Fast Acceleration of Muons:

RCS as accelerator and as collider ring, HTS magnet R&D

Vladimir SHILTSEV (Fermilab)

Muon Collider – EPPSU Preparatory Meeting, CERN

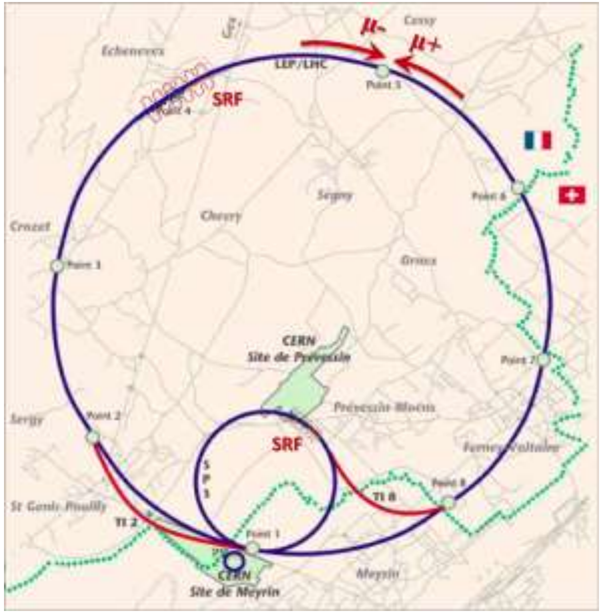
11 April 2019

Muon Collider : Where's the cost hidden?

- ee linear
  - ILC
  - CLIC
- ee circular
  - LEP3
  - FCC-ee
  - CepC
  - HF-FNAL

Cost Considerations : eg 14 TeV

- reuse the existing 27 km LHC tunnel, the 7 km SPS tunnel and most of CERN infrastructure.
- Beyond that – only very rough estimates (so called "*αβγ*-law")



$$Total\ Project\ Cost \approx \alpha \times (Length/10km)^{1/2} + \beta \times (Energy/TeV)^{1/2} + \gamma \times (Power/100MW)^{1/2}$$

- the incremental cost : "PS" configuration 2B\$ × sqrt(14TeV of SC magnets) +10 B\$× sqrt(0.02TeV of SRF)=8.9±3 B\$.
- "MAP" configuration : extra ~10B\$×sqrt(0.008 TeV of SRF)+ 2B\$×sqrt(0.2 for 20 MW)=1.8±0.6 B\$.
- "LEMC" configuration : extra ~1B\$×sqrt(0.045 TeV e+ ring)+ 10B\$×sqrt(0.001 TeV SRF) + 2B\$× sqrt(2.5 250 MW power)=3.6 ± 1.2 B\$

On the feasibility of a pulsed 14 TeV c.m.e. muon collider in the LHC tunnel
D. Neuffer and V. Shiltsev 2018 *JINST* **13** T10003

! 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 !** (~ 2-2.5 × *European Accounting*)

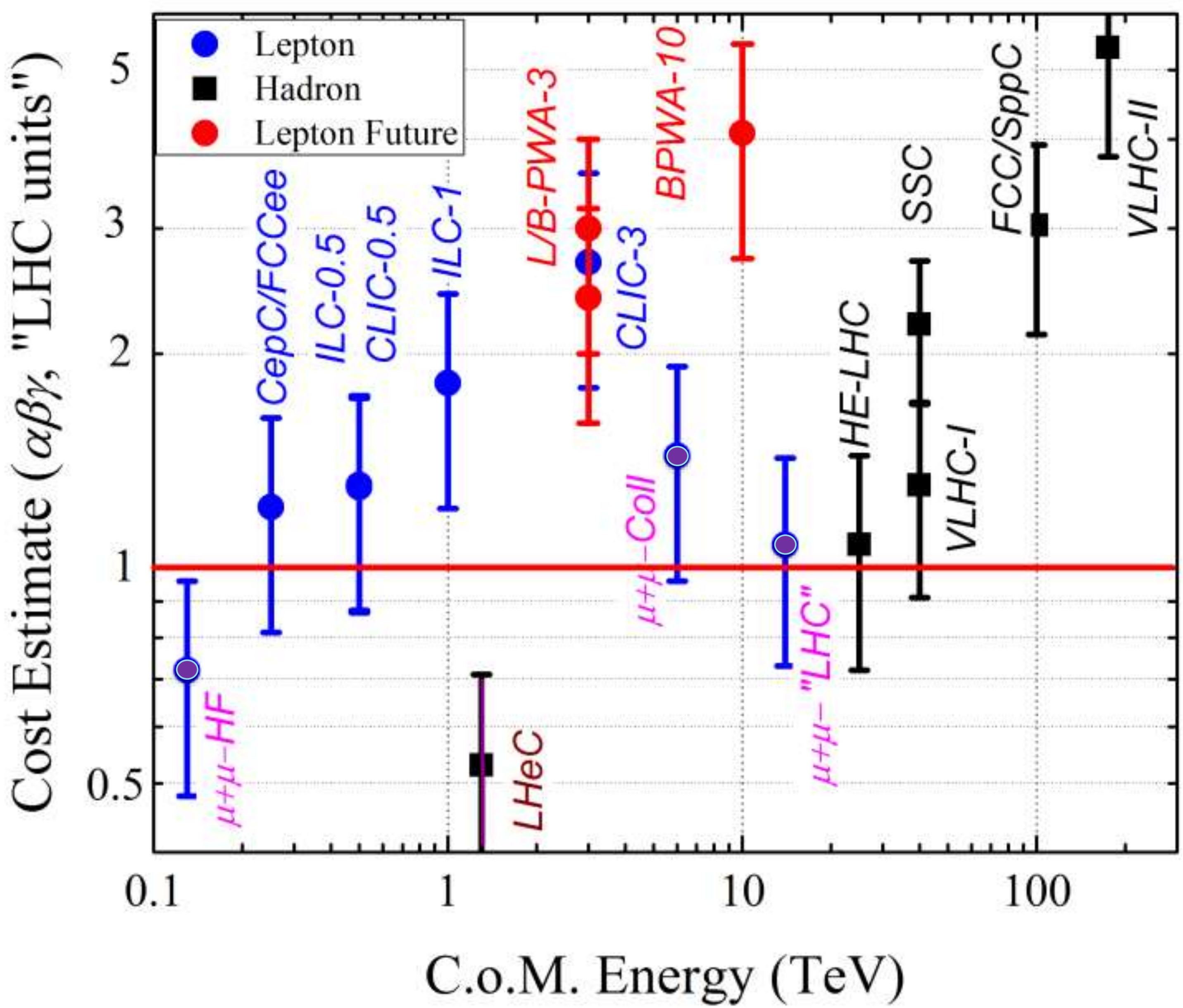
c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **$\alpha \approx$ 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!

V. Shiltsev, *A Phenomenological Cost Model for High Energy Particle Accelerators*, 2014 *JINST* 9 T07002 [arXiv:1404.4097].

