Accelerators in the 21st Century

Frank Zimmermann
Kolymbari, Crete,
28 August 2017

accelerator landscape in the 21st century

worldwide >30,000

particle accelerators:

- ☐ <1% basic research
- ☐ 5% applied research
- ☐ 35% medicine
- ☐ ~ 60% industry

Engines of discovery

1/3 of all physics Nobel prizes since 1939 linked to particle accelerators

Science tools

in Europe 18 synchrotron light sources and 8 FEL light sources; 2 neutron sources in operation (ISIS, SINQ), >3 more under construction (ESS,FRANZ,LENOS,…); more Nobel prizes “guaranteed”, great impact in all scientific domains

Medical accelerators

>14,000 accelerators for radiation therapy in hospitals worldwide,, >500 accelerators for isotope production, 19 particle cancer therapy centres in Europe

Industrial accelerators

Analysis and modification of surfaces with many areas of applications (ion implantation, treatment of polymers, sterilisation, environment, …

M. Vretenar

high energy particle accelerators

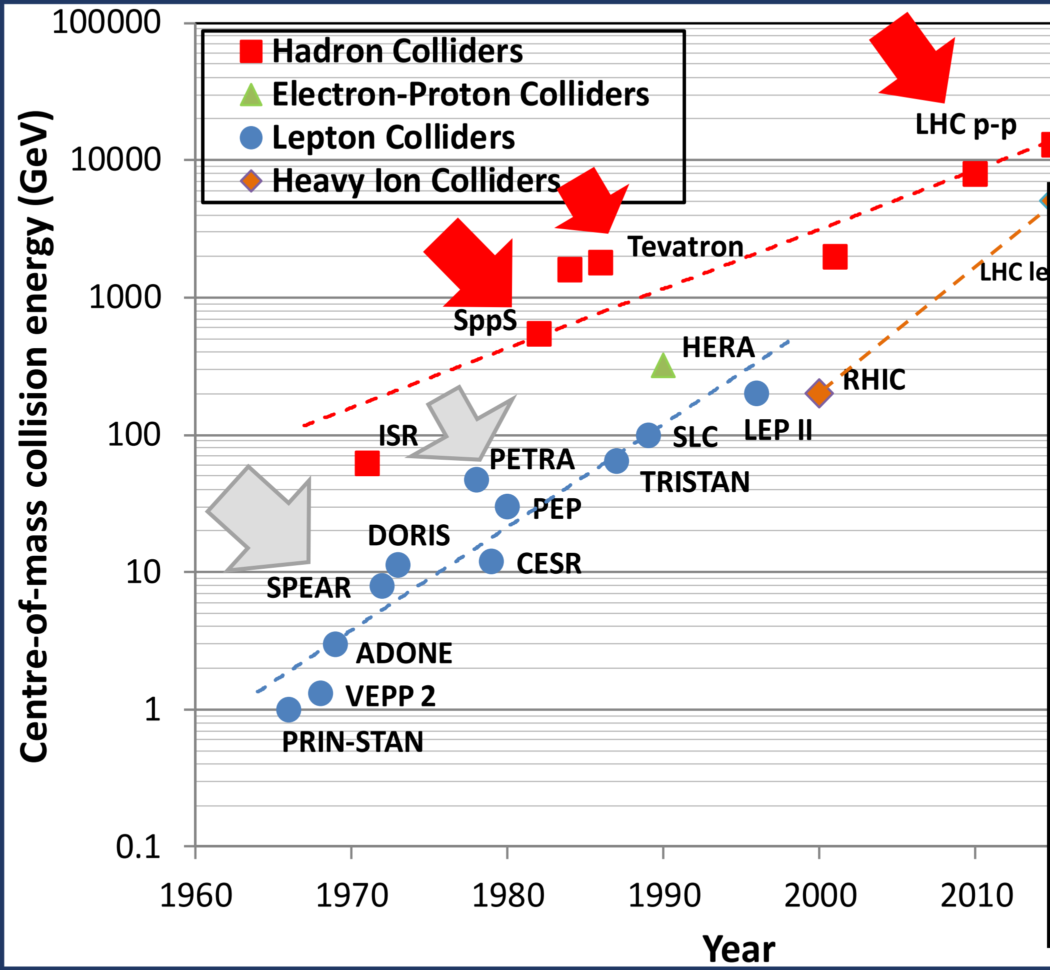
then ~1930

first cyclotron
E.O. Lawrence
11 cm diameter
1.1 MeV protons

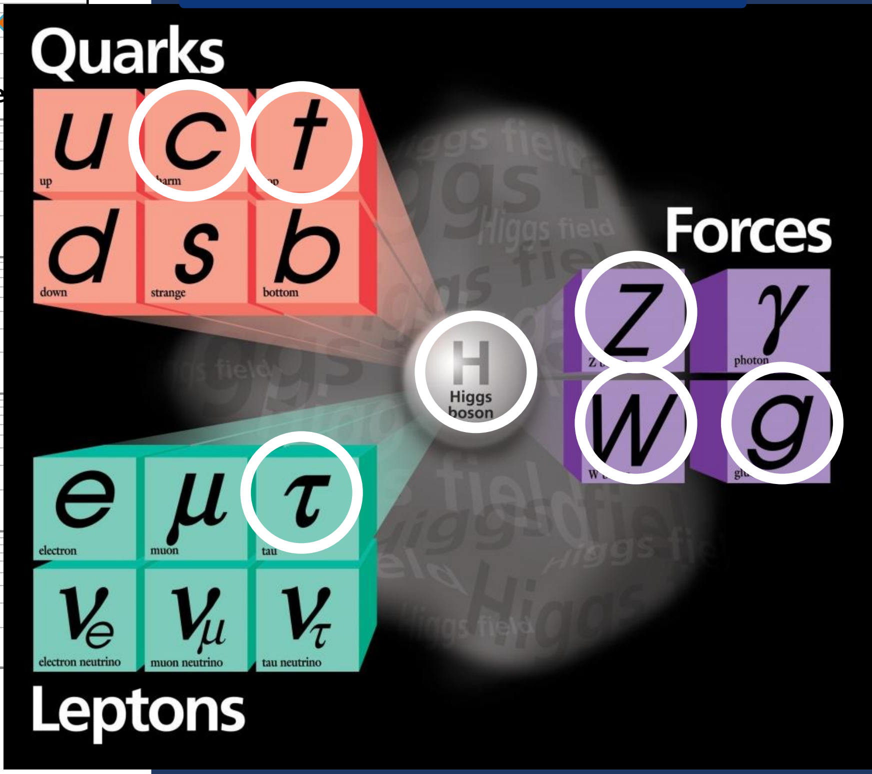
now ~2017

Large Hadron Collider
9 km diameter
7 TeV protons

colliders and discoveries



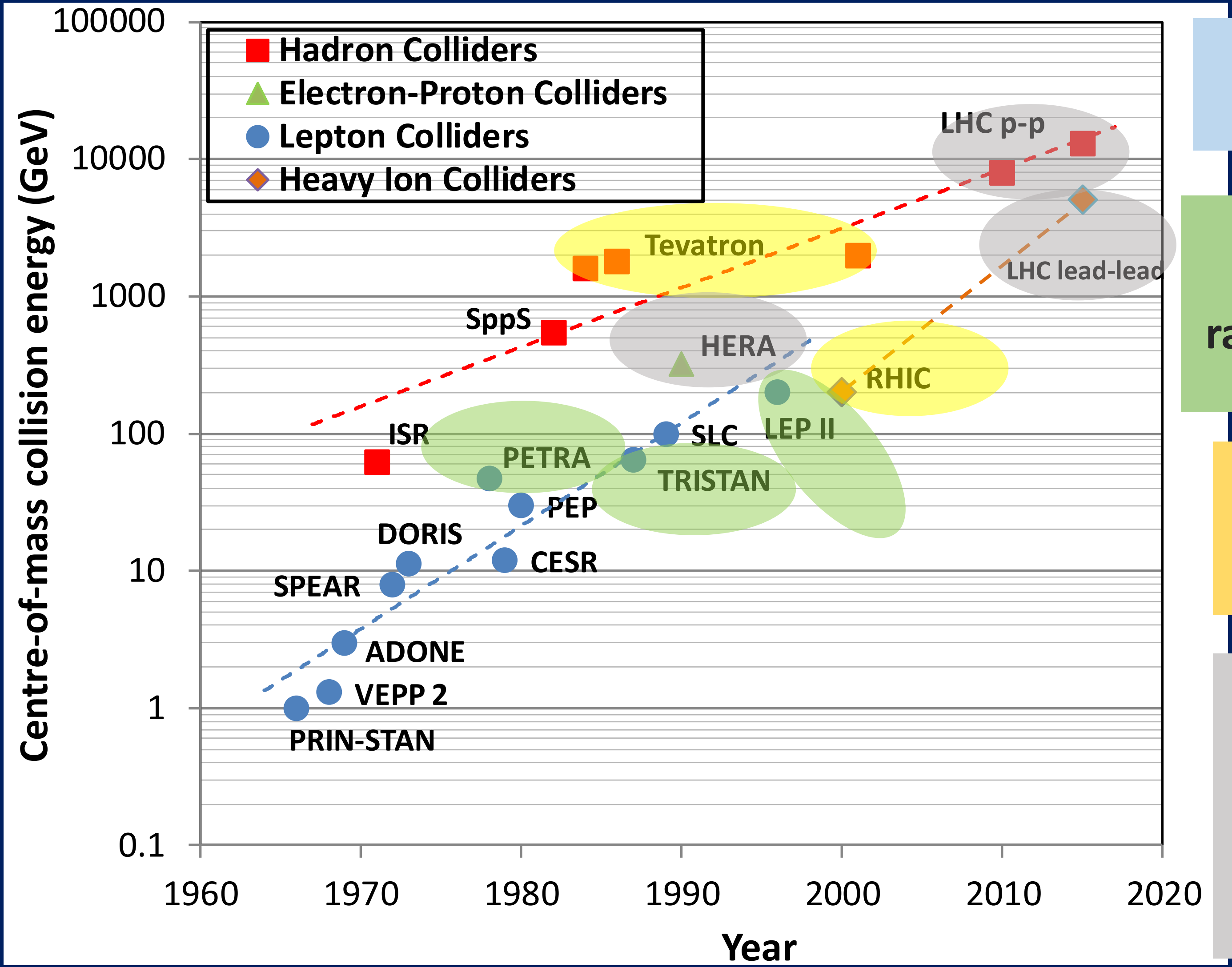
Standard Model
Particles and forces



powerful instruments for discovery and precision measurement

A. Ballarino

high energy particle accelerators since 1965



progress thanks to new technologies!

