Crystal Ball :

On the Future High Energy Colliders *

Vladimir Shiltsev
Fermilab, Batavia, IL , USA
Accelerator Physics Center
August 4, 2015

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

Content

Now & Past

LHC,Tevatron, B-fact’s, SSC…

“Near” Future

CepC, ILC, LHeC, FCC-ee…

Future

FCC-pp, SppC, Muon Collider, CLIC…

“Far” Future

.?.

Past and *Present* shape *Future*

- When one wants to analyze options for future HEP accelerators, the question comes to right balance btw

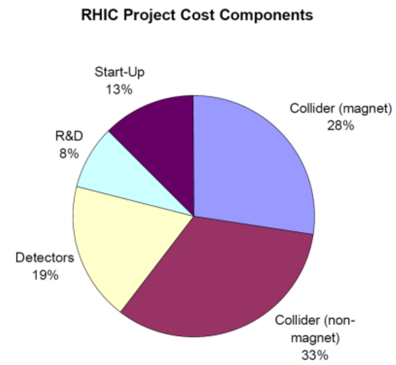
PHYSICS vs FEASIBILITY

- **FEASIBILITY** of an accelerator is actually complex:
  - Feasibility of **ENERGY**
    - Is it possible to reach the *E* of interest / what's needed ?
  - Feasibility of **PERFORMANCE**
    - Will we get enough physics out there / luminosity ?
  - Feasibility of **COST**
    - Is it affordable to build and operate ?
- **What can we learn/take from the past/present?**
  - (besides that all built/existing machines are feasible)

Cost Analysis

"Known" Costs for 17 Big Accelerators:

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



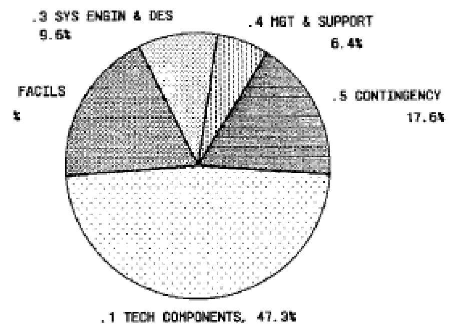
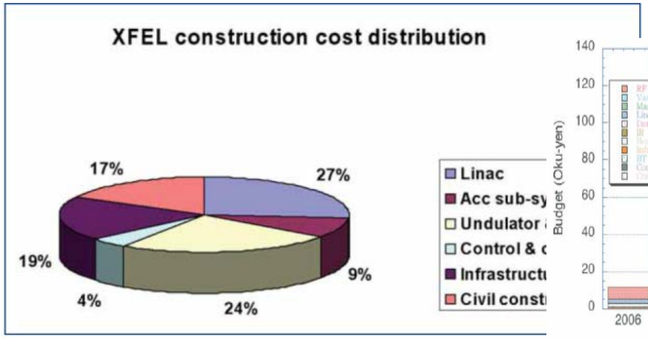
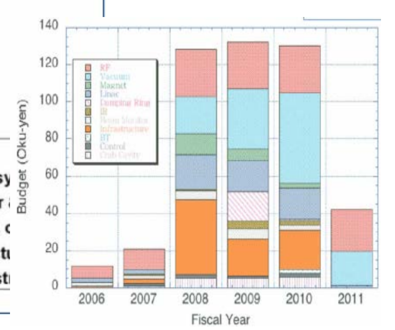
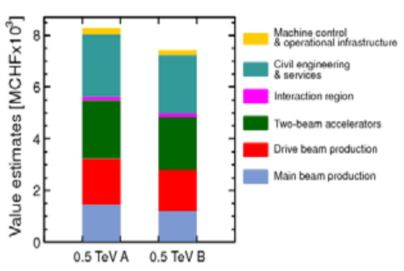
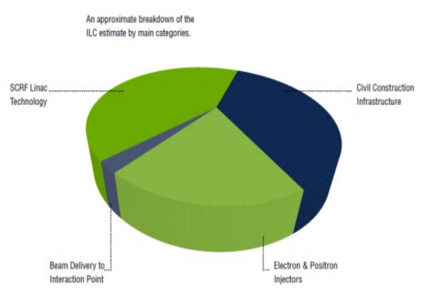


Figure 8.7-1. SSC cost estimate summary: Level 2 WBS categories.









Is it possible to parameterize the cost for known technologies ?

	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

2014 JINST 9 T07002

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

Raw Data:

look confusing

All are Different!

- **Parameters:**
  - energy ***E***
  - size/length ***L***
  - power ***P***
- **Currencies**
- **Years**
- **Technologies**
- **Accounting**