Energy Frontier Colliders in "LHC Units" (~10B$ TPC)



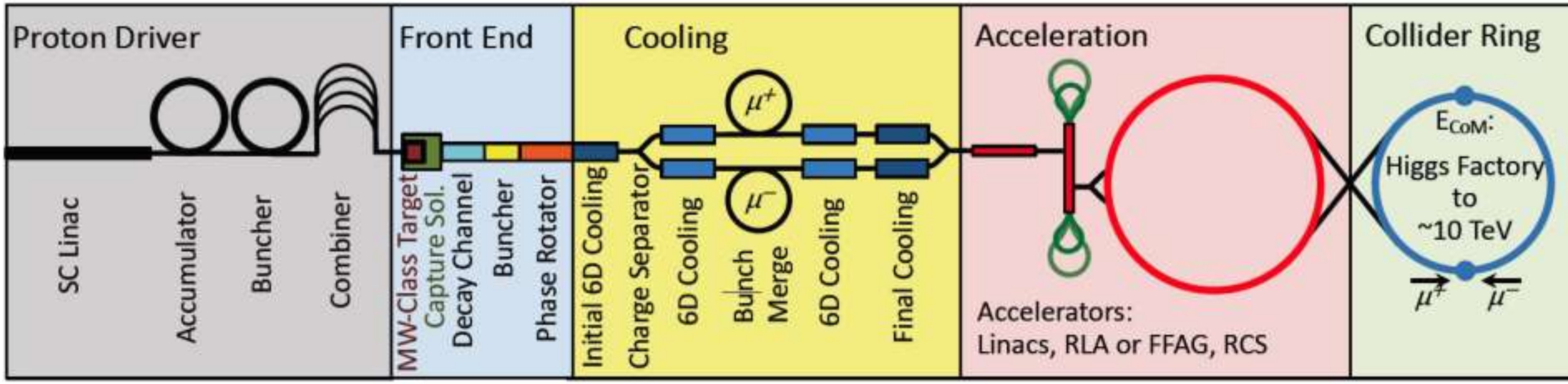
Muon Collider : Where's the Cost Hidden?

pp →π+π- → μ+μ-

μ+μ- captured, bunched and cooled

Acceleration to collision energy

Collision



4-8 GeV, 4 MW proton driver

Some 4 GeV of NC RF and ~100 m 4T SC solenoids + few 20T ones

~14-60+ GeV SRF in 2 RLAs (1 – 6+ km)