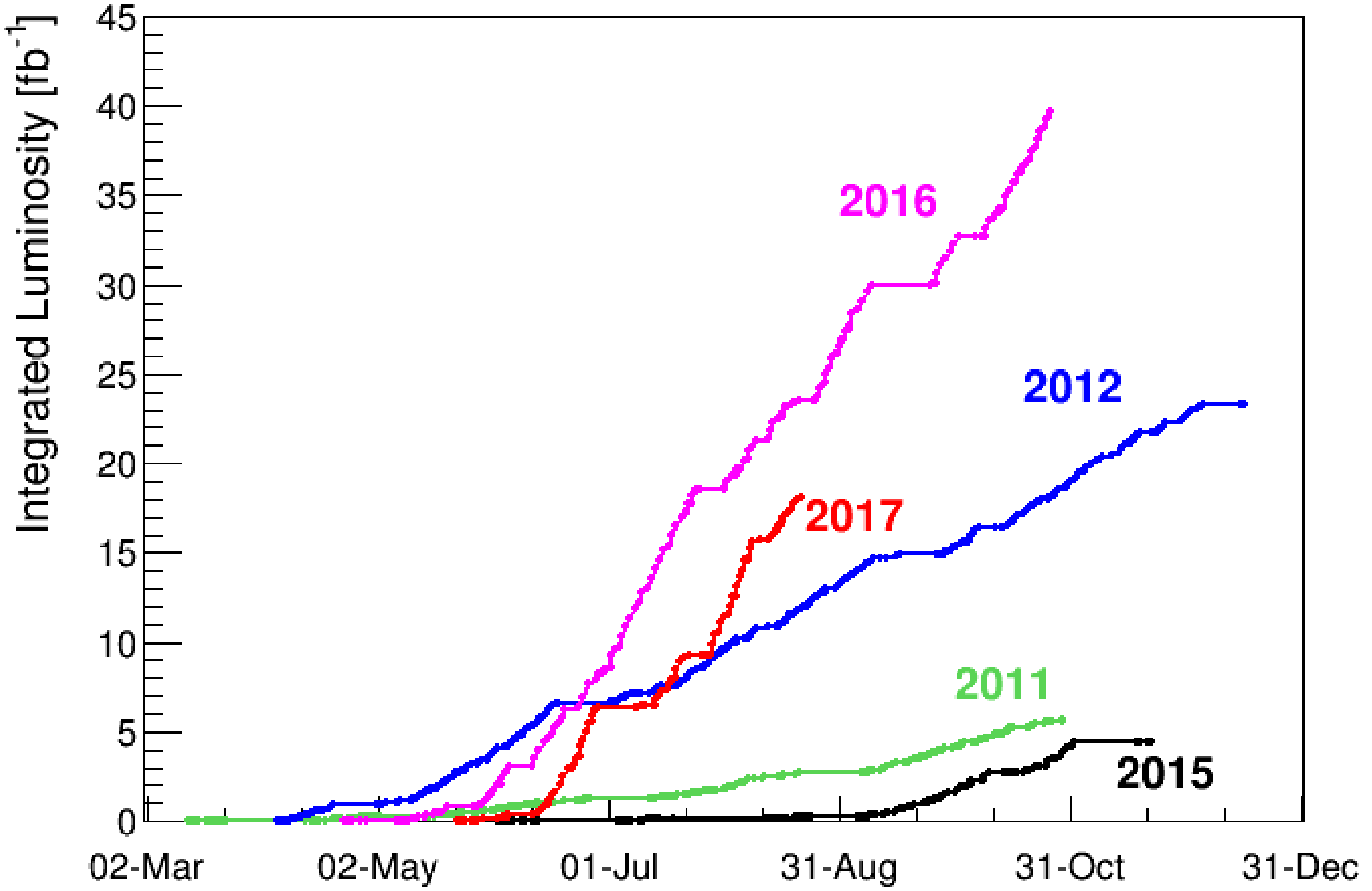
accelerators with SC radiofrequency system

accelerators with superconducting bending magnets

accelerators with SC radiofrequency systems and superconducting bending magnets

A. Ballarino, M. Benedikt, A. Yamamoto

LHC: today’s frontier collider



excellent performance at E_{cms}=13 TeV

energy frontier in the 21st century

- very large circular hadron collider - only feasible approach to reach 100 TeV c.m. collision energy in coming decades
- access to new particles (direct production) in few-TeV to 30 TeV mass range, far beyond LHC reach
- much-increased rates for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC

M. Mangano

hadron collider energy reach

$$\boxed{E \propto B_{dipole} \times \rho_{bending}}$$

cf. LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

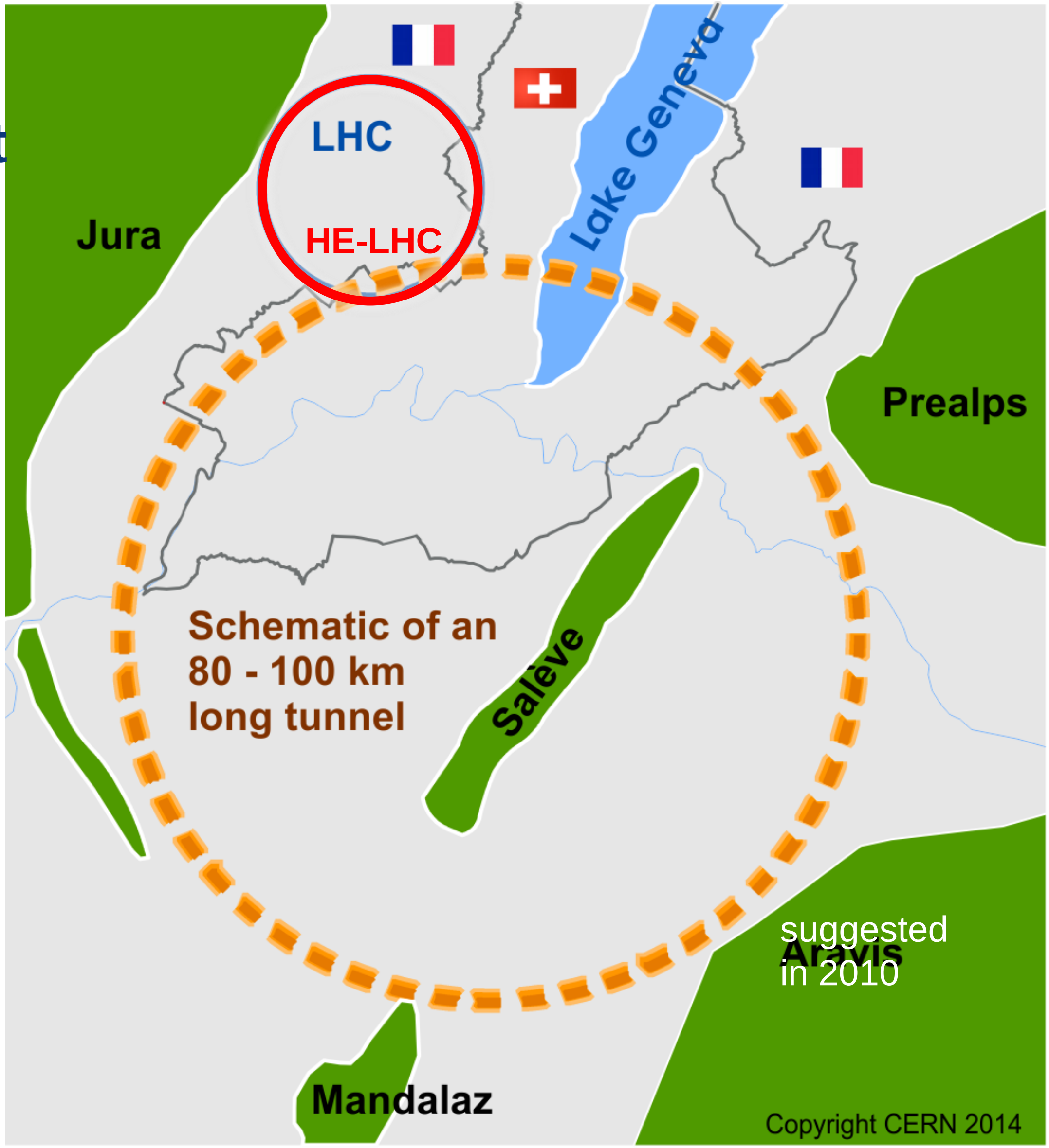
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to design:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

