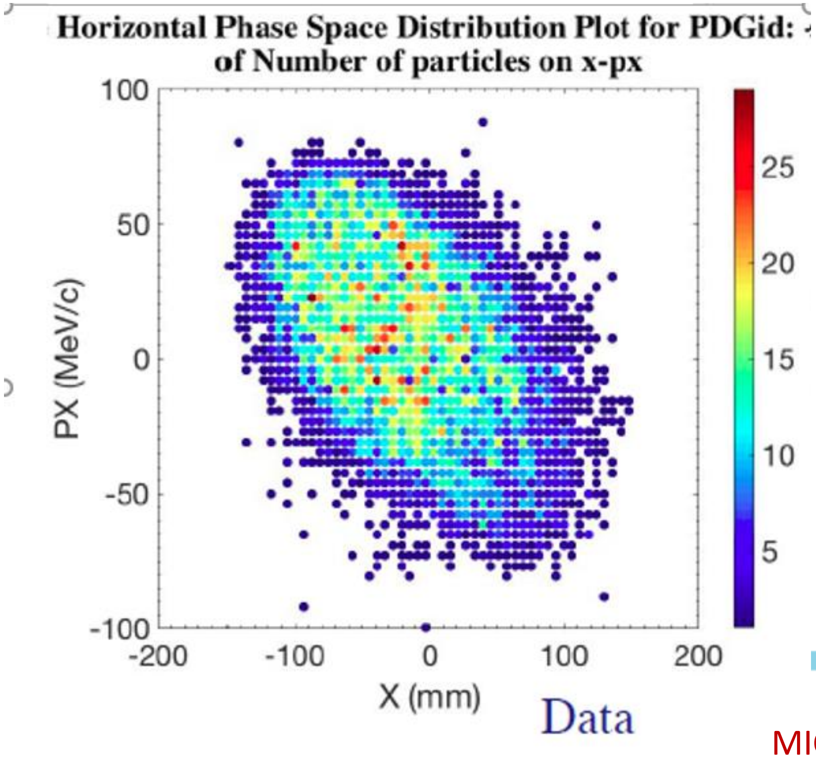
MICE

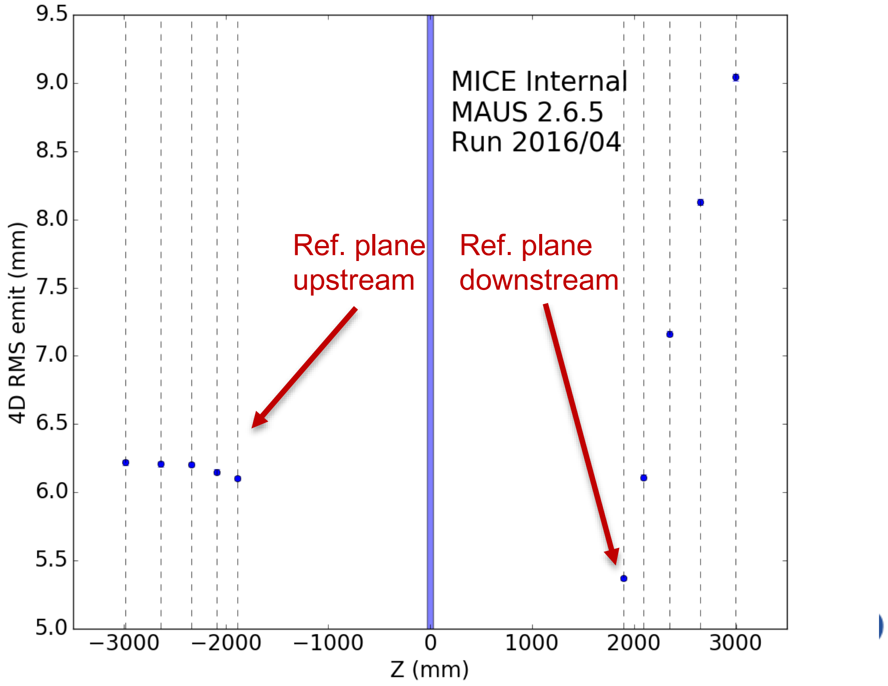
- at RAL
- 10M muon tracks
- cooling observed
  - w/o RF yet
- Re-accel’n in 2018





MICE Operation and Demonstration of Muon Ionization Cooling





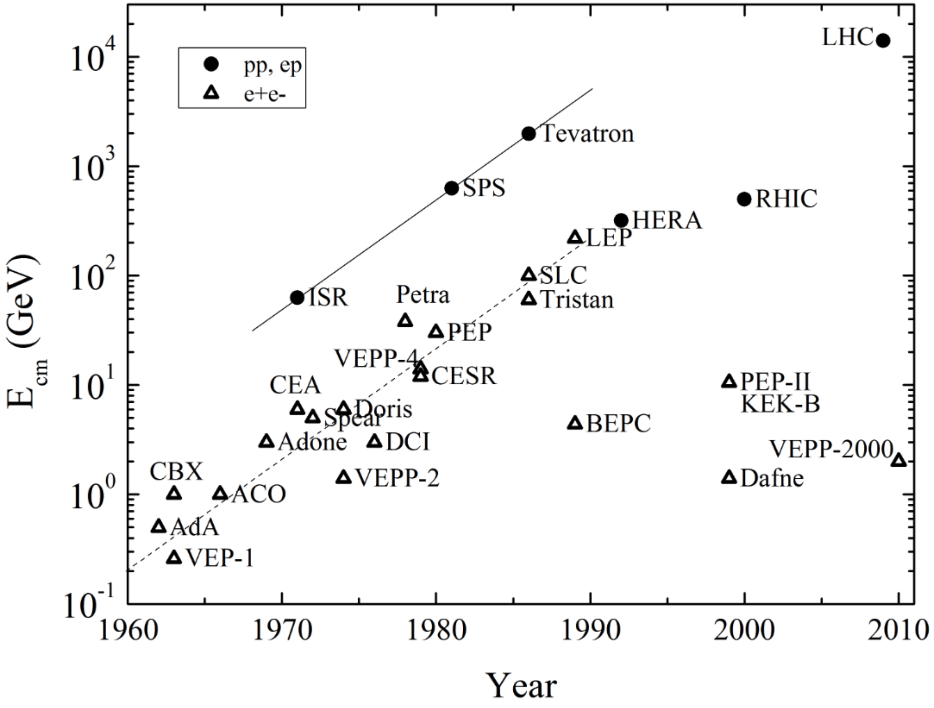
MICE (very) preliminary A.Bross, A.Liu, F.Drielsma