TPC (US Accounting) vs *European Accounting*

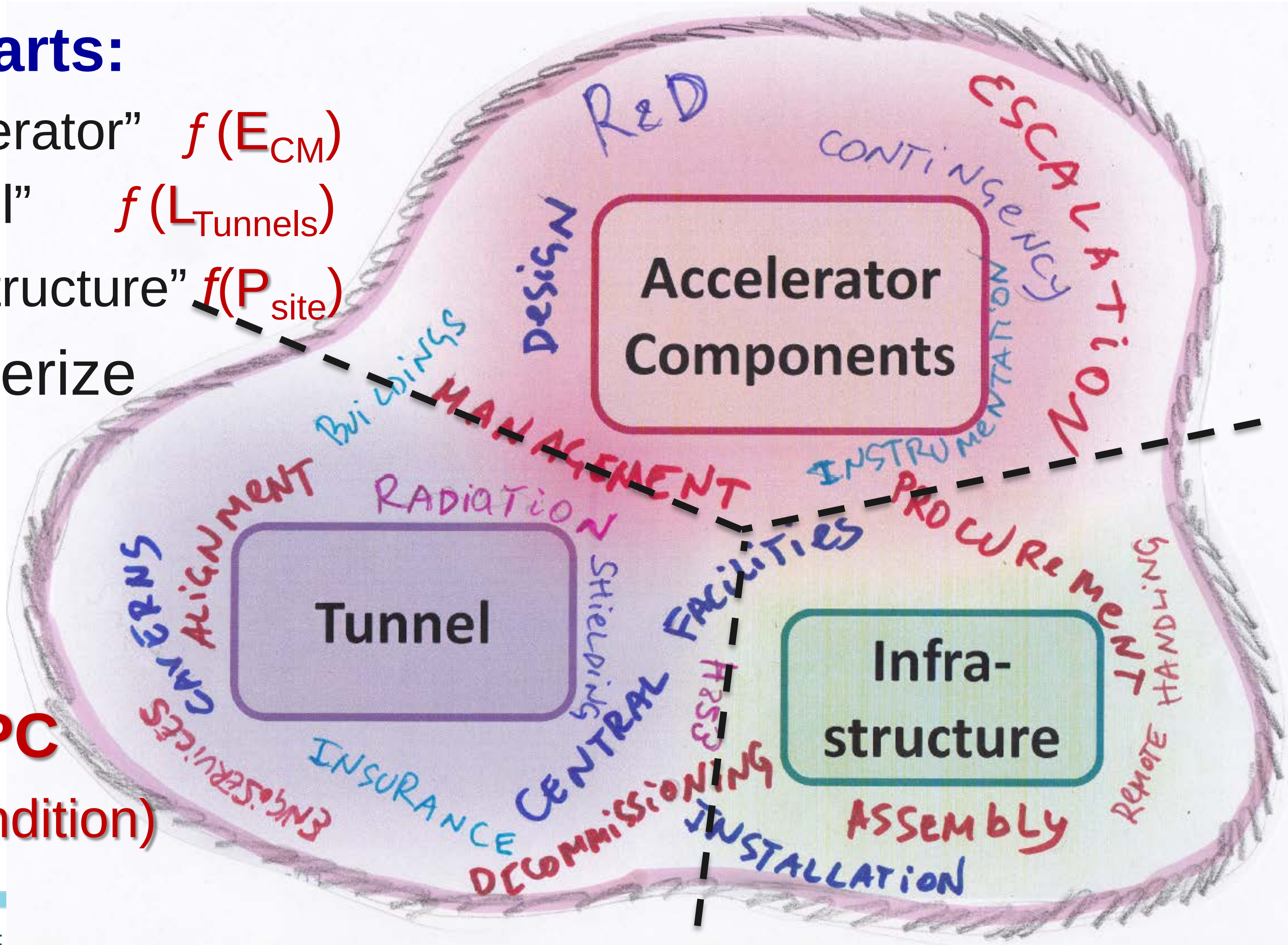
- To get the TPC one needs to include *SWF, OH, Escalation, Contingency, R&D, PED (often missed)*, and other *"missing elements"*

- TESLA (H.Edwards & P.Garbincius) ~ 1.95
- ITER (D. Lehman) ~ 2.3 (10% of 5B$=1.15B$)
- ILC (2008 DOE/OS) 16.5/6.7=**2.45** - ?

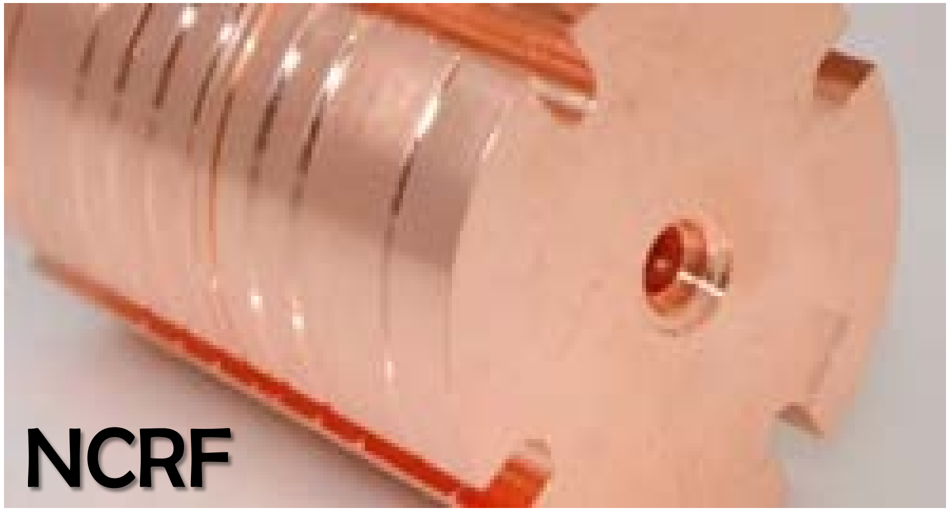
Use factor of 2-2.4 as typical

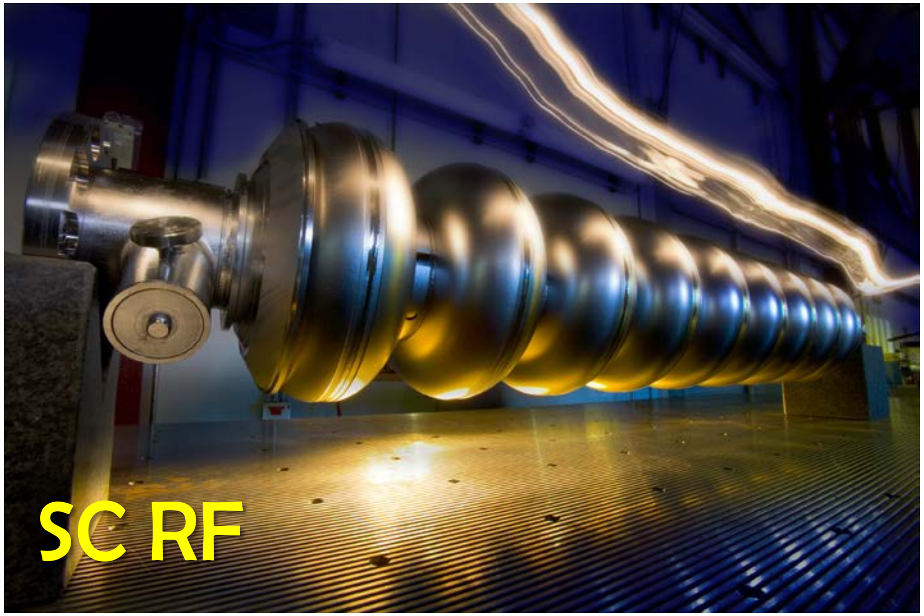
Approach: Though the TPC is complex mix → break it in just three parts