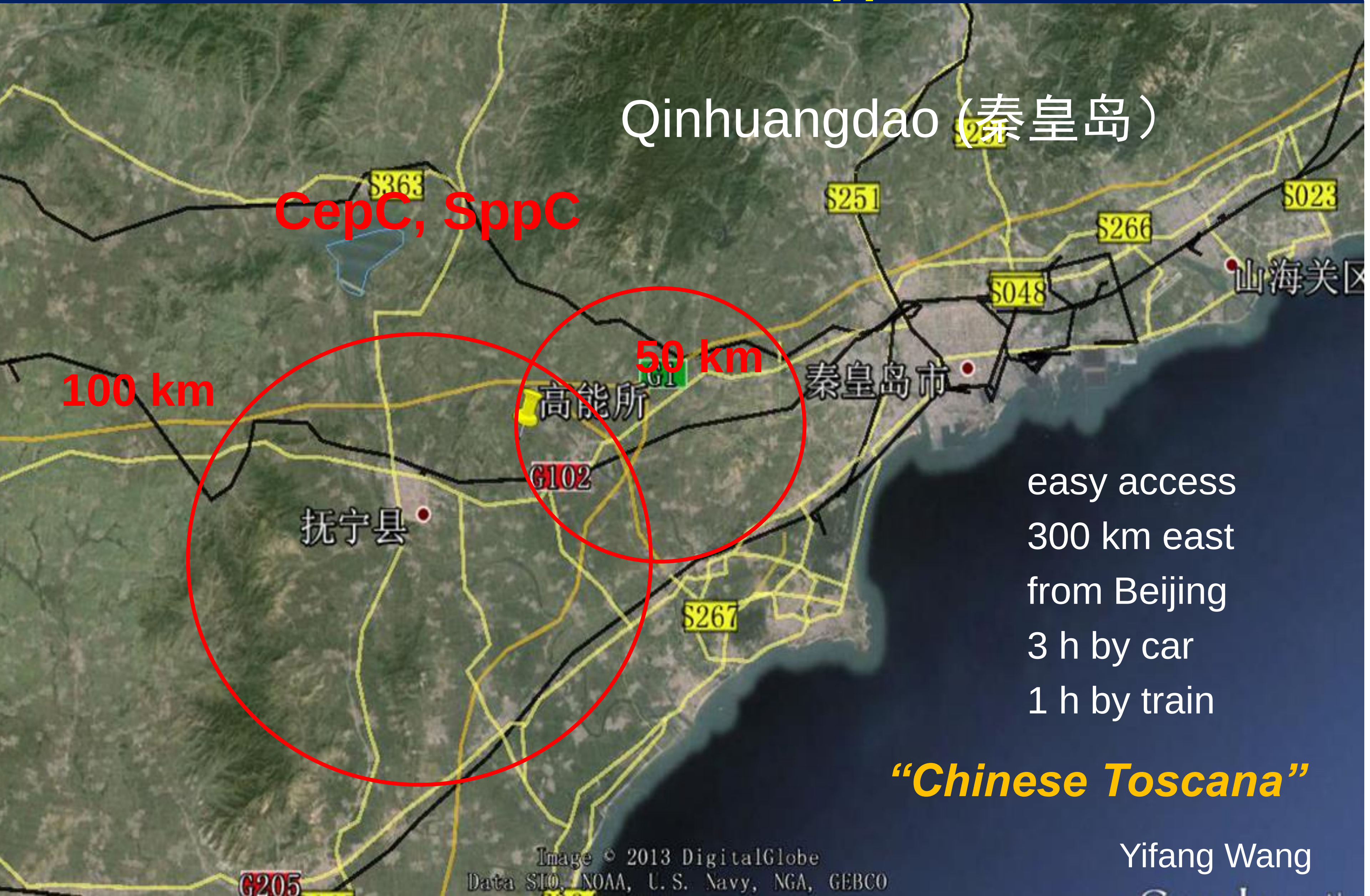
~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology



Copyright CERN 2014

CepC/SppC study (CAS-IHEP) 100 km (new baseline!) , e^+e^- collisions ~2028; *pp* collisions ~2042



easy access
300 km east
from Beijing
3 h by car
1 h by train

“Chinese Toscana”

Yifang Wang


天下第一關


海港区百佳小额贷款有限公司
Haigang District Baijia Petty Loan CO.,LTD
中国农业银行


TSINGTAO
青島啤酒
原漿
生啤酒原液
ORIGINAL BEER
酿酒师才能喝到的啤酒
净含量:5L
TSINGTAO
青島啤酒
原漿
生啤酒原液
ORIGINAL BEER
酿酒师才能喝到的啤酒

near proposed construction site and vinyards – bilingual beach resort (Chinese-Russian)

… Geneva beach for comparison

alternative CEPC sites

1) Qinhuangdao

(site technical exloring done)