3-14 TeV SC magnets, 6-27 km

10-15% for new 4 MW
"0" if 0.4-1 MW is enough

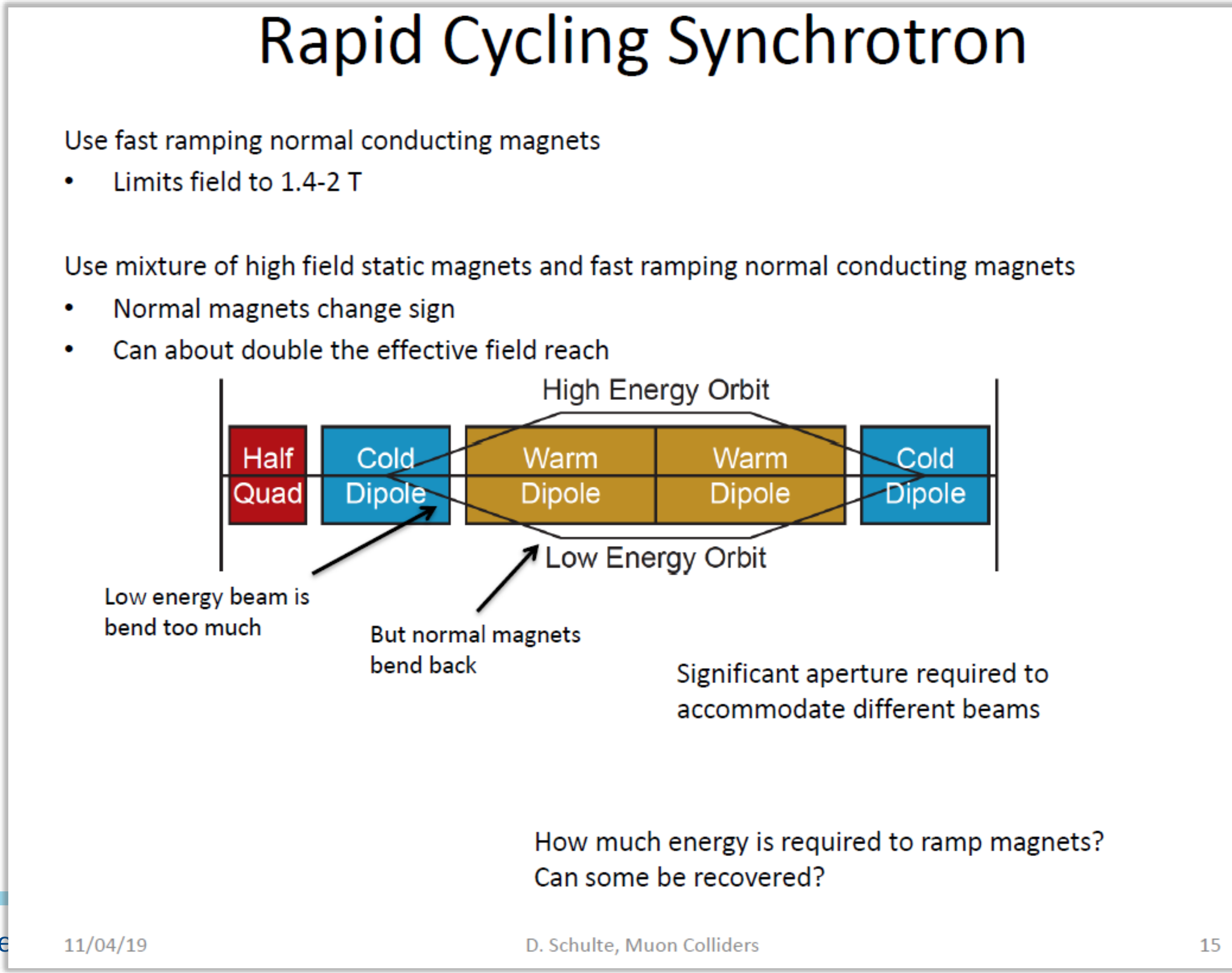
7-15%
1/2 RF
½ SCM

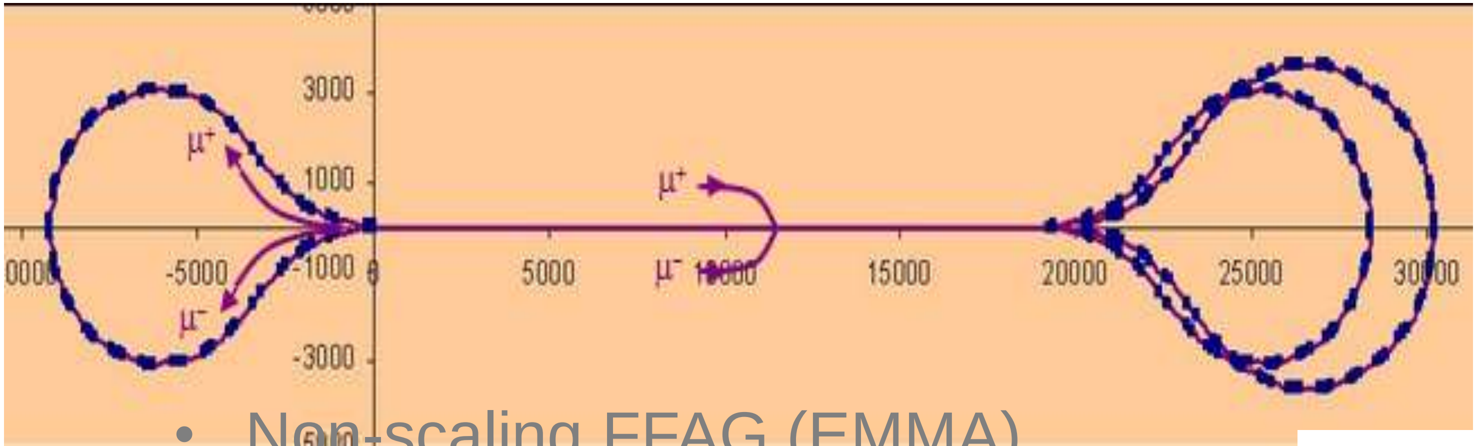
35-50%
1/3 SRF
1/3 Civil
1/3 Infrastr

40-50%
2/3 SCM
1/3 Civil

What can be used to save big?

- RF is ~5-10 x more expensive than SC – NC magnets
- Minimize RF → eg (from Daniel's talk)



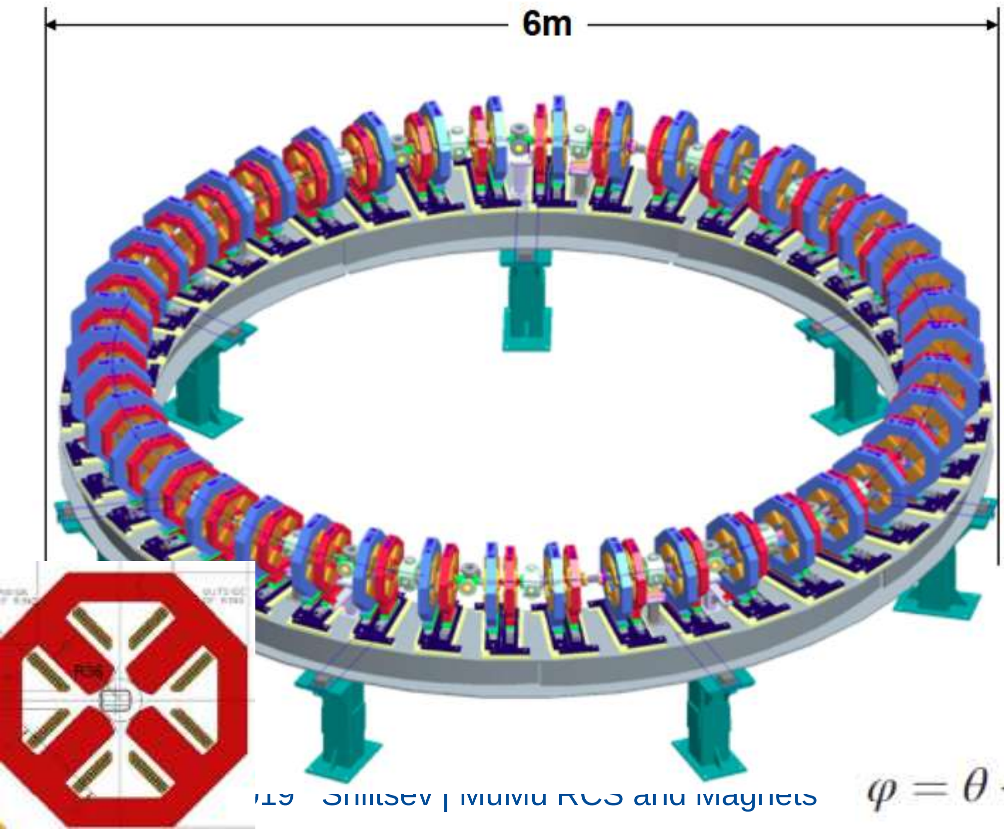


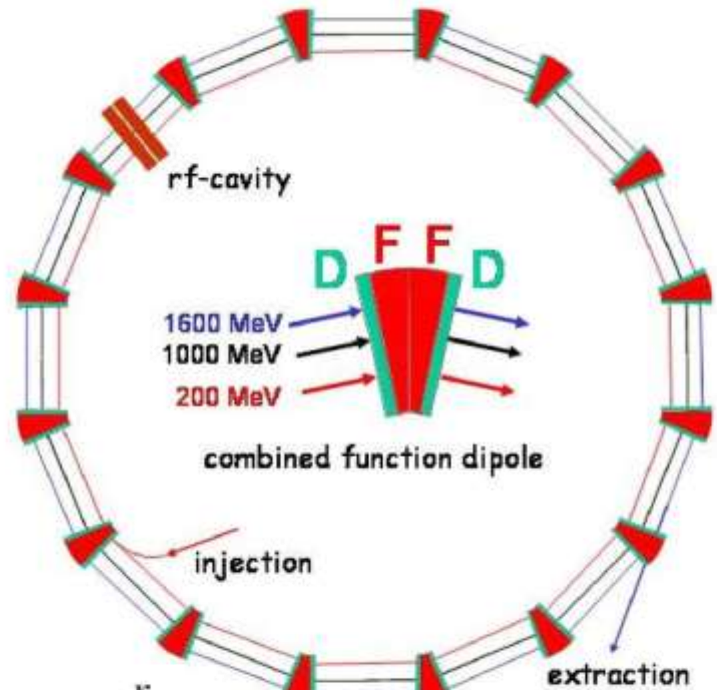
Recirculating Linear Accelerator (RLA)

- Non-scaling FFAG (EMMA)