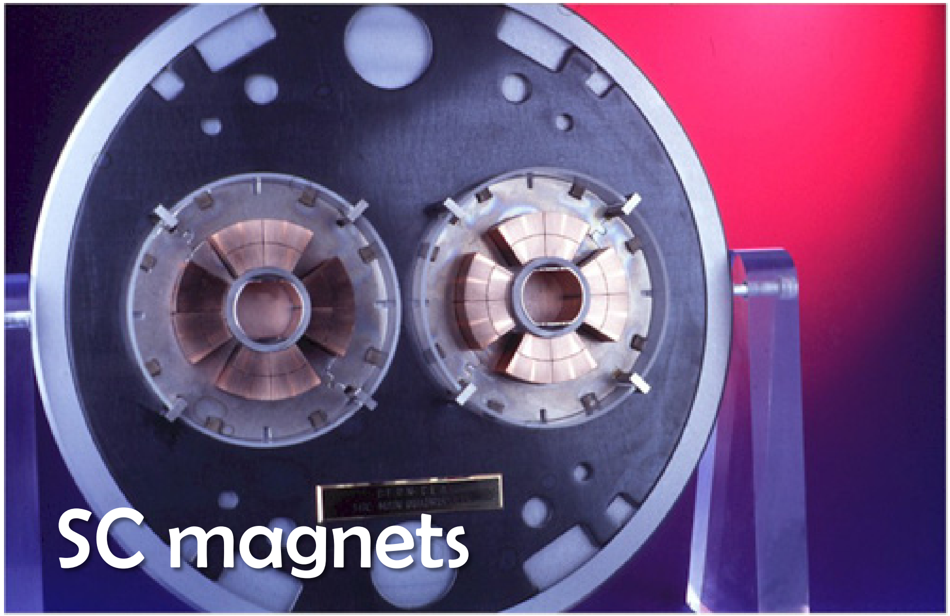
- **Three parts:**
  - "Accelerator" $f\,(E_{CM})$
  - "Tunnel" $f\,(L_{Tunnels})$
  - "Infrastructure" $f(P_{site})$
- Parameterize each by one parameter
- **Sum≡TPC** (unitarity condition)



Our Key “Feasible” Technologies







Phenomenological Cost Model

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

"Total Project Cost in **the US accounting**"

"Tunnels" – Cost Civil Construction

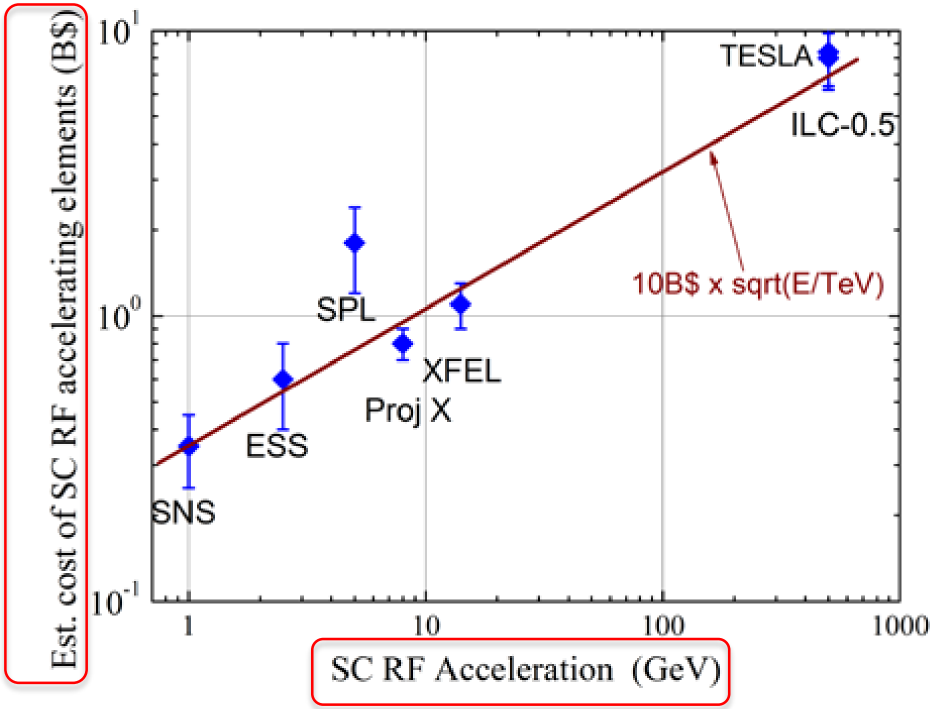
"Energy" – Cost of Accelerator Components