Race : Energy vs Luminosity

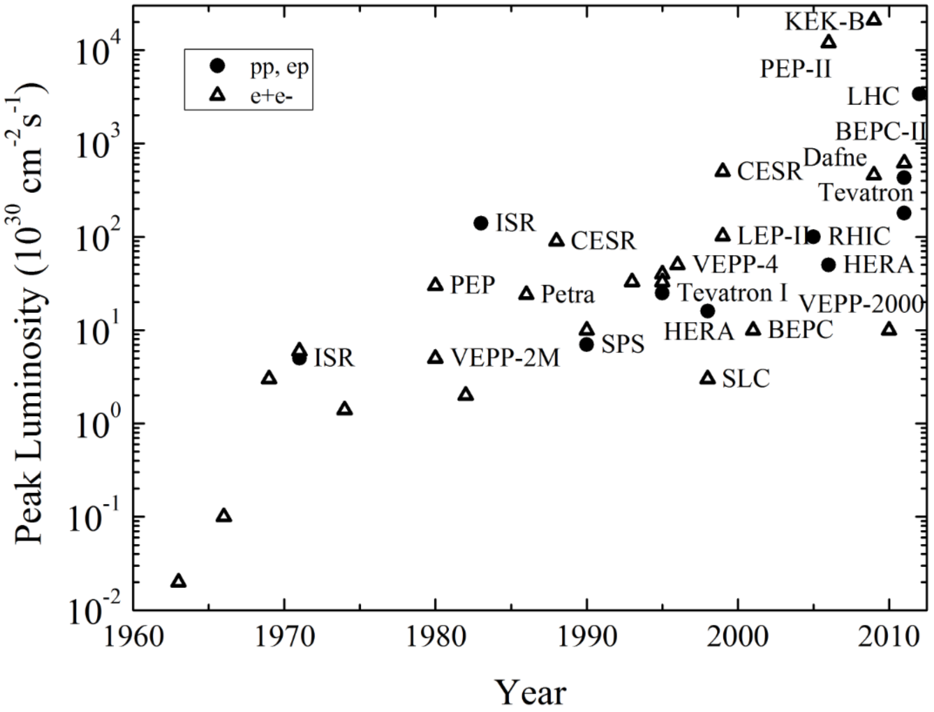
V.Shiltsev, Physics–Uspekhi, 2012, **55**:10, 965–976

Over the 5 decades of developments of the particle colliders

~4 orders of magnitude in ***E***



~6 orders of magnitude in ***L***

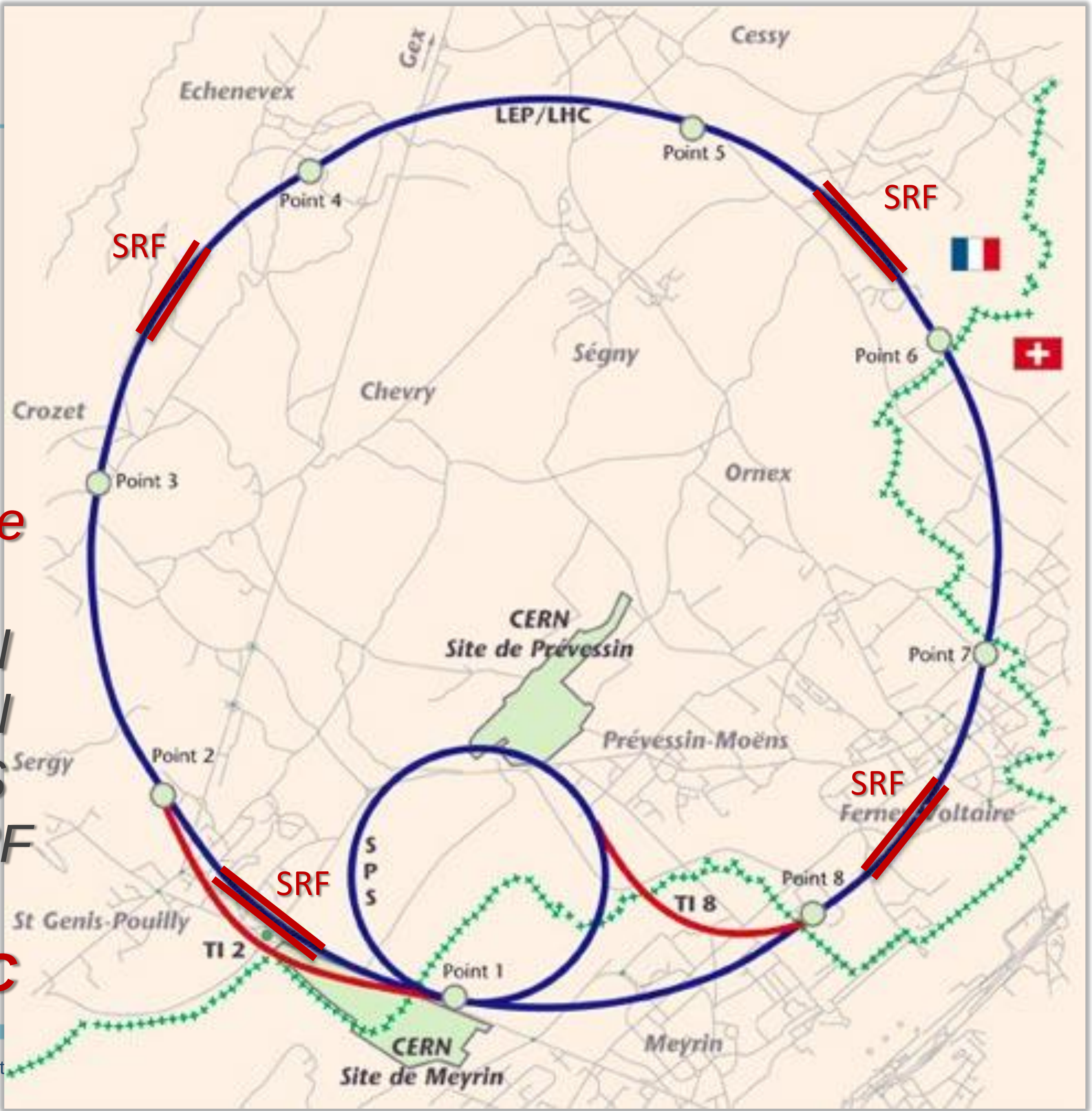


The reason (of faster pace of ***L***) is economical – the cost of new technological advances in acceleration is much higher than the cost of advances in performance (focusing, cooling, sources, etc)… and the latter are thus much more numerous

CMC

CERN Muon Collider

- *14 TeV cme*
- *LHC tunnel*
- *SPS tunnel and mb PS*
- *~7GeV SRF*
- ***Cost ~LHC***