Alternatives

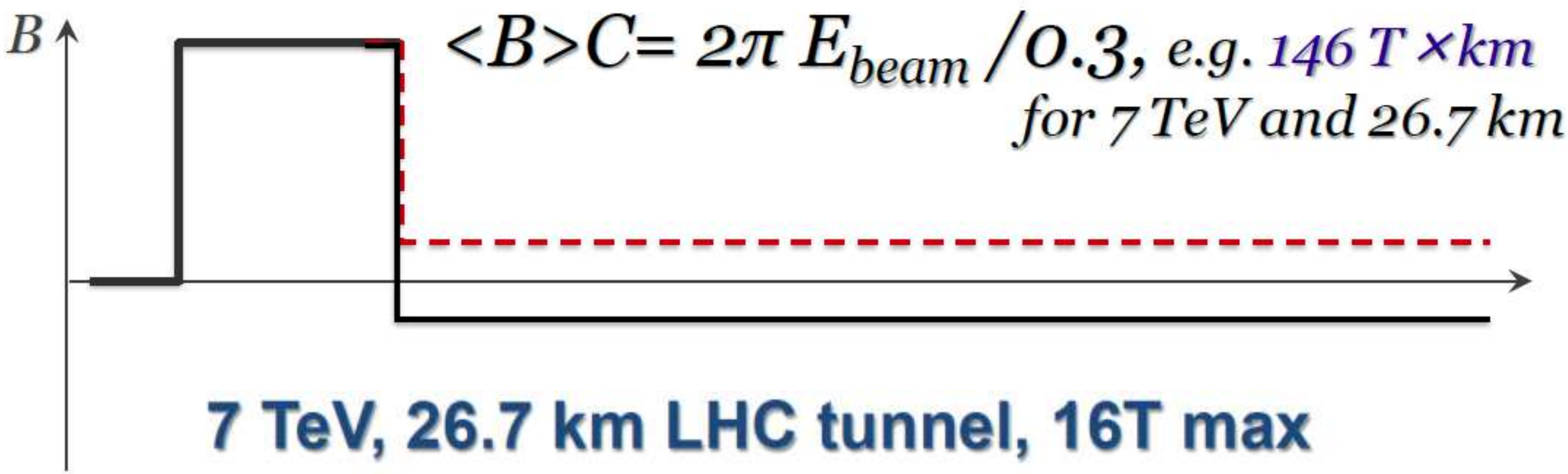
$$B_z(r,\theta) = B_{z0}\left(\frac{r}{r_0}\right)^k F(\varphi)$$





$$\varphi = \theta - \tan\delta \ln\frac{r}{r_0}$$

Acceleration: (1) pulsed magnets



7 TeV, 26.7 km LHC 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

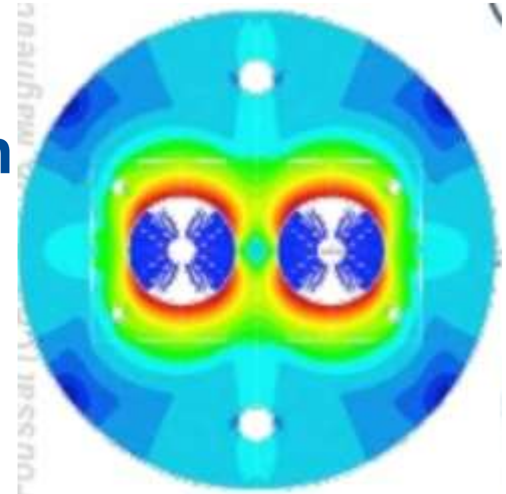
Table 1: Muon RCS accelerator parameters.

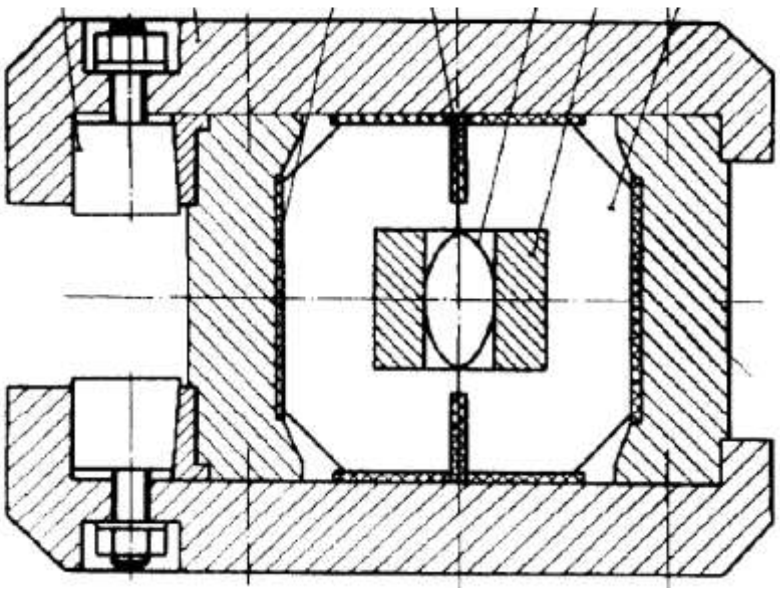
	“LHC-S”	“LHC-D”		“SPS”
C, km	26.7	26.7	26.7	6.9
E_{max}, TeV	7	7	4	0.45
E_{inj}, TeV	0.45	4	0.45	0.03
f_{rep}, Hz	5	4	4	20
ΔE/turn, GeV	14.0	3.5	9.2	3.7
B_{SC}, T	16	16	16	8
L_{SC}, km	4.8	7.1	2.9	0.63
B_{pls}, T	3.8	2.0	1.9	0.8
τ_{ramp}, ms	42	76	34	2.6
dB_{pls}/dt, T/s	180	52	112	615

Magnets:

- **DC – SC**
- **Pulsed – NC or SC**

FCC 16T Nb3Sn Dipole

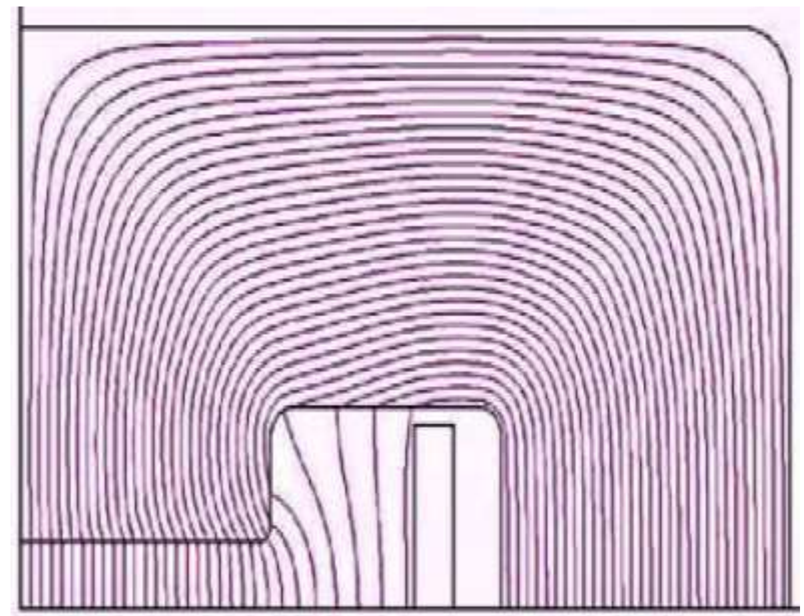




G.C. Willevald, V.N. Karasyuk, G.I. Silvestrov, T.V. Sokolova ИЯФ 2006-5

ts

5T, 2.8ms, 5Hz, 186kA, $2\cdot10^6$ pulses



Henryk Piekarz VOL. 24, NO. 3, JUNE 2014

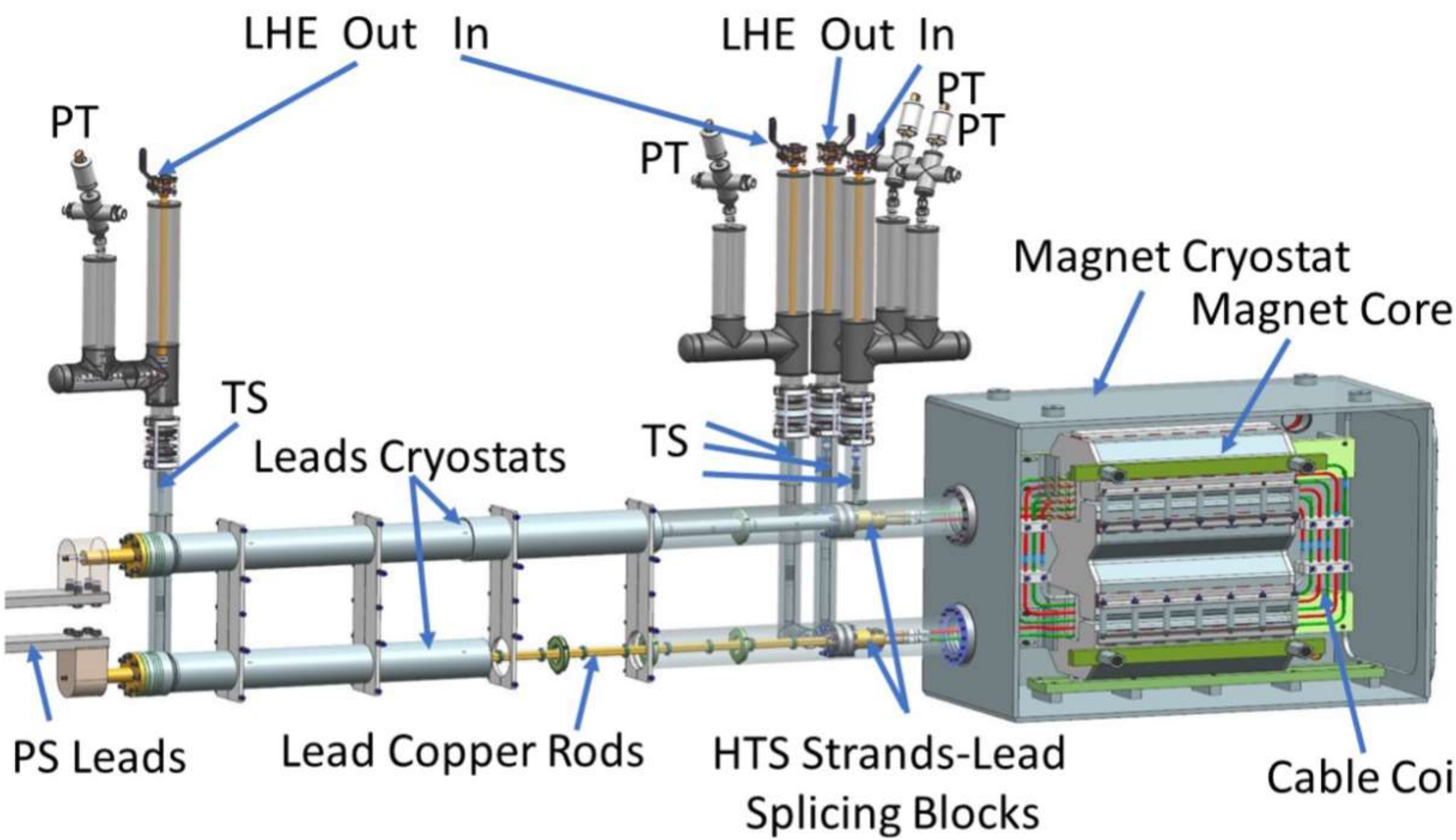
HTS 1.75T, ~1000T/s, 25kA

Record fast-cycling accelerator magnet based on high temperature superconductors

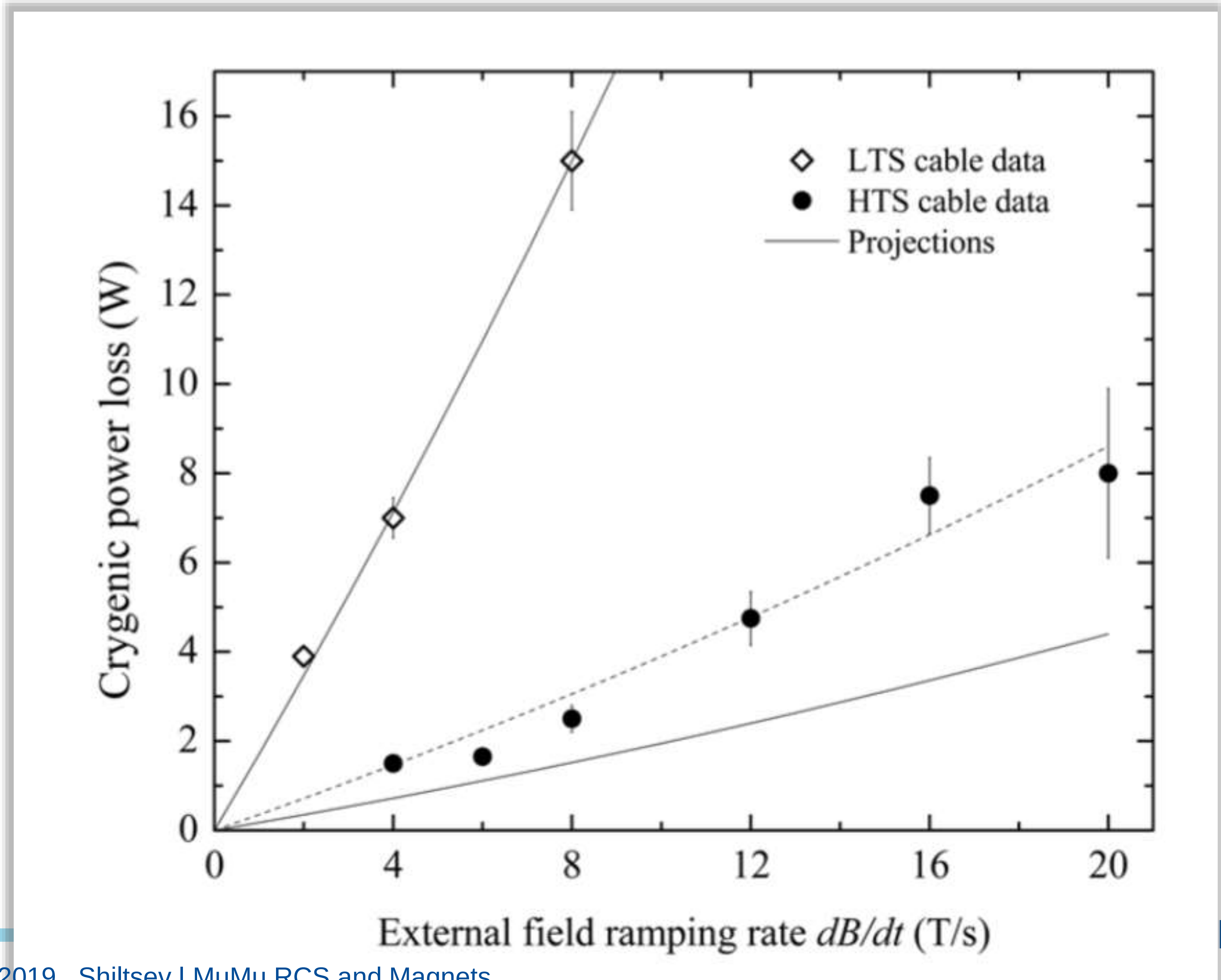
Henryk Piekarz, Steven Hays, Jamie Blowers, Bradley Claypool, Vladimir Shiltsev