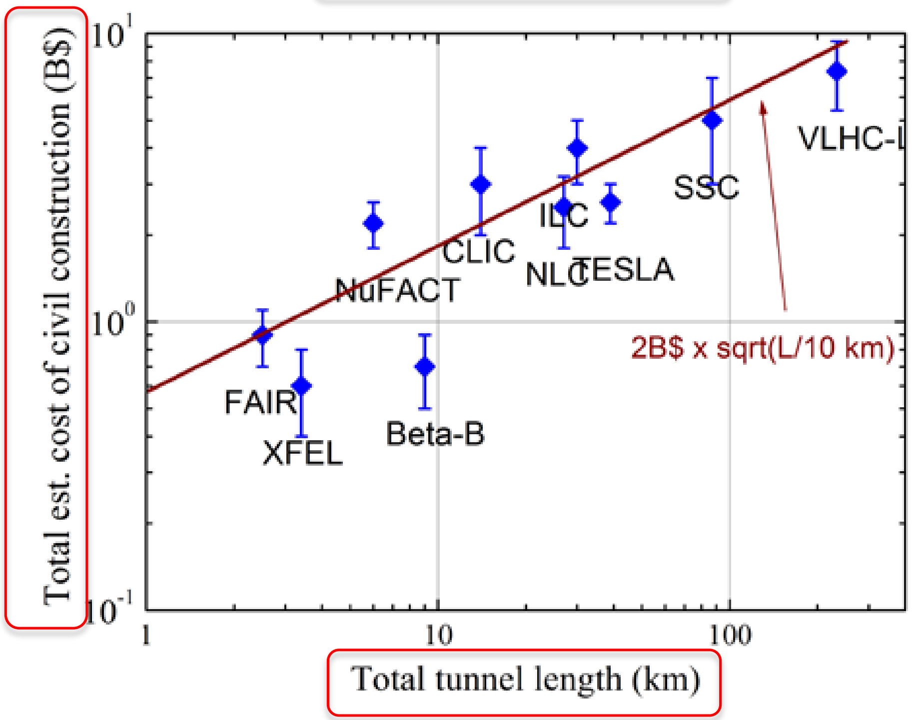
"Site Power"- Infrastructure

where *α,β,γ* – technology dependent constants

- **α≈ 2B$/sqrt(L/10 km)**
- **β≈ 10B$/sqrt(E/TeV)** for SC&NC RF
- **β≈ 2B$ /sqrt(E/TeV)** for SC magnets
- **β≈ 1B$ /sqrt(E/TeV)** for NC magnets
- **γ≈ 2B$/sqrt(P/100 MW)**

Illustrations





Comment:

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

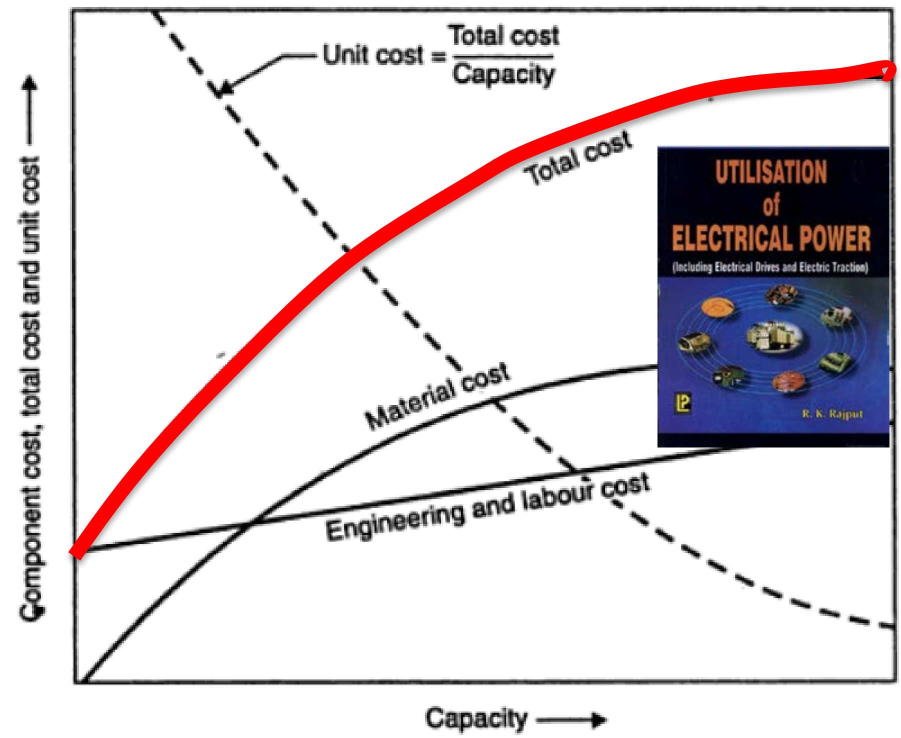
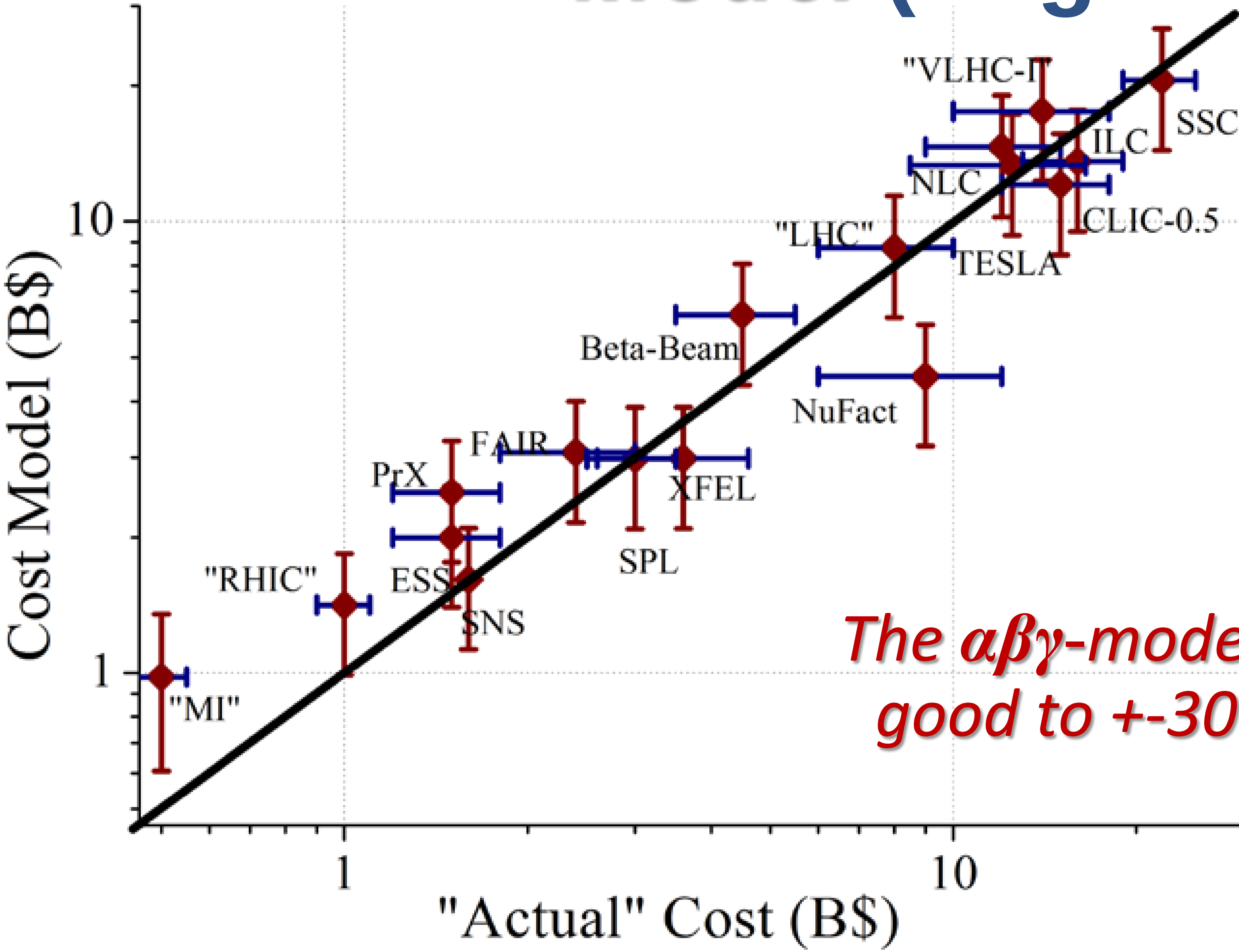