2) Shanxi Province

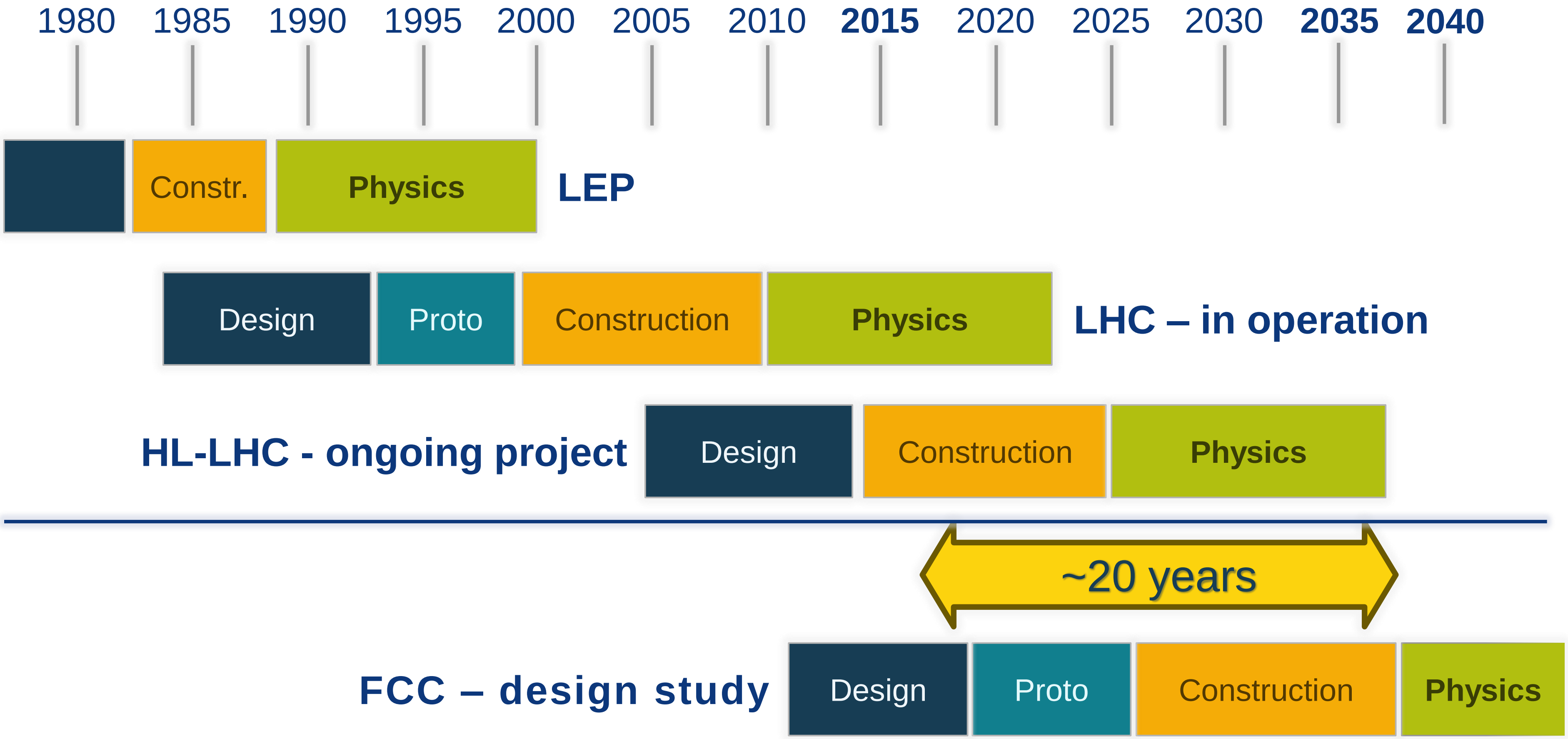
(under site technical exploring, started from Jan. 2017)

3) Near Shenzhen and Hongkong

(site technical exloring done)