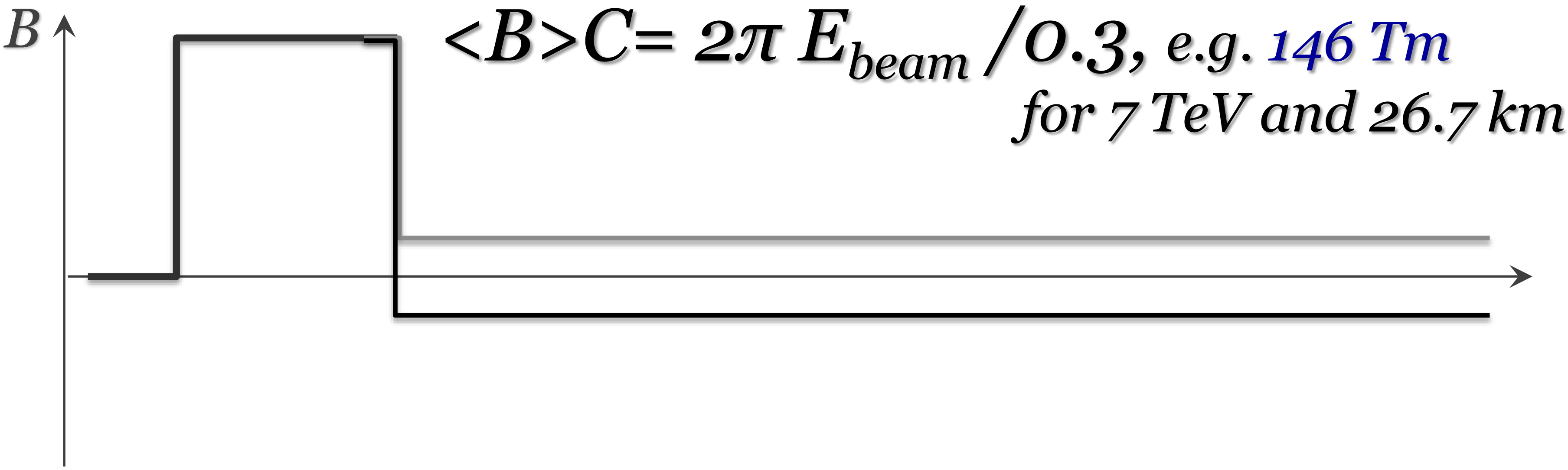


Assume RCS Acceleration

B_{max} : DC

B_{min} : pulsed from $-B_{min}$ to $+B_{min}$

Packing factor $\Pi<1$



$\langle B\rangle C = 2\pi E_{beam} / 0.3$, e.g. 146 Tm

for 7 TeV and 26.7 km

(Simple math)

- Acceleration range:

$$R = \frac{E_{max}}{E_{min}} = \frac{B_{max}L_{SC} + B_{min}L_{pulsed}}{B_{max}L_{SC} - B_{min}L_{pulsed}}$$

- If the ratio of fields : $f = \frac{B_{max}}{B_{min}}$ then : $\frac{L_{pulsed}}{L_{SC}} = f\,\frac{R-1}{R+1}$

  - and equation for the required fields reads :

$$\frac{2\pi}{0.3}E_{max} = < B > C = B_{max}\Pi C\,\frac{2R}{R(1+f)+1-f}$$

Example: 7 TeV, 26.7 km tunnel, 16T max

$$\frac{2\pi}{0.3} E_{max} = <B> C = B_{max} \Pi C \frac{2R}{R(1+f)+1-f}$$

146 T × km 26.7km 16T 0.85 0.4=1/2.5

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-4}$	B_{min}	E_{inj}
4.2	16	3.8T	0.45TeV
4.5	7	3.5T	1TeV
5	4	3.2T	4TeV
8	1.75	2.0T	9.1TeV

Example 2: 1 TeV, 6.9km tunnel, 16T max

$$\frac{2\pi}{0.3}E_{max} =< B > C = B_{max}\Pi C \frac{2R}{R(1+f)+1-f}$$

20.9 T × km 6.9km 16T 0.9 0.21=1/5

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-9}$	B_{min}	E_{inj}
10	9	1.6T	110 GeV
9.5	17	1.7T	60 GeV

Example 3: 60GeV,0.7km tunnel,16T max

$$\frac{2\pi}{0.3}\underset{\substack{\uparrow\\ 1.26\ \mathrm{T}\times\mathrm{km}}}{E_{max}} =< B > \underset{\substack{\uparrow\\ 0.7\mathrm{km}}}{C} = \underset{\substack{\uparrow\\ 16\mathrm{T}}}{B_{max}}\underset{\substack{\uparrow\\ 0.9}}{\Pi} C\,\underset{\substack{\uparrow\\ 0.125=1/8}}{\frac{2R}{R(1+f)+1-f}}$$

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-15}$	B_{min}	E_{inj}
16	15	1.0T	5 GeV

To sum up: 14 TeV *CMC*

- **One can build a 14 TeV cme $\mu+\mu-$ collider at CERN if:**
  - Re-use tunnels 26.7km LHC, 6.9km SPS, 0.7km PS
  - 16 T SC magnets (DC), need ~5 km
  - Pulsed ±3.5 T magnets, with ramp ~100ms, need ~20km
  - Pulsed ±2 T magnets, with ramp ~10ms, need ~6km
  - Pulsed ±1 T magnet, with ramp ~1ms, need ~1km
- **The *αβγ*-model predicts TPC ~12B$ ±4**
  - 5B$ SC magnets, 3B$ NC magnets, 2B$ SRF, 2B$ 100MW power infrst.
  - ~ cost of LHC; ~6B$ in European accounting
- **"Free cookie" – if one has 24 T SC magnets**
  - Either 4x luminosity can be achieved with collider in SPC tunnel – that requires 7 km of 24T magnets
  - Or 7 TeV cme in the LHC tunnel with just 3T pulsed magnets

Summary

- **Future energy frontier colliders are expensive:**
  - *αβγ*-model approx. well NC/SC Magnets and RF
  - Significant fraction is in civil and site power infrastructure
- **Possible options/preemptive measures:**
  1. Re-use existing (injectors, tunnels, etc)
     - Though saves a lot, works only at few places (big existing labs)
  2. Develop traditional technology to lower cost by a factor (SC mag, SRF)
     - Decade(s) of R&D, ongoing… need to be more aggressive
  3. *"Move to China!"* or some other place to save big factor
     - The advantage might disappear in 10-15 years from now
  4. Wait till new acceleration technology matures (plasma) and lower cost
     - Progress over past 2 decades impressive but no sign of cost feasibility yet… R&D
  5. *"Get more with same energy"* = *μ*+*μ*- (e.g., 14 TeV CERN MC)
     - Need to develop challenging pulsed magnets (NC? SC?), other smart ideas
     - But the switch to muons is inevitable in a long run…