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

Total Cost vs Model (Log-Log)



The αβγ-model is good to +-30%

Part II: "Near" Future Facilities

		E_{cm}	L	P	αβγ-TPC
FCC_{ee}	CERN	0.25	100	300	10.9±3
CepC	China	0.25	55	500	10.2±3
ILC	Japan	0.5	36	163	13.1±4 *
		TeV	*km*	*MW*	*B$*

** official 2013 est. 7.8B$+13,000 FTEs (Eur.Acct.)*

Energy* Feasibility – *No Doubt!

Cost* Feasibility – *?? TBD ??

Feasibility of *Performance*

- **Luminosities : ~(2-5)10^{34}/IP**
  - **feasible, but there are issues**
    - Luminosity vs SRF power - trade off ($P=I\ \Delta E_{pass}$) (power consumption in general)
    - HOM heat-load in the cold RF system
    - *beam-strahlung*: DA, lifetime, IR optics *
    - beam-beam effects
    - pretzel separation if one ring
    - Earth field effects if injection energy is low
    - Not so easy injector: e+/e- source and booster

“Unfair Competitive Advantage”

- **CepC :** ***the project to be built in China***

Case study: modern light sources

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$

Fermilab

Part III: Future Colliders

		E_{cm}	L	P	$\alpha\beta\gamma$-TPC
CLIC	CERN	3	60	589	27.0±8
Muon C.	US?	6	20	230	14.4±5
FCC_{pp}	CERN	100	100	400	30.3±9
SppC	China	50+	54	300	25.5±9
		TeV	*km*	*MW*	*B$*

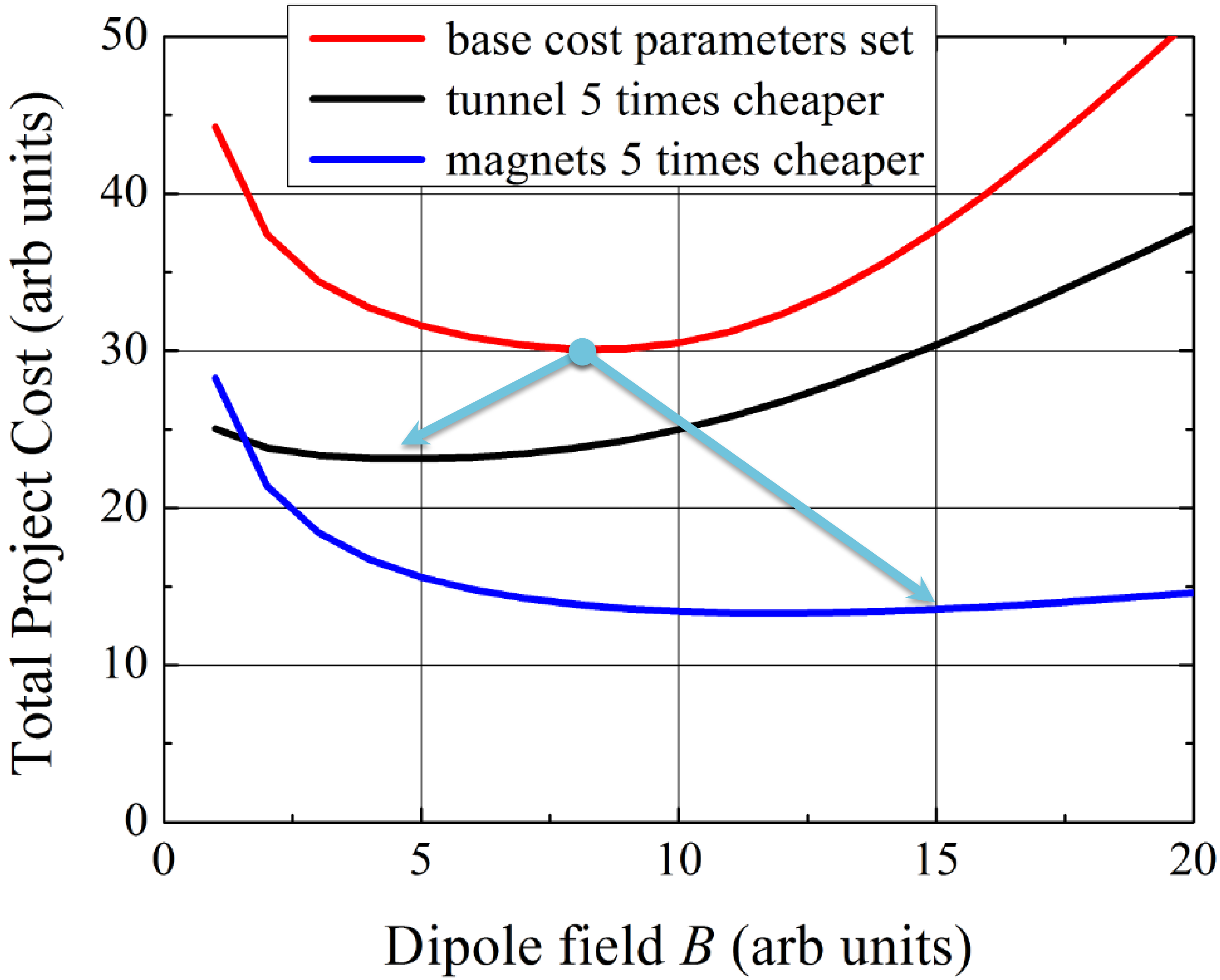
Cost Feasibility – ?? probably not ??