M. Koratzinos, HongKong

CERN Circular Colliders & FCC



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035** **2040**

Constr. | **Physics** | **LEP**

Design | Proto | Construction | **Physics** | **LHC – in operation**

HL-LHC - ongoing project | Design | Construction | **Physics**

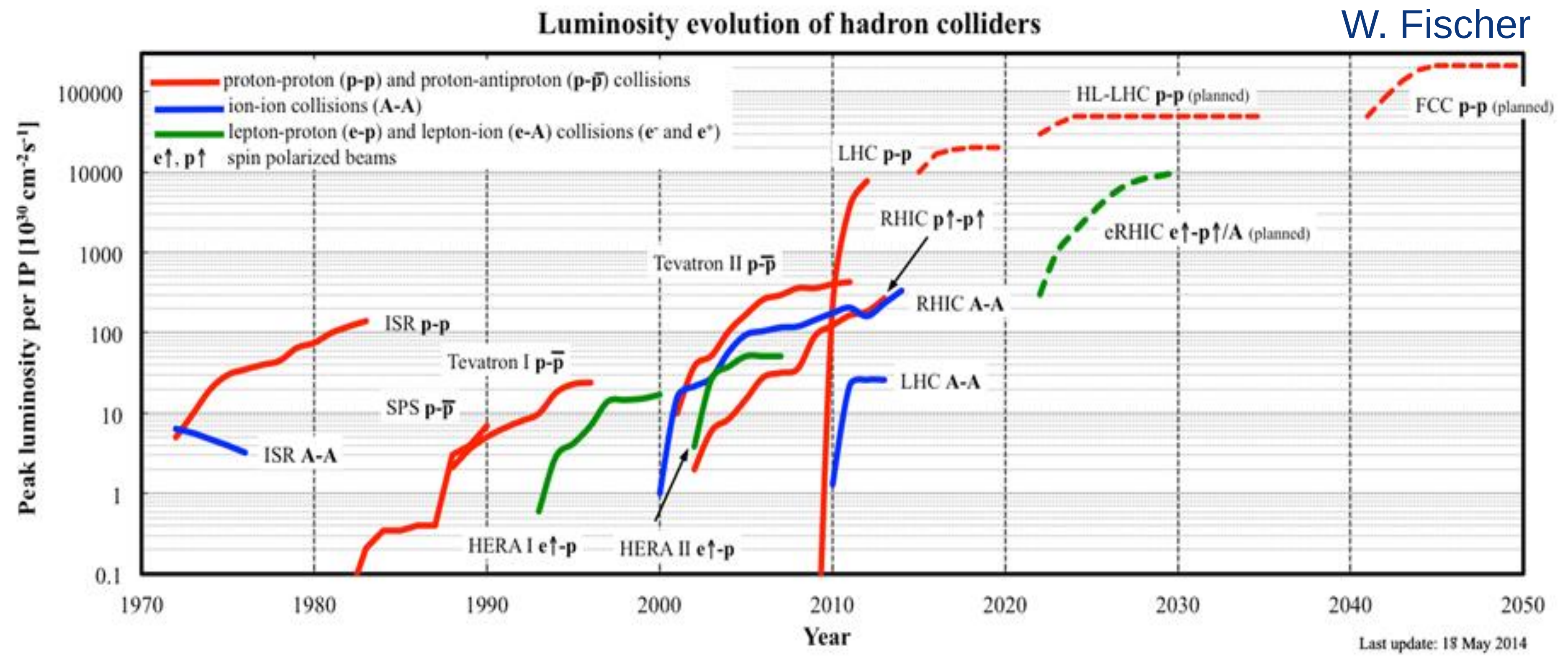
~20 years

FCC – design study | Design | Proto | Construction | **Physics**

must advance fast now to be ready for the period 2035 – 2040

milestone: CDR by end 2018 for next update of European Strategy

hadron collider history & forecast



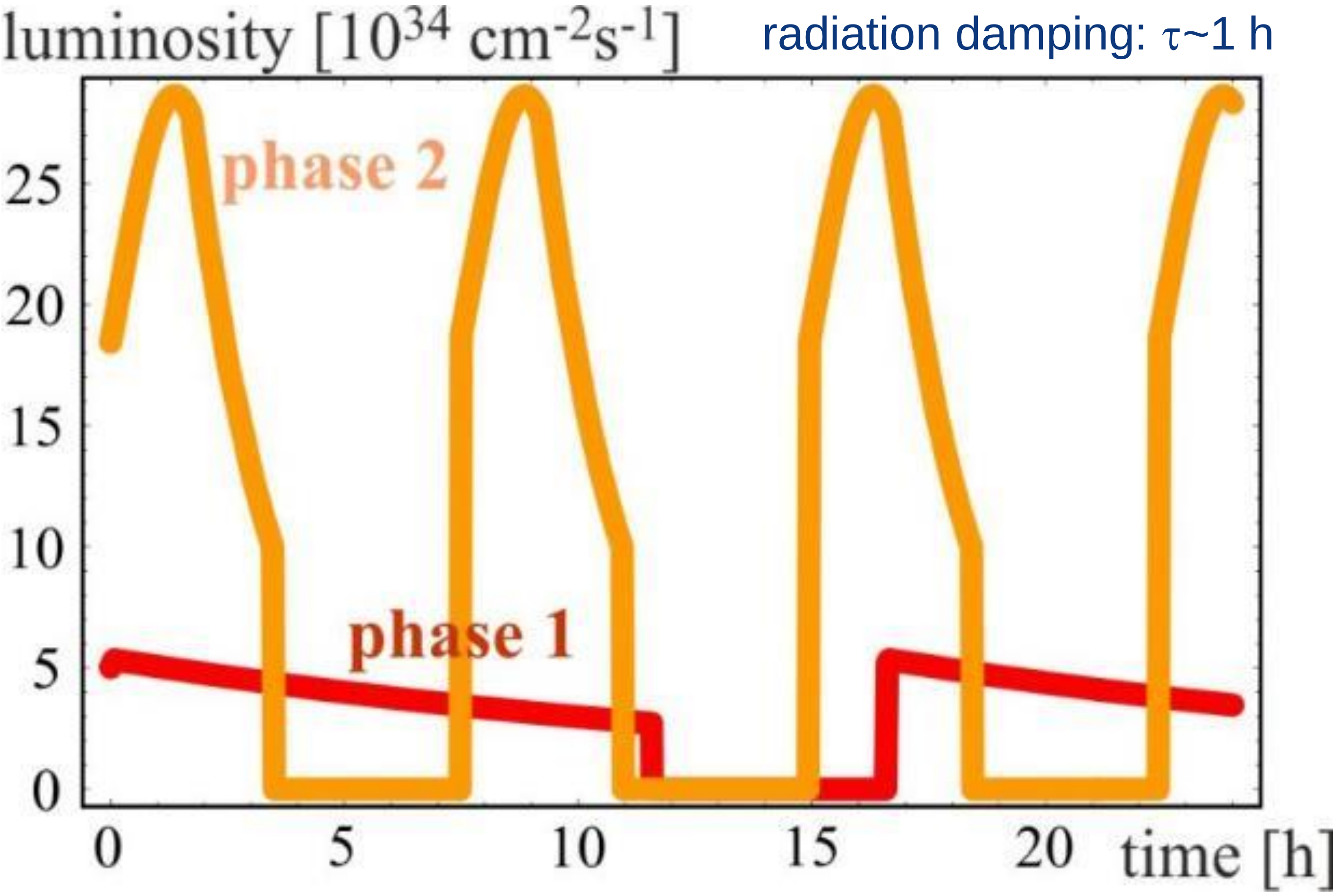
W. Fischer

hadron collider peak luminosity as a function of year – for past, operating, and proposed facilities

hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	**100**		**27**	14
dipole field [T]	**16**		**16**	8.3
circumference [km]	**100**		**27**	27
beam current [A]	**0.5**		**1.12**	(1.12) 0.58
bunch intensity [10^{11}]	**1 (0.2)**		**2.2**	(2.2) 1.15
bunch spacing [ns]	**25 (5)**		**25 (5)**	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	**2.2 (0.44)**		**2.5 (0.5)**	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	**1.1**	**0.3**	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	**30**	**25**	(5) 1
peak #events/bunch crossing	170	**1000** (200)	**800** (160)	(135) 27
stored energy/beam [GJ]	**8.4**		**1.4**	(0.7) 0.36
SR power / beam [kW]	**2400**		**100**	(7.3) 3.6
transv. emit. damping time [h]	**1.1**		**3.6**	25.8
initial proton burn off time [h]	17.0	**3.4**	**3.6**	(15) 40

luminosity evolution over 24 h



PRST-AB 18, 101002 (2015)

for both phases:

beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ξ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