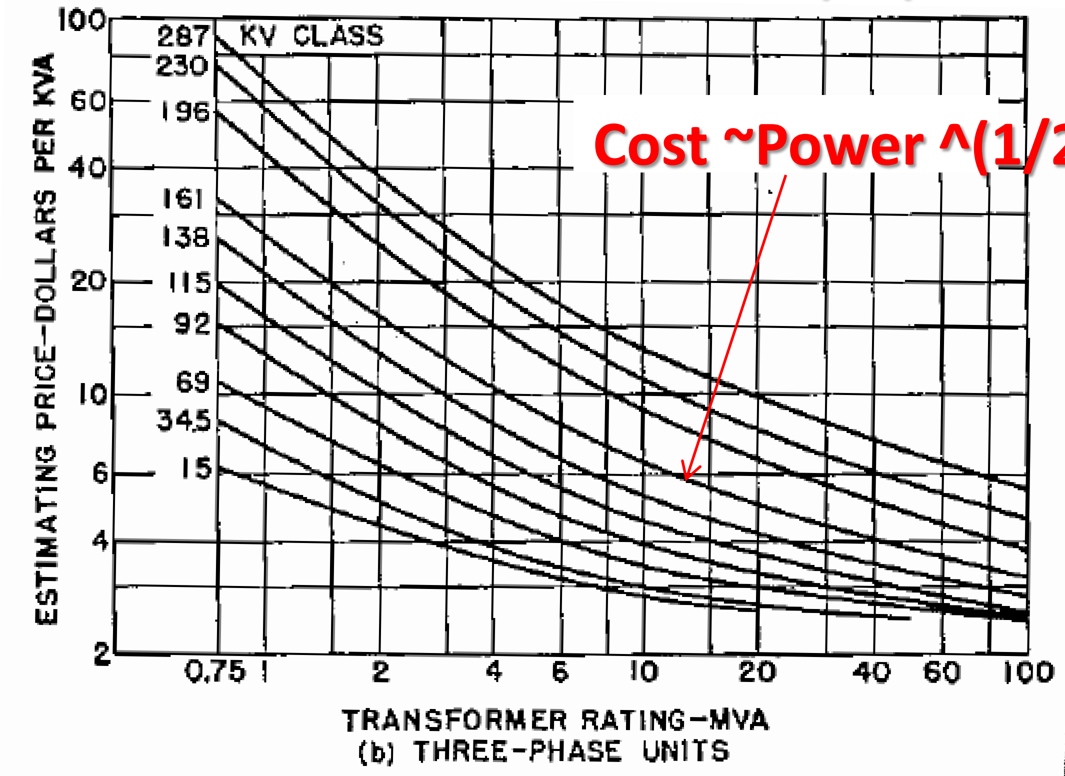
Thank You for Your Attention!

Back up slides

As an example: transformers

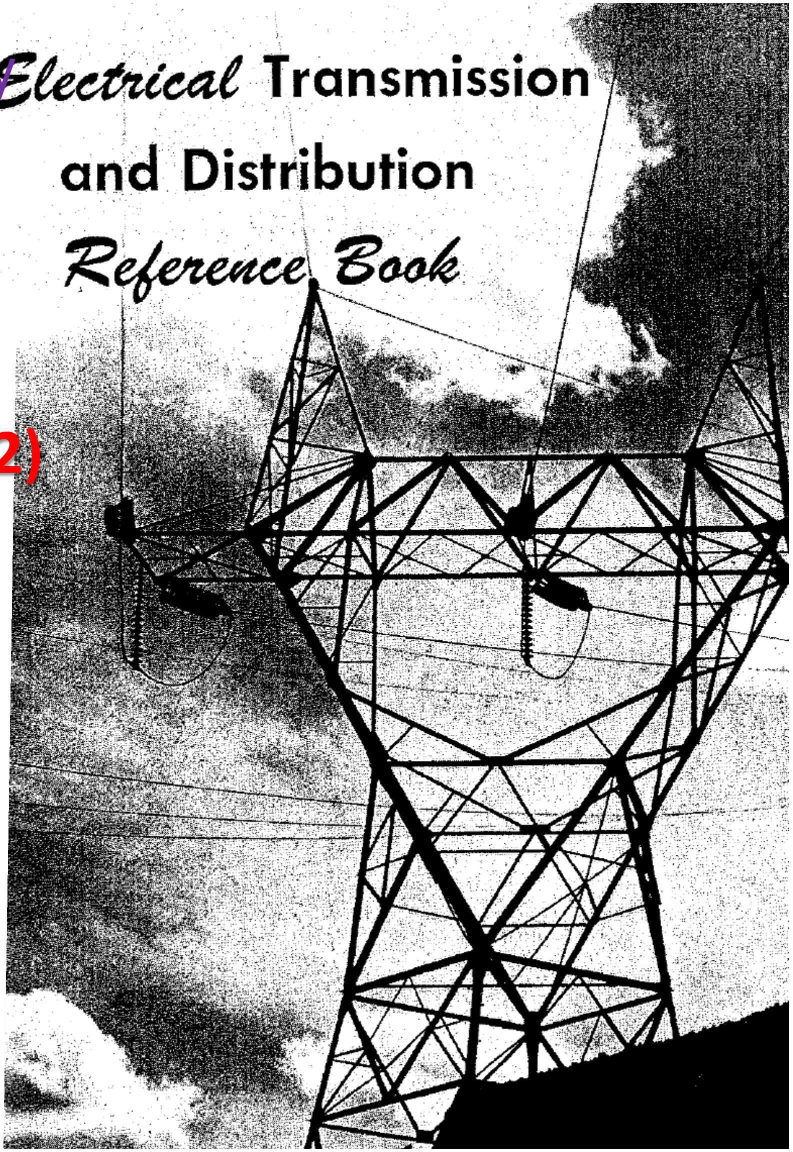
- Cost ~ Size^3
- Power (MVA) ~ Size^4
- So , Cost ~ (Power)^(3/4

From basic theory



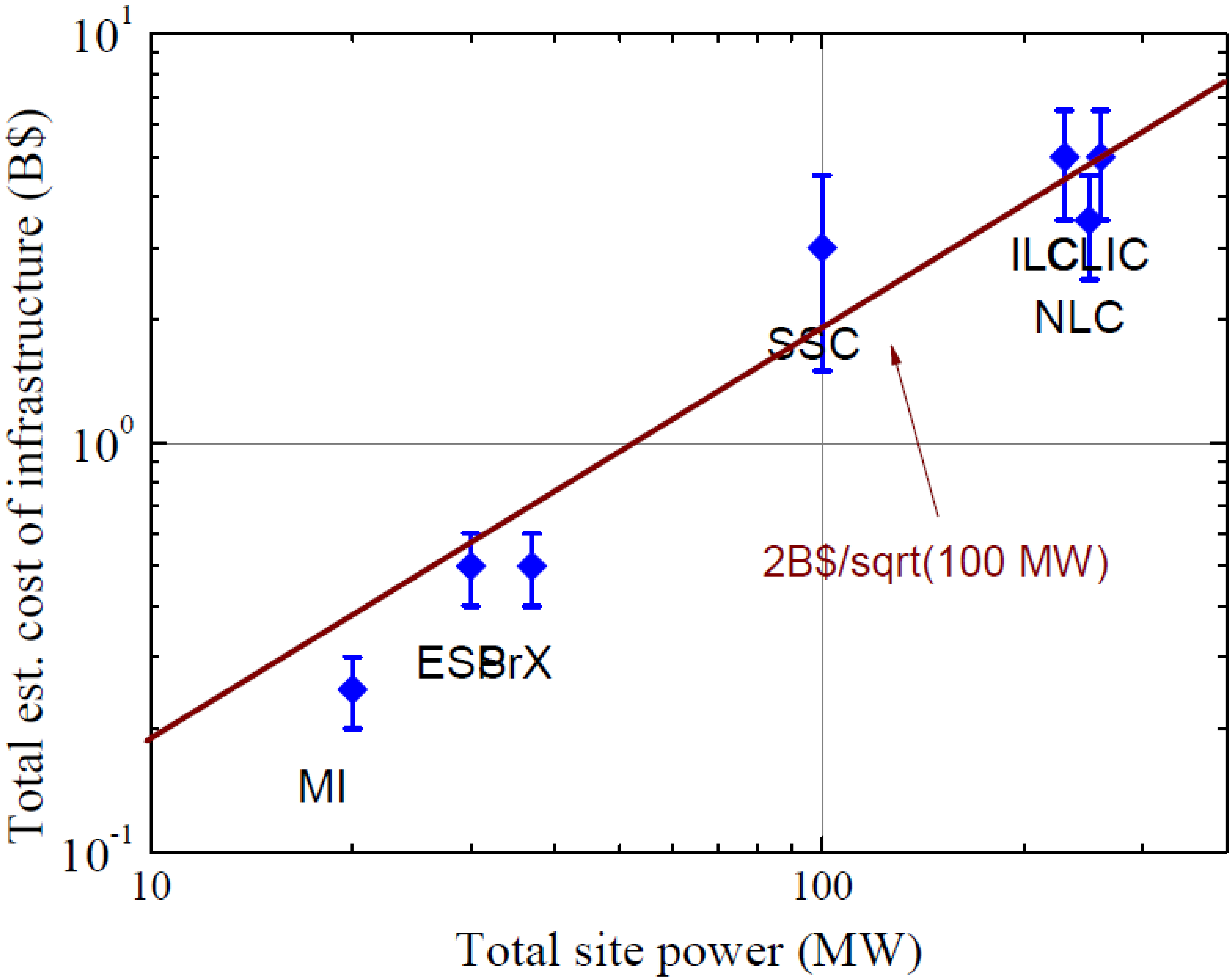
Cost ~Power ^(1/2)