...if tunnel/injector exist ...Muon Collider cheapest

Feasibility of *Energy*

		100 MV/m @ 1e-7 spark
CLIC	**NC RF**	**tough**
Muon C.	**SCMag**	**no doubt**
FCC	**HF-SCMag**	**not (now)**
SppC	**HF-SCMag**	**not (now)**
		16-20 T magnets for >70 TeV

100 TeV *pp* : Qualitative Cost Dependencies



* for illustration purposes only

Feasibility of *Performance*

- **CLIC:** *e+e-* **~5 10^{34}**
  - **very tough** **
- **Muon Coll:** *μ+μ-* **~2 10^{34}**
  - **impossible now** ***
- **FCC/SppC:** *pp* **~5 10^{34}**
  - **very tough** **

(each * is about 1 order of magnitude)

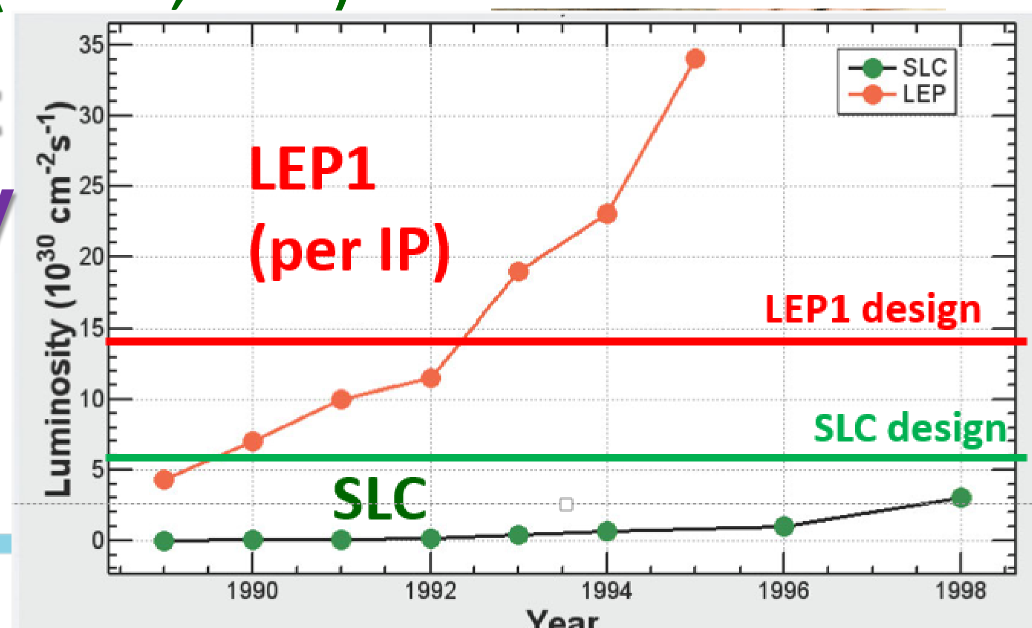
Fermilab

Two Comments:

1. Availability of experts :
   - "Oide Principle" : *1 Accelerator Expert can spend intelligently only ~1 M$ a year*
   - + it takes significant time to get the team together (XFEL, ESS)

K.Oide (KEK)

2. It takes time to get to design Luminosity
   - often 3-7 years



Part IV: Is There "Far" Future ?

- Post-100 TeV "Energy Frontier" assumes
  - 300-1000 TeV (*20-100 × LHC*)
  - "decent luminosity" (TBD)
- Surely we know:

circular collider

1. For the same reason there is no circular ***e+e-*** collider above Higgs-F there will be no circular ***pp*** colliders beyond 100 TeV → **LINEAR**

$$L \propto \frac{\eta P_{wall}}{E^3} \frac{\xi_y}{\beta_y}$$

2. Electrons radiate 100% *beam-strahlung* (<3 TeV) and in focusing channel (<10 TeV) → ***μ+μ-*** or ***pp***

linear collider

$$L \propto \frac{\eta_{\text{linac}} P_{wall}}{E} \frac{N_\gamma}{\sigma_y}$$

"Phase-Space" is Further Limited

- "Live within our means": for 20-100 × LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

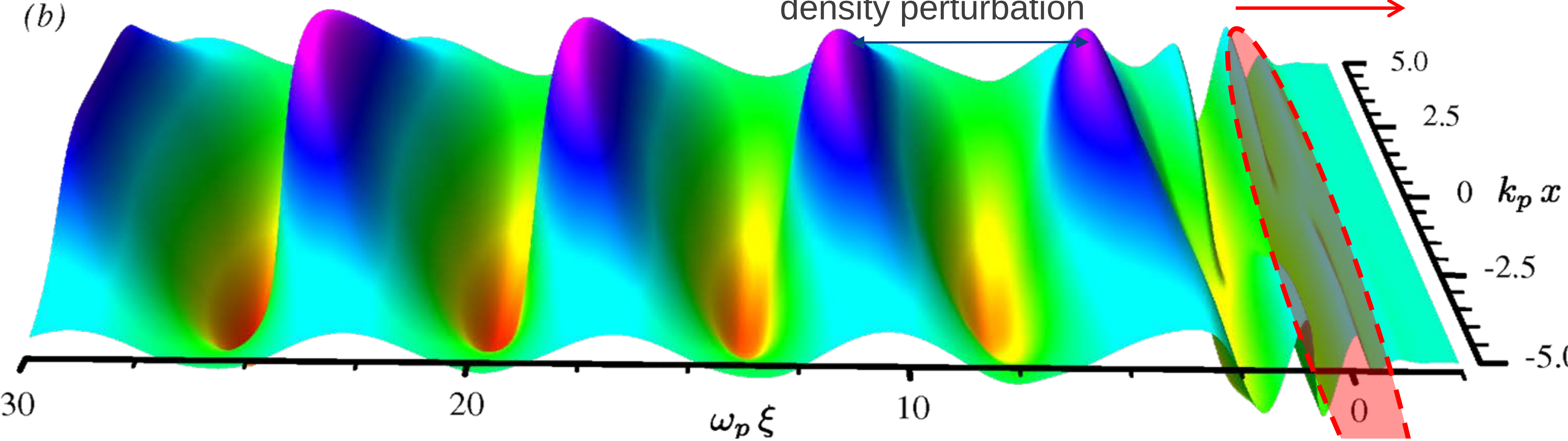
→**New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)**