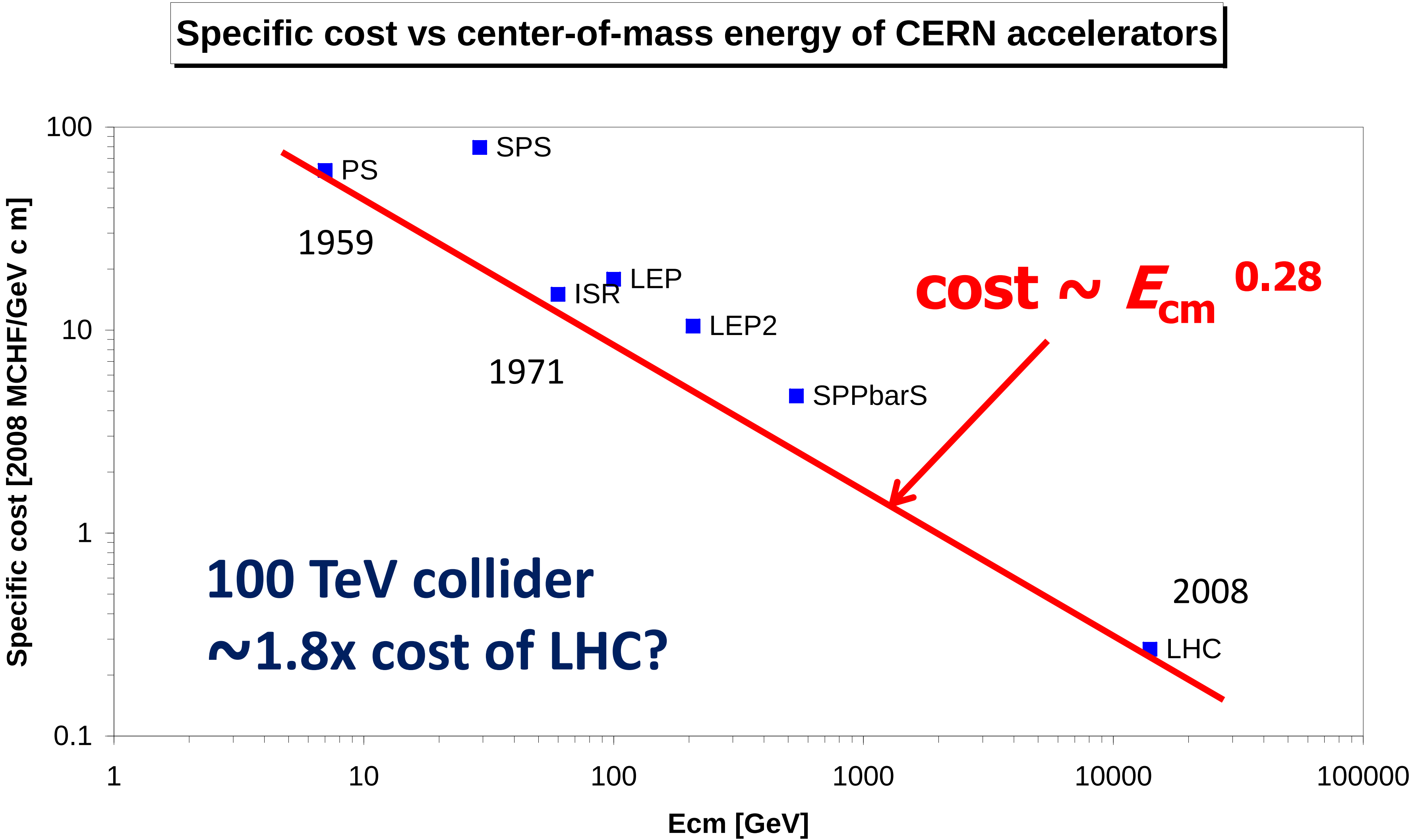
phase 2: β^*=0.3 m, ξ_{tot}=0.03, t_{ta}=4 h, 1000 fb^{-1} / year

SPPC main parameters

Parameter	Unit	SPPC			FCC	
		PreCDR	“CDR”	“Ultimate”		
Circumference	km	54.4	100	100	100	
c.m. energy	TeV	70.6	75	125-150	100	
dipole field	T	20	12	20-24	16	
injection energy	TeV	2.1	2.1	4.2	3.3	
#IPs		2	2	2	2	
luminosity per IP	10^{35} cm^{-2}s^{-1}	1.2	1.0	-	0.5	3.0
norm. emittance	μm	4.1	2.4	?	2.2 (0.44)	
IP beta function	m	0.75	0.75	-	1.1	0.3
beam current	A	1.0	0.7	-	0.5	
bunch separation	ns	25	25	-	25 (5)	25 (5)
bunch population	10^{11}	2.0	1.5	-	1.0 (0.2)	1.0 (0.2
SR power /beam	MW	2.1	1.1	-	2.5	
SR heat load/ap	W/m	45	13	-	30	