Fig. 48—Curve for estimating prices of oil-immersed, 60-cycle, two-winding, type OA power transformers.



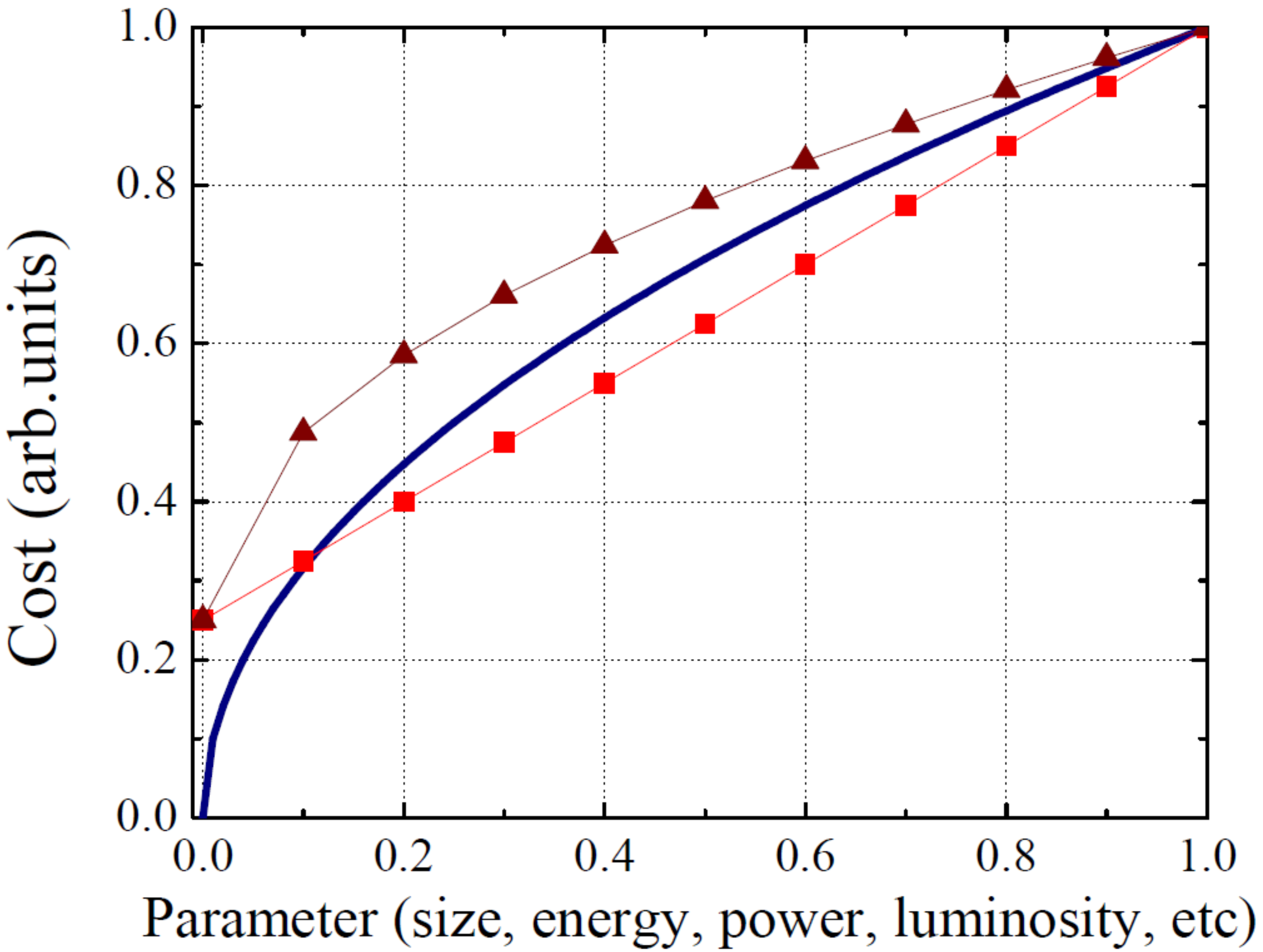
Electrical Transmission
and Distribution
Reference Book

“Infrastructure”