SC magnets equiv. ~ 0.5 GeV per meter (LHC)

3. Only one option for >30 GeV/m known now:
dense plasma→ that excludes *protons*→ only *muons*

Plasma Waves

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



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

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**

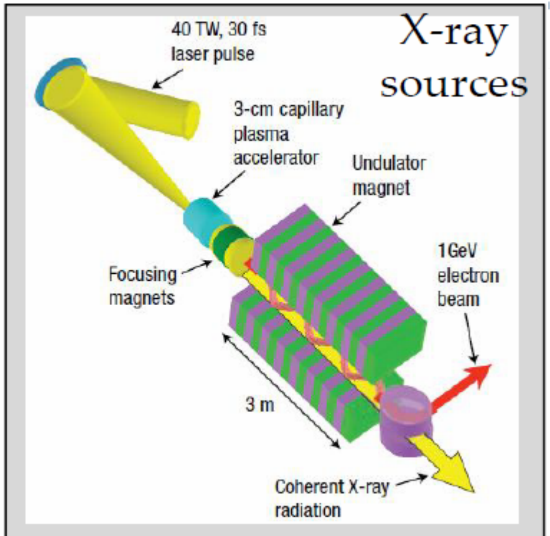
Option C: Crystals & Muons

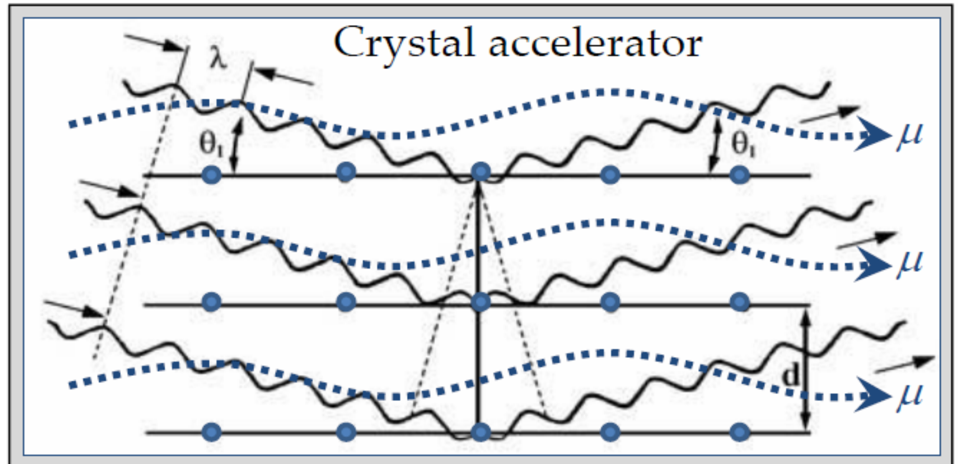
n~10^{22} cm^{-3}, **10 TeV/m →**

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

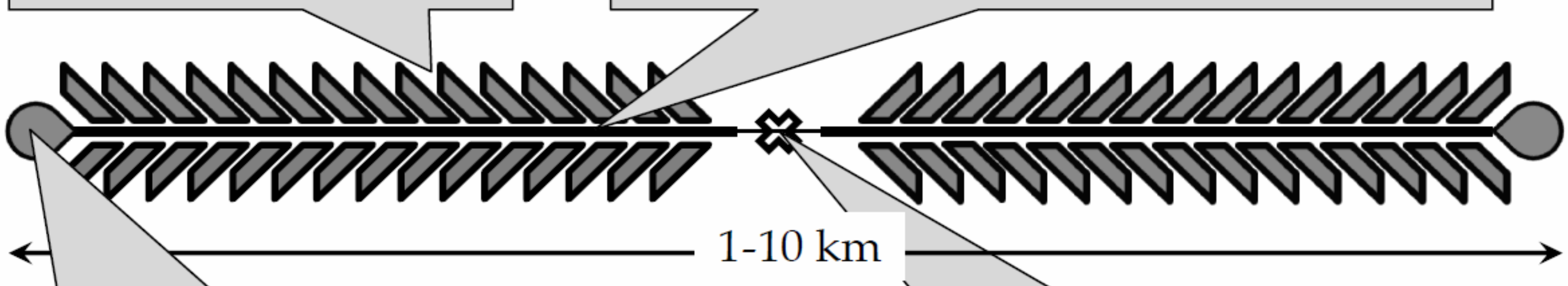
PeV = 1000 TeV

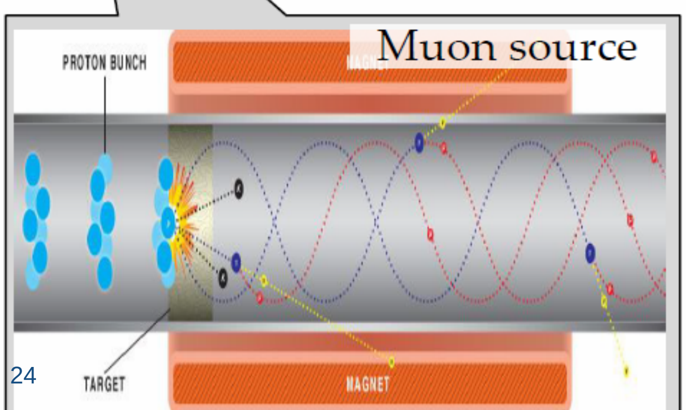
V.Shiltsev, Phys. Uspekhy 55 965 (2012)