(Submitted on 9 Mar 2019)

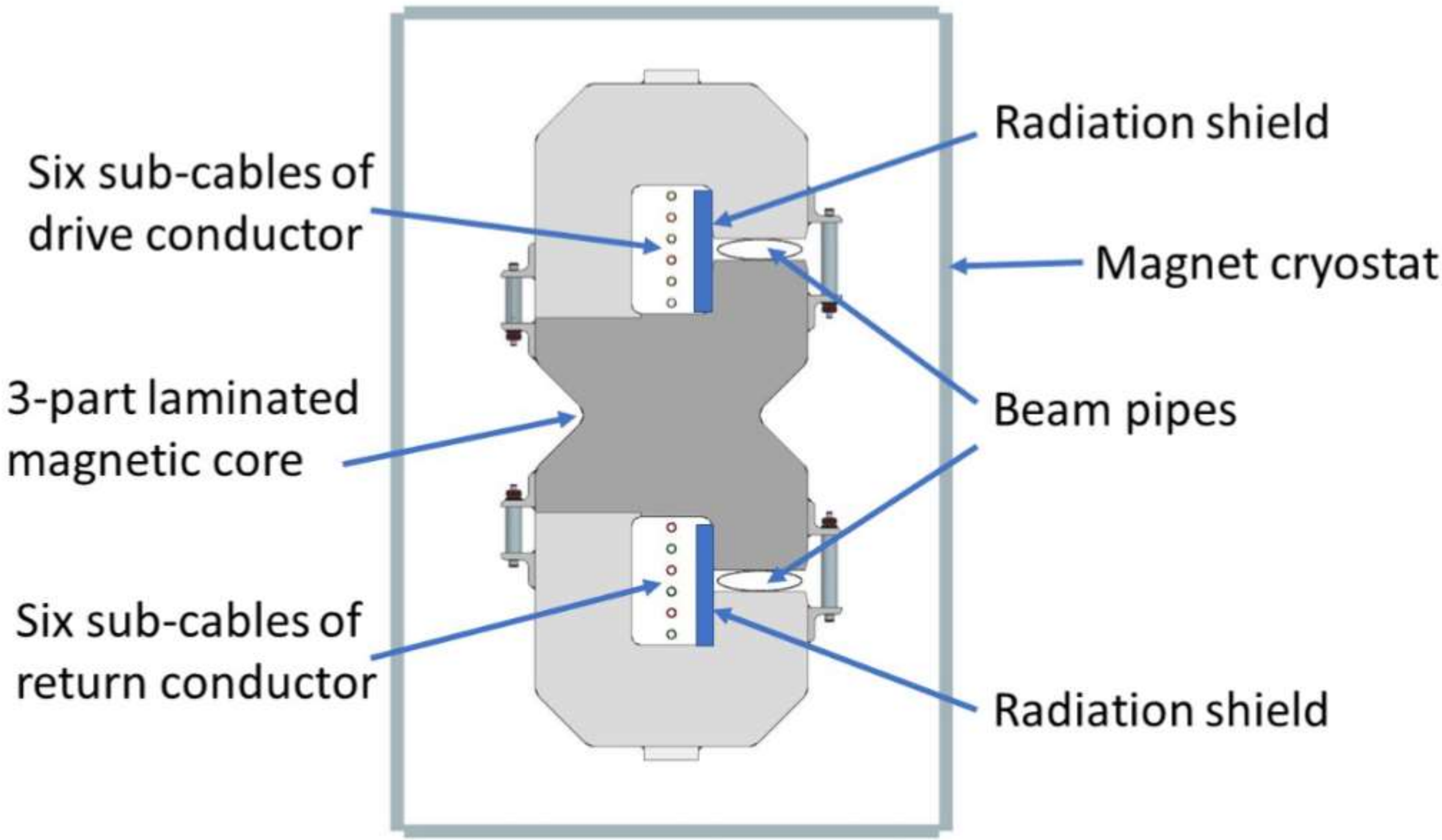
arXiv:1903.03853



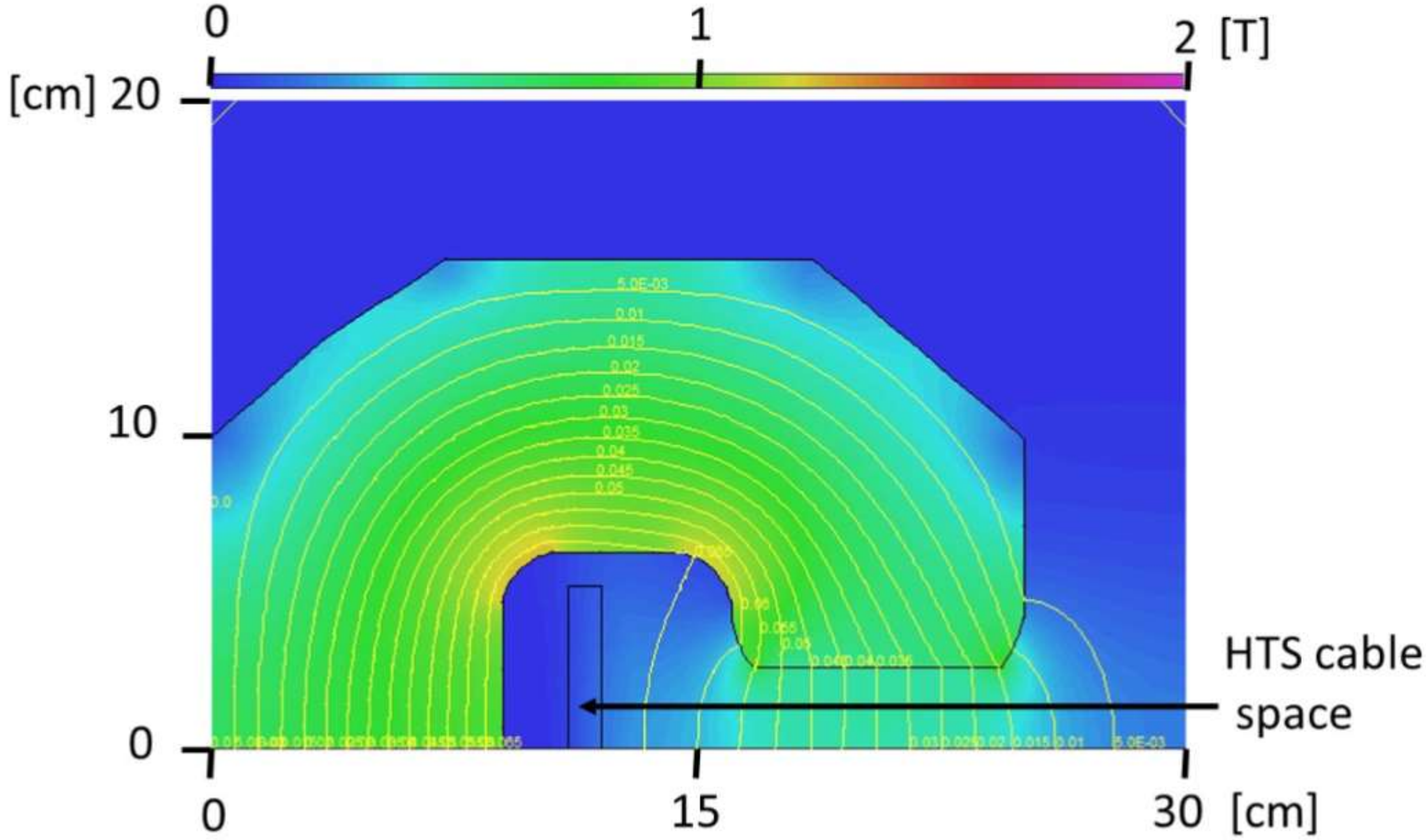
HTS Conductor has Small AC Losses (~ 1/5 – 1/10 LTS) + Operates at Higher T (30-60 K vs 2-4 K)