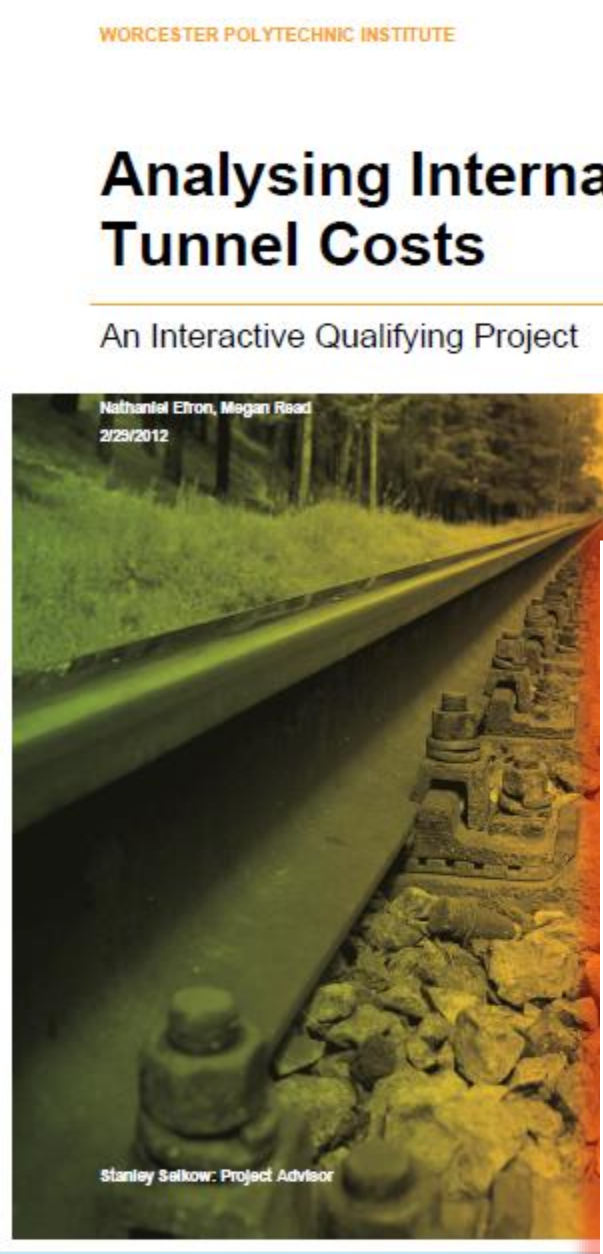


Functional dependence

- Recurring theme: “zero-cost” + some growing function can be reasonably well described by *sqrt*(Parameter)



