Crystal Ball: On the Future High Energy Colliders *

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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)
“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, v-Factory

Is it possible to parameterize the cost for known technologies?
## All are Different!

- **Parameters:**
  - energy $E$
  - size/length $L$
  - power $P$

- **Currencies**

- **Years**

- **Technologies**

- **Accounting**

### Raw Data: look confusing

| SSC | 11.8 B$ \text{ (1993)}$ | 40 | SC Mag | Estimates changed many times $[6–8]$ | 87 | $\sim 100$ | 19–25 |
| FNAL MI | 260 MS (1994) | 0.12 | NC Mag | “old rules”, no OH, existing injector $[9]$ | 3.3 | $\sim 20$ | 0.4–0.54 |
| RHIC | 660 MS (1999) | 0.5 | SC Mag | Tunnel, some infrastructure, injector re-used $[10]$ | 3.8 | $\sim 40$ | 0.8–1.2 |
| VLHC-I | 4.1 B$ \text{ (2001)}$ | 40 | SC Mag | “European accounting”, existing injector $[12]$ | 233 | $\sim 60$ | 10–18 |
| NLC | $\sim 7.5$ B$ \text{ (2001)}$ | 1 | NC RF | $\sim 6$ B$ \text{ for 0.5 TeV collider, } [13]$ | 30 | 250 | 9–15 |
| SNS | 1.4 B$ \text{ (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 | $\sim 40$ | 7–11 |
| CLIC | 7.4–8.3 B CHF (2012) | 0.5 | NC RF | “European accounting” $[16]$ | 18 | 250 | 12–18 |
| Project X | 1.5 B$ \text{ (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 | $\sim 10$ | 2.9–4.0 |
| NuFactory | 4.7–6.5 B€ (2012) | 0.012 | NC RF | Mixed accounting, w. contingency $[19]$ | 6 | $\sim 90$ | 7–11 |
| Beta-Beam | 1.4–2.3 B€ (2012) | 0.1 | SC RF | Mixed accounting, w. contingency $[19]$ | 9.5 | $\sim 30$ | 3.7–5.4 |
| SPL | 1.2–1.6 B€ (2012) | 0.005 | SC RF | Mixed accounting, w. contingency $[19]$ | 0.6 | $\sim 70$ | 2.6–4.6 |
| FAIR | 1.2 B€ (2012) | 0.003–0.8 | SC Mag | “European accounting” $[20]$, 6 rings, existing injector | $\sim 3$ | $\sim 30$ | 1.8–3.0 |
| ILC | 7.8 BS (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 |
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 $\rightarrow$ 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$\equiv$TPC** (unitarity condition)
Our Key “Feasible” Technologies

Normal Conducting Magnets

NCRF

SC RF

SC magnets
Phenomenological Cost Model

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

where \( \alpha, \beta, \gamma \) — technology dependent constants

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

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

Comment:

Fig. 9.5. Variation of costs of power plant versus its capacity.
Total Cost vs Model (Log-Log)

The $\alpha \beta \gamma$-model is good to +/-30%
### Part II: “Near” Future Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Country</th>
<th>$E_{cm}$ (TeV)</th>
<th>$L$ (km)</th>
<th>$P$ (MW)</th>
<th>$\alpha\beta\gamma$-TPC</th>
<th>Cost Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCCee</td>
<td>CERN</td>
<td>0.25</td>
<td>100</td>
<td>300</td>
<td>10.9 ± 3</td>
<td><strong>No Doubt!</strong></td>
</tr>
<tr>
<td>CepC</td>
<td>China</td>
<td>0.25</td>
<td>55</td>
<td>500</td>
<td>10.2 ± 3</td>
<td><strong>No Doubt!</strong></td>
</tr>
<tr>
<td>ILC</td>
<td>Japan</td>
<td>0.5</td>
<td>36</td>
<td>163</td>
<td>13.1 ± 4 *</td>
<td><strong>No Doubt!</strong></td>
</tr>
</tbody>
</table>

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

**Energy Feasibility – No Doubt!**

**Cost Feasibility – ?? TBD ??**
Feasibility of Performance

Luminosities: \( \sim (2-5) \times 10^{34} / \text{IP} \)

- feasible, but there are issues

- Luminosity vs SRF power - trade off \( P = I \Delta E_{\text{pass}} \)
  (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 inflation, convert to USD and scale to $\sqrt{1 \text{ km}}$:

$350 \text{ M}$
$772 \text{ M}$
$1040 \text{ M}$
$1024 \text{ M}$
### Part III: Future Colliders

<table>
<thead>
<tr>
<th></th>
<th>$E_{cm}$ (TeV)</th>
<th>$L$ (km)</th>
<th>$P$ (MW)</th>
<th>$\alpha\beta\gamma$-TPC (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CLIC</strong></td>
<td>3</td>
<td>60</td>
<td>589</td>
<td>$27.0 \pm 8$</td>
</tr>
<tr>
<td><strong>Muon C. US?</strong></td>
<td>6</td>
<td>20</td>
<td>230</td>
<td>$14.4 \pm 5$</td>
</tr>
<tr>
<td><strong>FCC$_{pp}$</strong></td>
<td>100</td>
<td>100</td>
<td>400</td>
<td>$30.3 \pm 9$</td>
</tr>
<tr>
<td><strong>SppC</strong></td>
<td>50+</td>
<td>54</td>
<td>300</td>
<td>$25.5 \pm 9$</td>
</tr>
</tbody>
</table>

**Cost Feasibility** – ?? probably not ??

...if tunnel/injector exist ...Muon Collider cheapest
Feasibility of Energy

CLIC | NC RF | tough
---|---|---
Muon C. | SCMag | no doubt
FCC | HF-SCMag | not (now)
SppC | HF-SCMag | not (now)

100 MV/m @ 1e-7 spark

16-20 T magnets for >70 TeV
100 TeV $pp$: Qualitative Cost Dependencies

- Base cost parameters set
- Tunnel 5 times cheaper
- Magnets 5 times cheaper

Total Project Cost (arb units) vs. Dipole field $B$ (arb units)

* For illustration purposes only.
Feasibility of Performance

- **CLIC**: $e^+e^- \sim 5 \times 10^{34}$
  - very tough **

- **Muon Coll**: $\mu^+\mu^- \sim 2 \times 10^{34}$
  - impossible now ***

- **FCC/SppC**: $pp \sim 5 \times 10^{34}$
  - very tough **

(each * is about 1 order of magnitude)
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)

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 \((20-100 \times LHC)\)
  - “decent luminosity” (TBD)

• Surely we know:
  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 \(\rightarrow\) LINEAR
  2. Electrons radiate 100% beam-strahlung (<3 TeV) and in focusing channel (<10 TeV) \(\rightarrow\) \(\mu+\mu-\) or pp
“Phase-Space” is Further Limited

• “Live within our means”: for $20-100 \times LHC$
  - $< 10 \text{ B}$
  - $< 10 \text{ km}$
  - $< 10 \text{ MW (beam power, ~100MW total)}$

→ New technology should provide $>30 \text{ GeV/m}$ @

- total component cost $< 1M$/m (~NC magnets now)
- SC magnets equiv. ~ 0.5 GeV per meter (LHC)

3. Only one option for $>30 \text{ GeV/m}$ known now: dense plasma → that excludes protons → only muons
Plasma Waves


Plasma wave: electron density perturbation

Laser/beam pulse \( \sim \lambda_p/c \)

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

**Option A:**
Short intense e-/e+/p bunch
Few \(10^{16}\text{cm}^{-3}, 6\text{ GV/m over 0.3m}\)

**Option B:**
Short intense laser pulse
\(\sim10^{18}\text{cm}^{-3}, 50\text{ GV/m over 0.1m}\)

First looks into “Plasma-Collider”: **staging kills!** \(<E>\sim2\text{ GV/m,}\)
Option C: Crystals & Muons

\[ n \approx 10^{22} \text{ cm}^{-3}, \quad 10 \text{ TeV/m} \Rightarrow \]

\[ E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[ \frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 \left[ 10^{18} \text{ cm}^{-3} \right]} \text{ PeV} = 1000 \text{ TeV} \]

\[ n_\mu \approx 1000 \quad n_\beta \approx 100 \quad f_{\text{rep}} \approx 10^6 \quad L \approx 10^{30-32} \]

Paradigm Shift: Energy vs Luminosity

fundamental problem: limited facility power

\[ P_b = I_b E \]

\[ I_b = \frac{P_b}{E} \]

\[ L \sim \frac{P_b}{E} \]
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 ($\alpha\beta\gamma$ - 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!