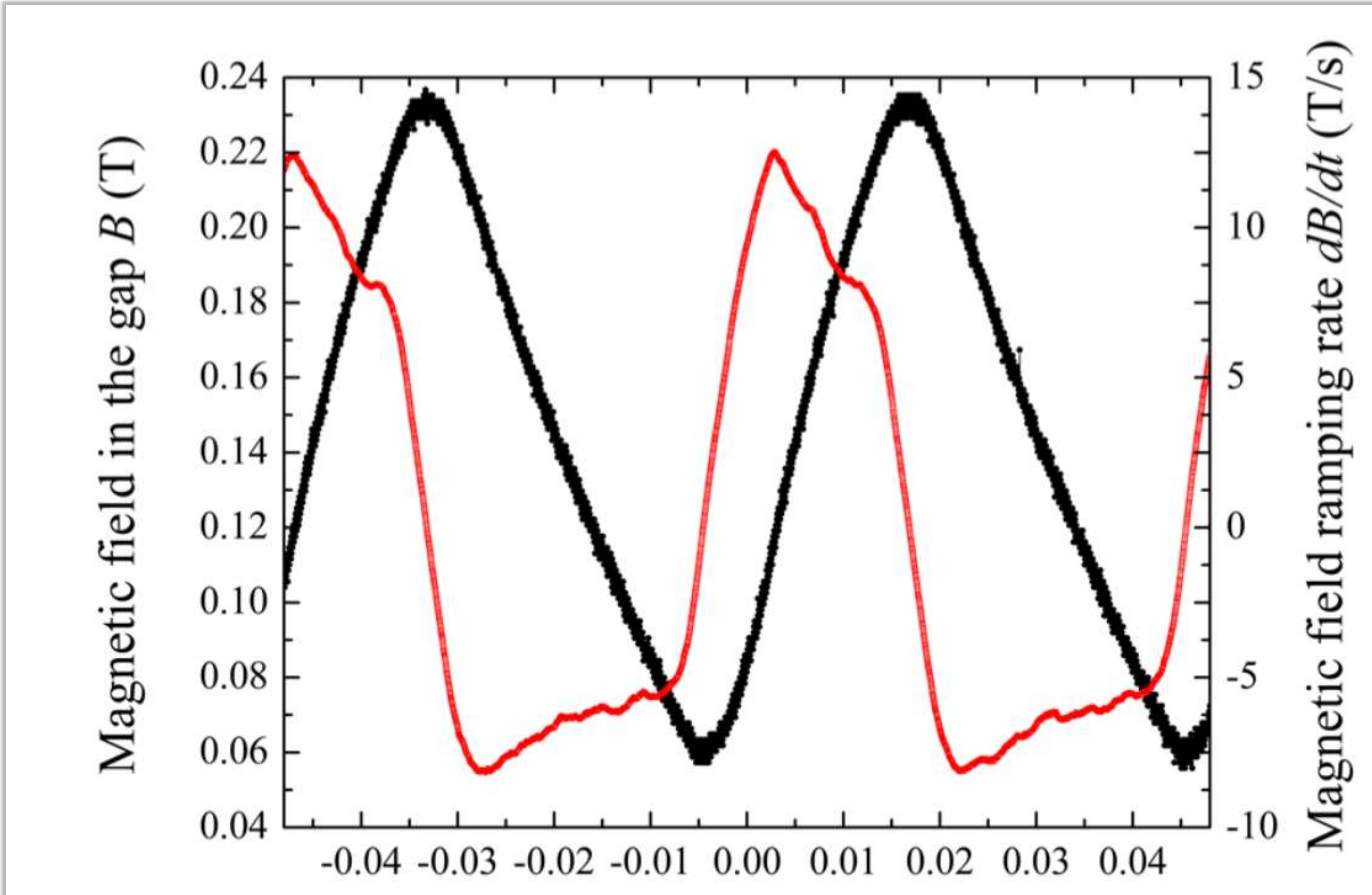
(Accelerator) Double-Bore HTS Magnet



Dipole filed in the gap (1/4 shown)



The result : PS limited (1.5V max) – 12 T/s, 2.4kG



Next: Upgrade Power Supply – 100-200 T/s, ~2 T max

Summary

- Muon Colliders do have cost advantages
  - $$ total construction cost
  - $$ / TeV
  - $$ / ab^{-1}
  - Operations
- Each MC option requires cost optimization
  - Higgs Factory, 3 TeV, 6 TeV, 14 TeV “LHC”, MAP/LEMC
- Acceleration system is great part of the cost
  - RCS might be very cost efficient
  - Initial R&D success indicate record high 12 T/s with HTS magnets (need 5-100) but needs further effort
- Should be part of the *EuroMAP*

Thank You for Your Attention!

Discussion : "Granada Message"

1. despite ups and downs over the past 20 years, the mumu concept is not going away and the reasons are [...]
2. μμ offers a "moderately conservative-moderately innovative" way to cost affordable energy frontier colliders
3. major advantages/promises are [...]
4. key challenges are [...]
5. to claim feasibility (CDR-level) in, say, 5(10?) years we need [....R&D program goals ....]

Luminosity and Cooling

- Option "PS": use existing proton source 24 GeV, 8 bunches $6 \cdot 10^{12}$ protons at 1.2Hz → on target → ionization cooling of muons
- Option "MAP" : build dedicated 8 GeV proton source $2 \cdot 10^{14}$ p/pulse at 5Hz → on target → ionization cooling of muons
- Option "Low Emittance" :~45 GeV 6.3km circumference e+ storage ring → 0.3mm Be target → ~10^{-7} muon pairs per e^+ bunch (100 bunches of 3×10^{11} e^+) → 63m 22 GeV μ rings accumulate μ's for ~ 2500 turns, obtaining bunches of ~4.5×10^7 μ's at ~2200Hz (10^{11} μ/s) → fast RLA

BACK-UP SLIDES

Table 2: Options for a 14 TeV μ^+-μ^- collider.