Cost of Tunnel



WORCESTER POLYTECHNIC INSTITUTE

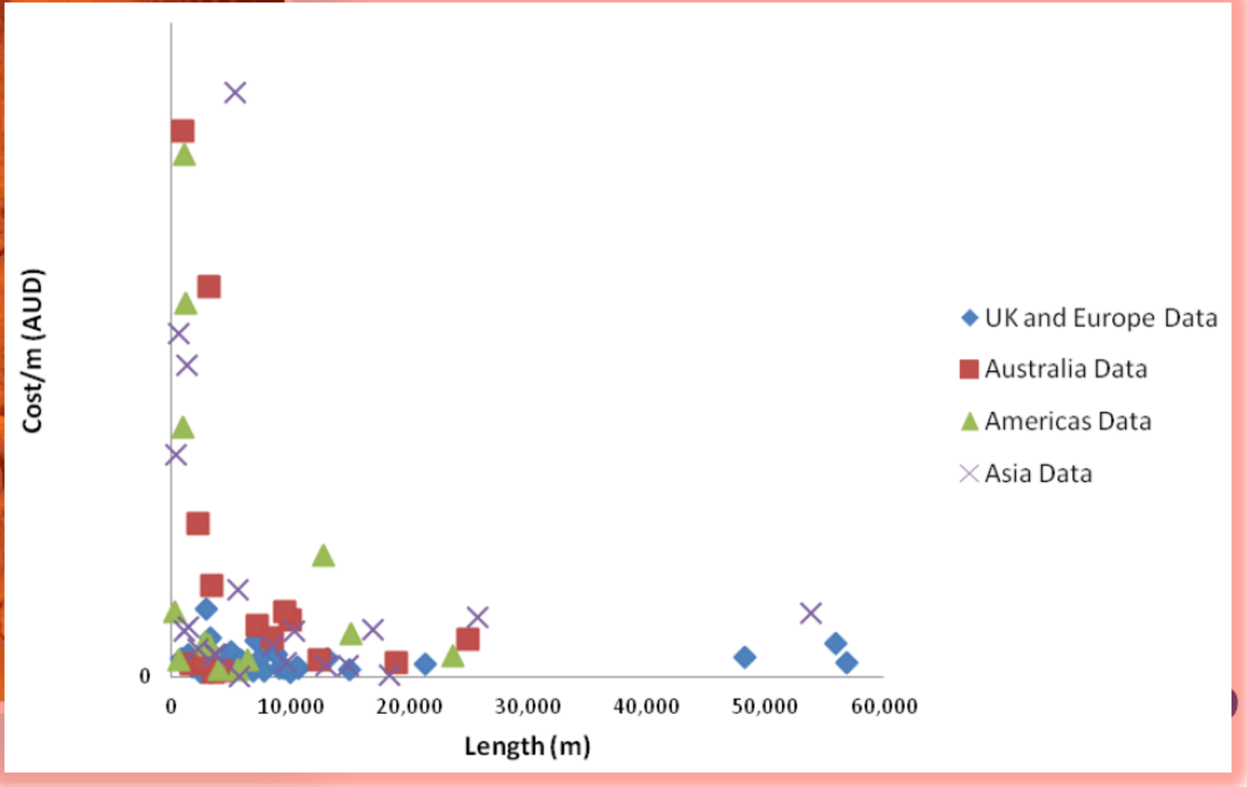
Analysing International Tunnel Costs

An Interactive Qualifying Project

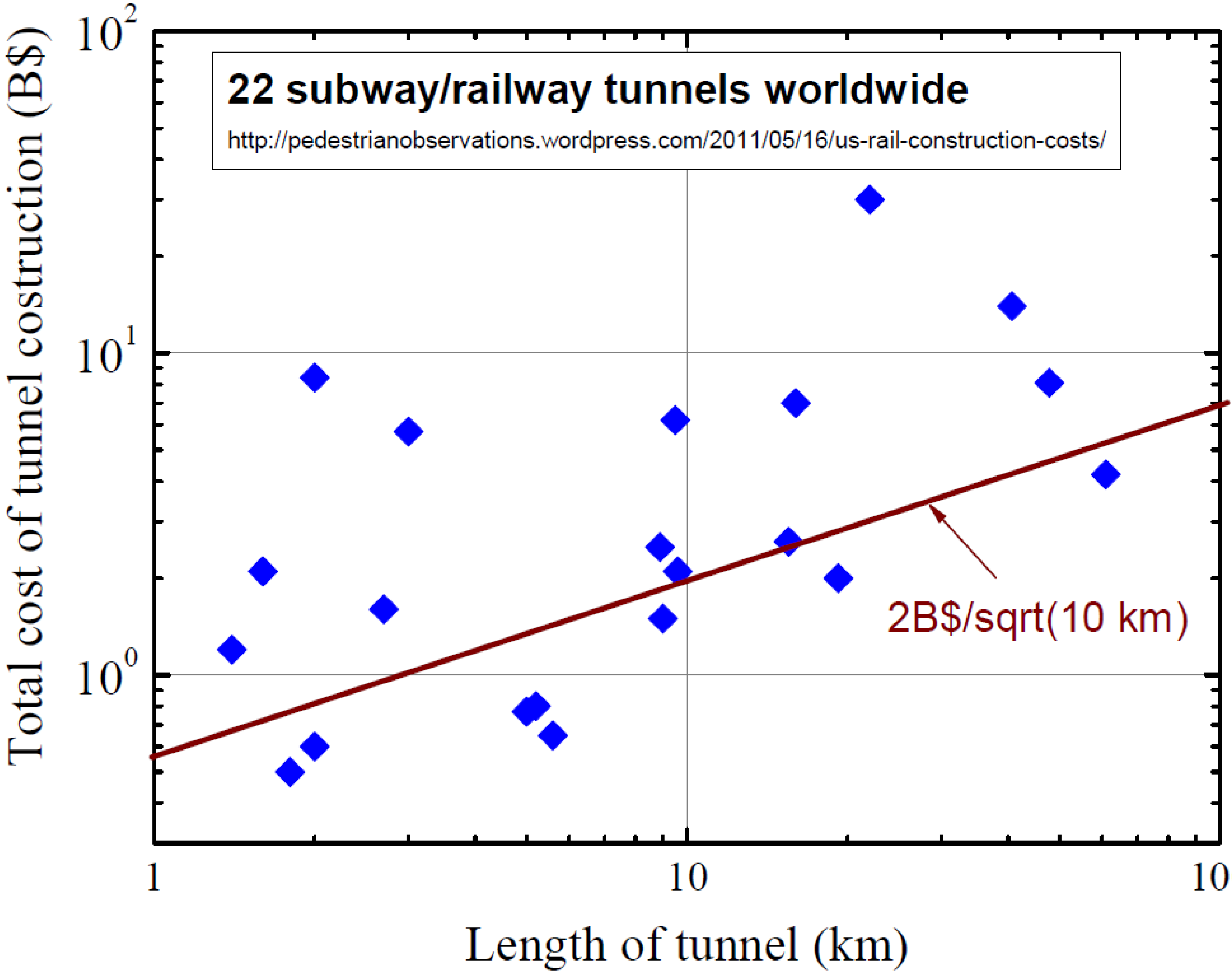
Nathaniel Efron, Megan Read
2/29/2012

Stanley Selkow: Project Advisor

- Some 100 tunnels world wide



Tunnels: Worldwide

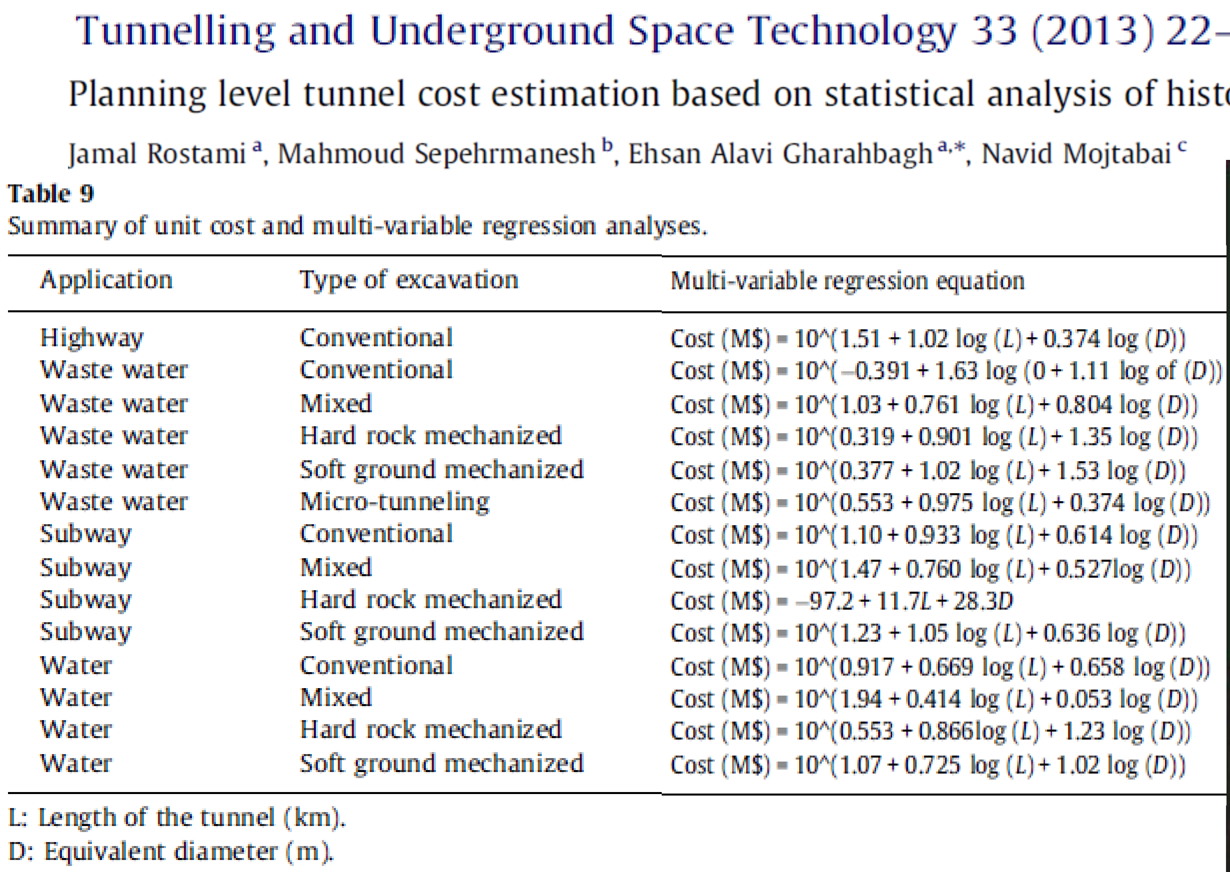


22 subway/railway tunnels worldwide

http://pedestrianobservations.wordpress.com/2011/05/16/us-rail-construction-costs/

More on Tunneling cost

- Do not expect Cost ~ ($L \times D^2$) = meter^3 !



Tunnelling and Underground Space Technology 33 (2013) 22–33

Planning level tunnel cost estimation based on statistical analysis of historical data

Jamal Rostami [a], Mahmoud Sepehrmanesh [b], Ehsan Alavi Gharahbagh [a,*], Navid Mojtabai [c]

Table 9
Summary of unit cost and multi-variable regression analyses.

Application	Type of excavation	Multi-variable regression equation
Highway	Conventional	Cost (M\$) = $10^\wedge(1.51 + 1.02 \log(L) + 0.374 \log(D))$
Waste water	Conventional	Cost (M\$) = $10^\wedge(-0.391 + 1.63 \log(0 + 1.11 \log \text{ of } (D))$
Waste water	Mixed	Cost (M\$) = $10^\wedge(1.03 + 0.761 \log(L) + 0.804 \log(D))$
Waste water	Hard rock mechanized	Cost (M\$) = $10^\wedge(0.319 + 0.901 \log(L) + 1.35 \log(D))$
Waste water	Soft ground mechanized	Cost (M\$) = $10^\wedge(0.377 + 1.02 \log(L) + 1.53 \log(D))$
Waste water	Micro-tunneling	Cost (M\$) = $10^\wedge(0.553 + 0.975 \log(L) + 0.374 \log(D))$
Subway	Conventional	Cost (M\$) = $10^\wedge(1.10 + 0.933 \log(L) + 0.614 \log(D))$
Subway	Mixed	Cost (M\$) = $10^\wedge(1.47 + 0.760 \log(L) + 0.527 \log(D))$
Subway	Hard rock mechanized	Cost (M\$) = $-97.2 + 11.7L + 28.3D$
Subway	Soft ground mechanized	Cost (M\$) = $10^\wedge(1.23 + 1.05 \log(L) + 0.636 \log(D))$
Water	Conventional	Cost (M\$) = $10^\wedge(0.917 + 0.669 \log(L) + 0.658 \log(D))$
Water	Mixed	Cost (M\$) = $10^\wedge(1.94 + 0.414 \log(L) + 0.053 \log(D))$
Water	Hard rock mechanized	Cost (M\$) = $10^\wedge(0.553 + 0.866 \log(L) + 1.23 \log(D))$
Water	Soft ground mechanized	Cost (M\$) = $10^\wedge(1.07 + 0.725 \log(L) + 1.02 \log(D))$