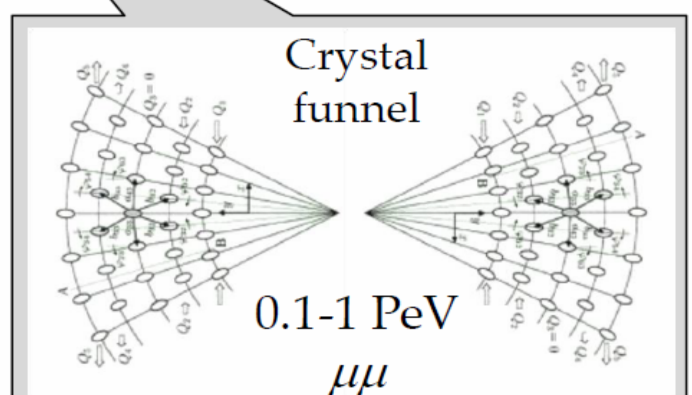




n_μ ~1000
n_B ~100
f_{rep} ~10^6
L ~10$^{30\text{-}32}$







Paradigm Shift : *Energy* vs *Luminosity*

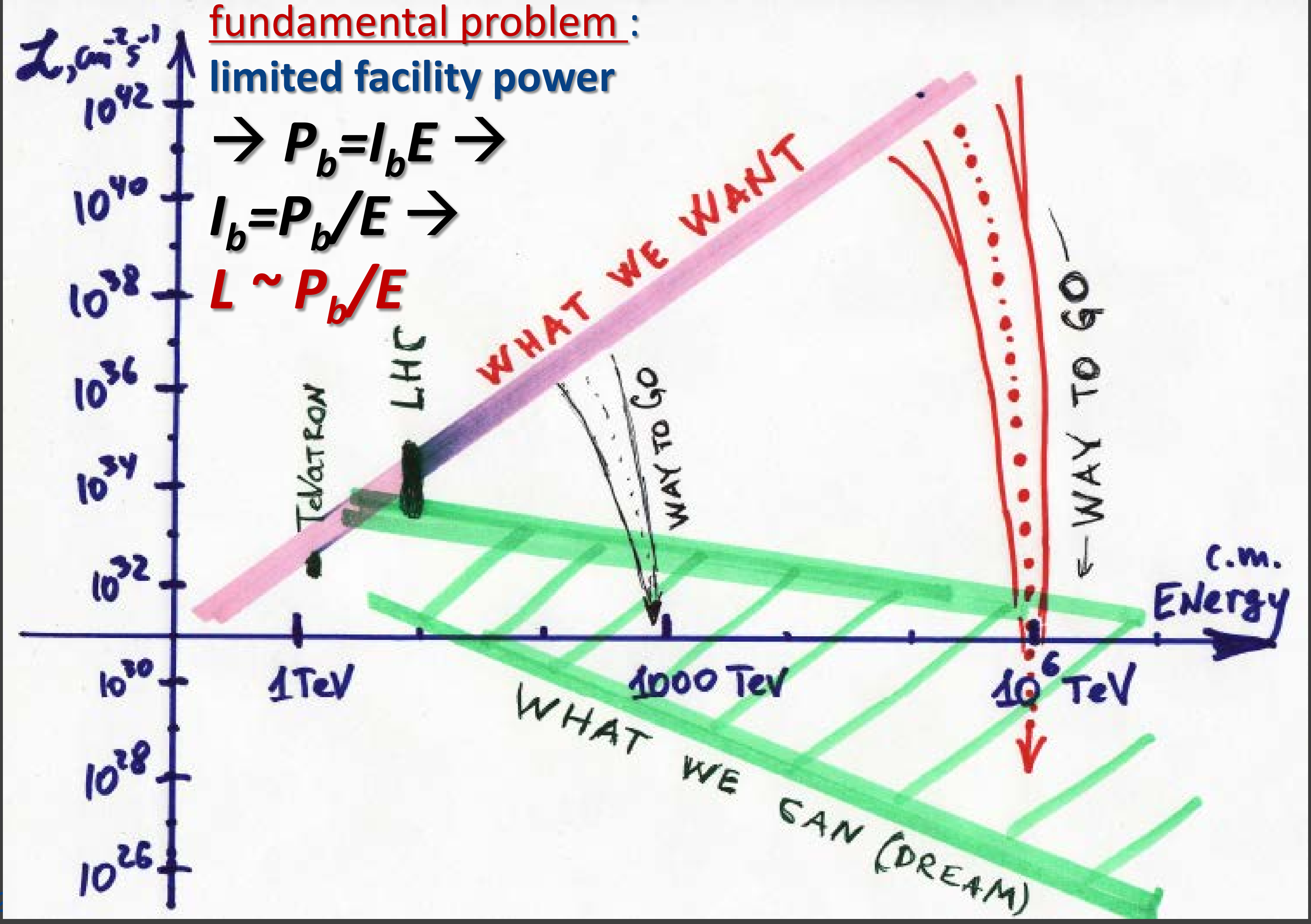
fundamental problem :

limited facility power

→ $P_b = I_b E$ →

$I_b = P_b / E$ →

$L \sim P_b / E$



HEP's "Far" (or "Far-Far") Future

- **Good News**
  - options **EXIST**
    - 300-1000 TeV muons in plasma/crystals
- **Bad News**
  - It will be

High

Energy

Low

Luminosity

Conclusions (1)

PAST AND PRESENT LESSONS

- Success of Colliders : 29 built over 50 yrs, *O*(10) TeV c.m.e.
- The progress has greatly slowed down due to increasing size, complexity and cost of the facilities.
- Accelerator technologies of RF and magnets are well developed and costs understood (*αβγ* - model)

"NEAR" FUTURE DIRECTIONS (5-15 years)

- CepC, TLEP and ILC are not simple but "~feasible" in terms of energy, luminosity and possibly cost
- CepC seems to have "unfair competitive advantage" (cost)
- Start building the accelerator team NOW (~700-1000)
- Do not expect luminosity on *"Day 1"* (more like *"Year 4-5"*)

Conclusions (2)

FUTURE ENERGY FRONTIER COLLIDERS (15-30 years)

- **All have serious issues: 3 TeV CLIC** - with performance and cost, **6 TeV Muon Collider** - with performance, **70-100 TeV FCC/SppC** - with cost and performance
- Key R&D for **FCC/SppC** is to reduce the **cost of ~16-20 T** magnets by factor **~3-5** – it will take ~**2 decades** → start **NOW**
- Three regions are open for such collaboration

"FAR" FUTURE OUTLOOK (> 30 years)

- Not many options for **30-100 xLHC !!!**
- Actually, only: **linear acceleration of muons in dense plasma**
- In any case, that will be High Energy Low Luminosity facility (still ~10 orders of magnitude better than cosmics)

Thank You for Your Attention!