Parameter	"PS"	"MAP"	"LEMC"
Avg. luminosity	$1.2 \cdot 10^{33}$	$3.3 \cdot 10^{35}$	$2.4 \cdot 10^{32}$
Beam $\delta E/E$	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2 \cdot 10^{11}$	$2 \cdot 10^{12}$	4.5×10^7
n_b	1	1	1
$\varepsilon_{t,N}$ mm-mrad	25	25	0.04
β^*, mm	1	1	0.2
σ^*(IR), µm	0.6	0.6	0.011
Bunch length, mm	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$6 \cdot 10^{12}$	$2 \cdot 10^{14}$	$3 \cdot 10^{13}$
Driver beam power	0.17MW	1.6MW	40 MW
Acceleration, GeV	1-3.5, 3.5-7 RCS	1-3.5, 3.5-7 RCS	40 GV, RLA 20 turn
ν radiation, mSv/yr	0.08	1.5	0.015

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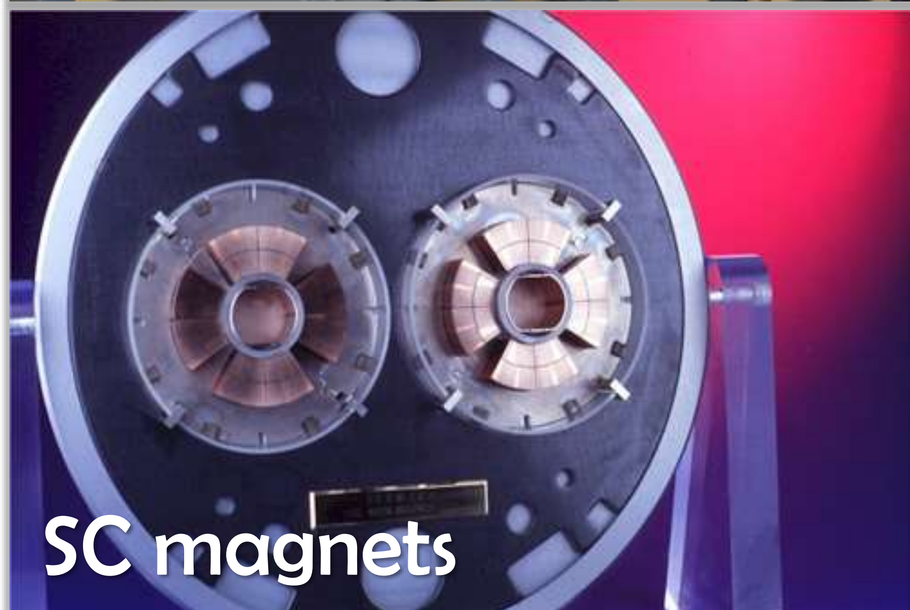
Neutrino Radiation

$$Dose \cong 0.57 \frac{N_{\mu}{}' E_{\mu}{}^{3}}{R_{x}{}^{2}} mSv / year$$

- $N_\mu{}'$ in 10^{13}/s, E_μ is in TeV and R_x is 36 km for a 100m depth
- All options are safe

Four "Proven" Technologies



… 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:

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

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

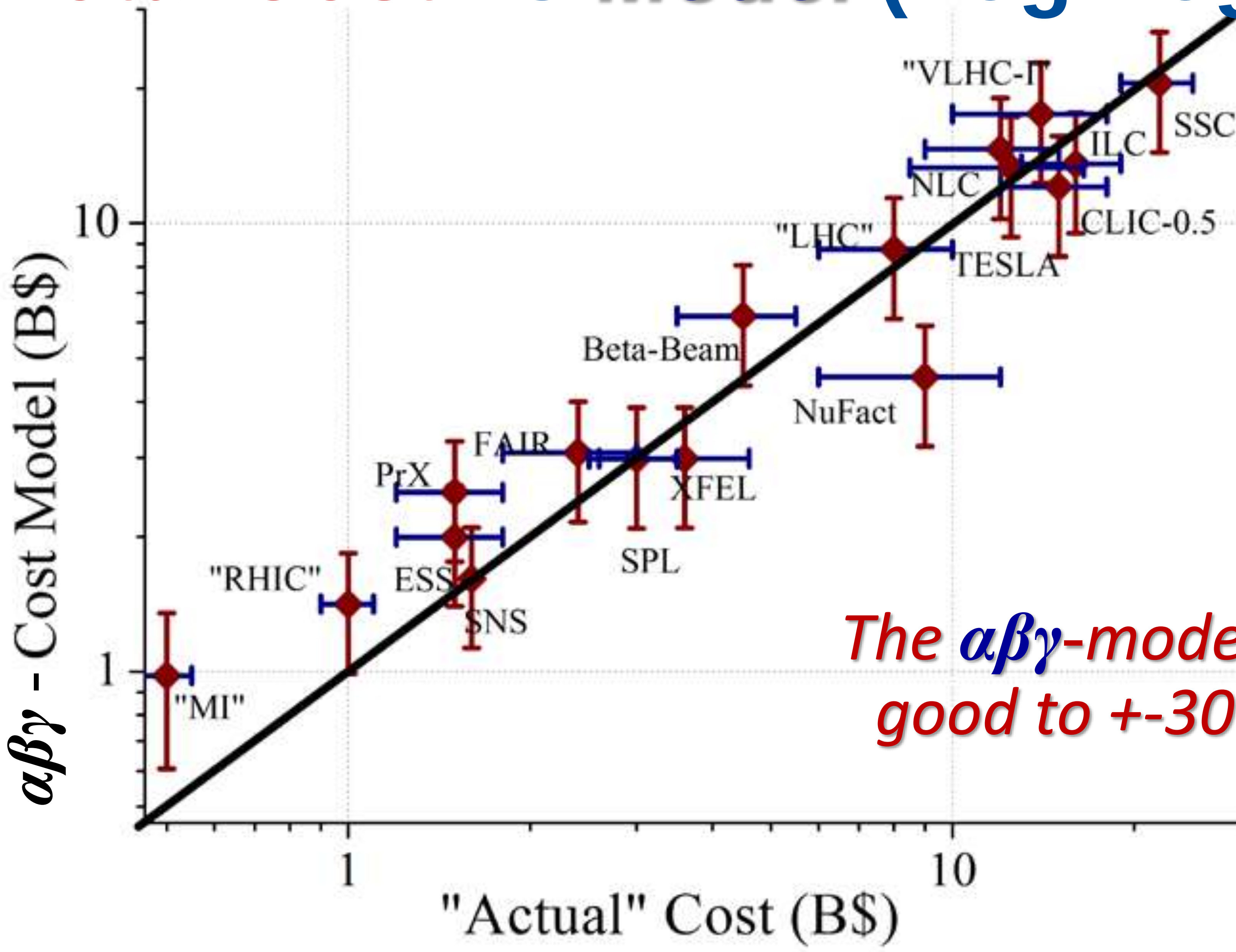
b) **"US-Accounting" = TPC !** (~ 2-2.5 × *European Accounting*)

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

- ***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)**

USE AT YOUR OWN RISK!

Total Cost vs *Model* (Log-Log)



The αβγ-model is good to +-30%