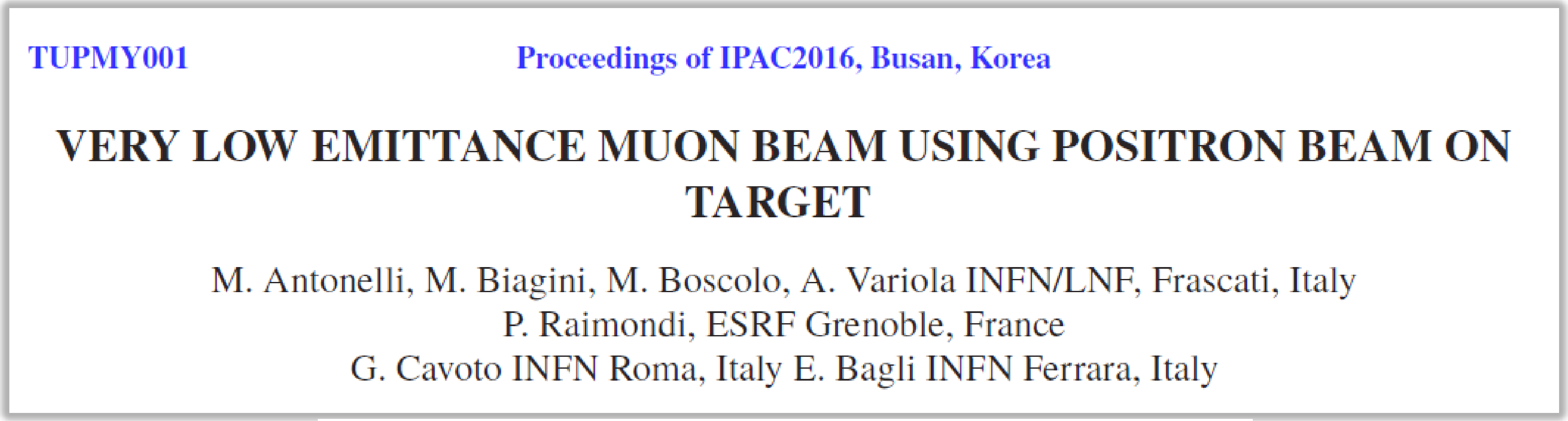
L: Length of the tunnel (km).
D: Equivalent diameter (m).

Data on 270 tunnels world wide

Tunnelling and Underground Space Technology

Cost ~ $L^\wedge(0.4\text{-}1)\ D^\wedge(0.6\text{-}1.5)$

New Approaches (1)



TUPMY001 Proceedings of IPAC2016, Busan, Korea

VERY LOW EMITTANCE MUON BEAM USING POSITRON BEAM ON TARGET

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P. Raimondi, ESRF Grenoble, France
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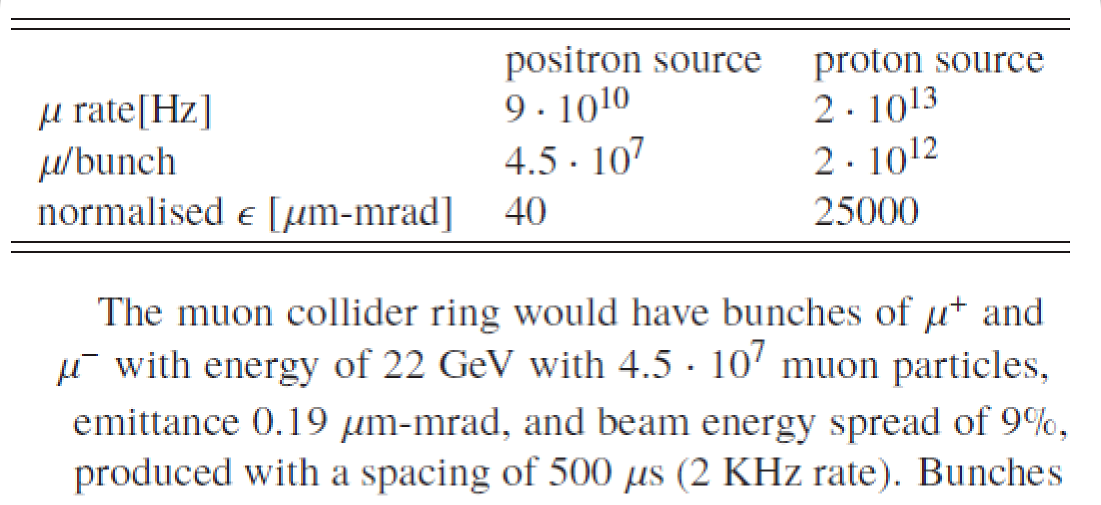
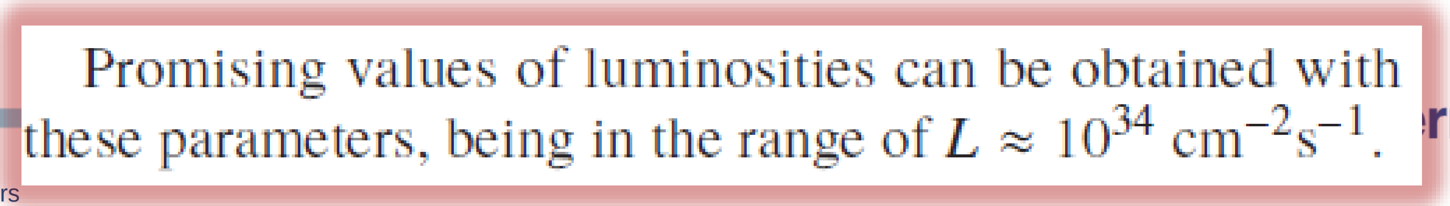


	positron source	proton source
μ rate[Hz]	$9 \cdot 10^{10}$	$2 \cdot 10^{13}$
μ/bunch	$4.5 \cdot 10^{7}$	$2 \cdot 10^{12}$
normalised ϵ [μm-mrad]	40	25000

The muon collider ring would have bunches of μ^+ and μ^- with energy of 22 GeV with $4.5 \cdot 10^7$ muon particles, emittance 0.19 μm-mrad, and beam energy spread of 9%, produced with a spacing of 500 μs (2 KHz rate). Bunches



Promising values of luminosities can be obtained with these parameters, being in the range of $L \approx 10^{34}$ cm^{-2}s^{-1}.