J. Tang

cost of future accelerators



Specific cost vs center-of-mass energy of CERN accelerators

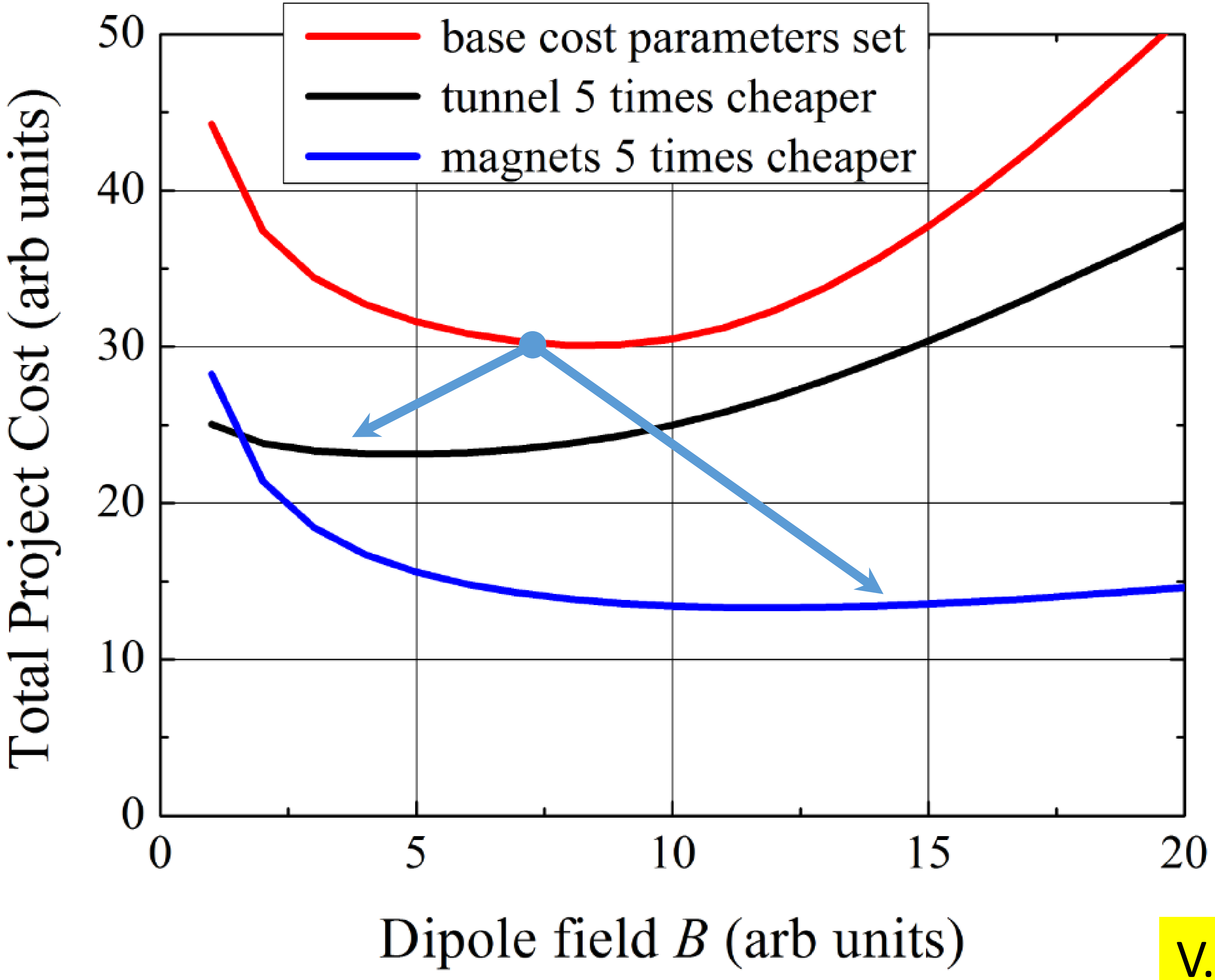
cost ~ $E_{cm}^{0.28}$

100 TeV collider
~1.8x cost of LHC?

P. Lebrun, RFTech 2013

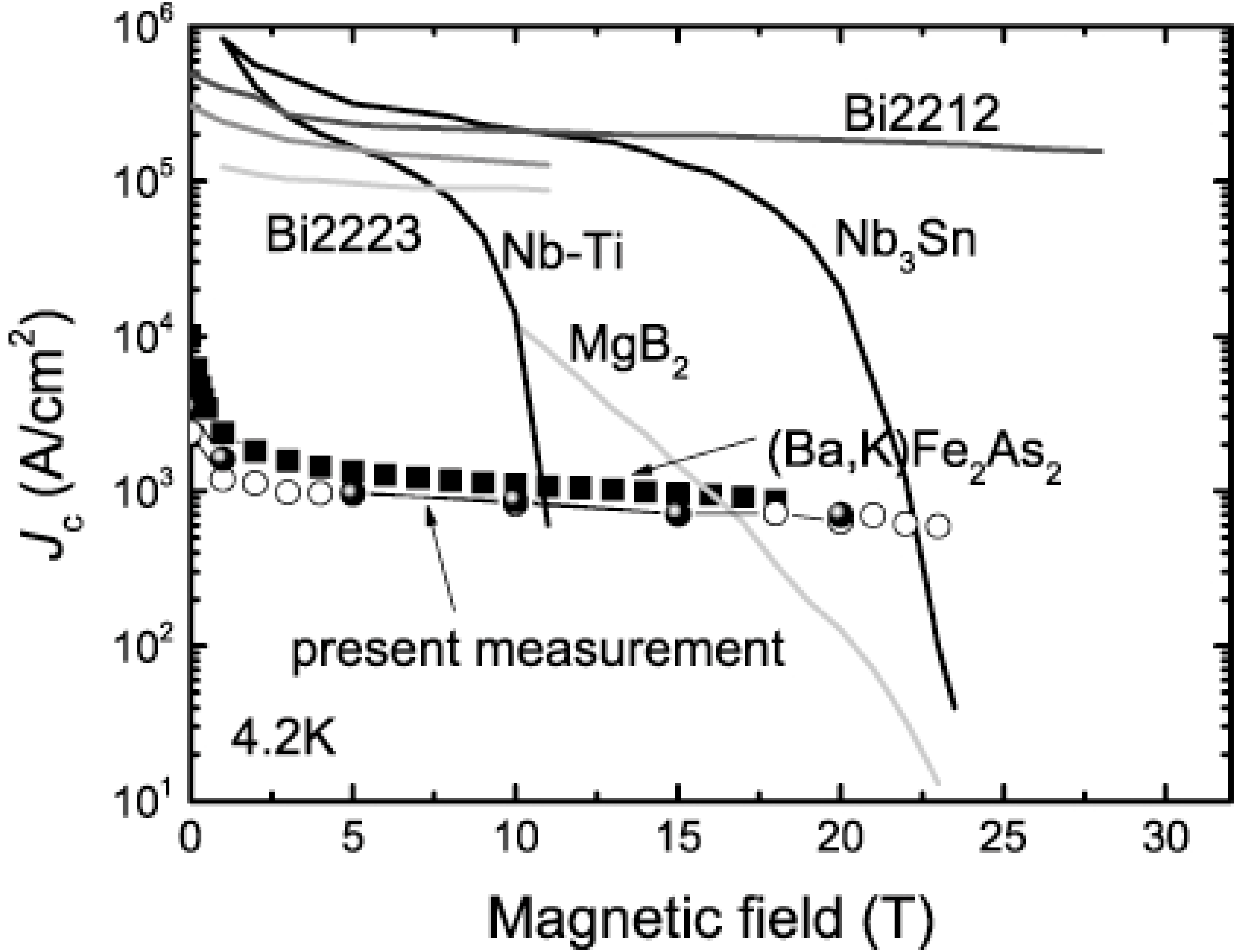
develop technology to lower the cost

100 TeV *pp* : Qualitative Cost Dependencies



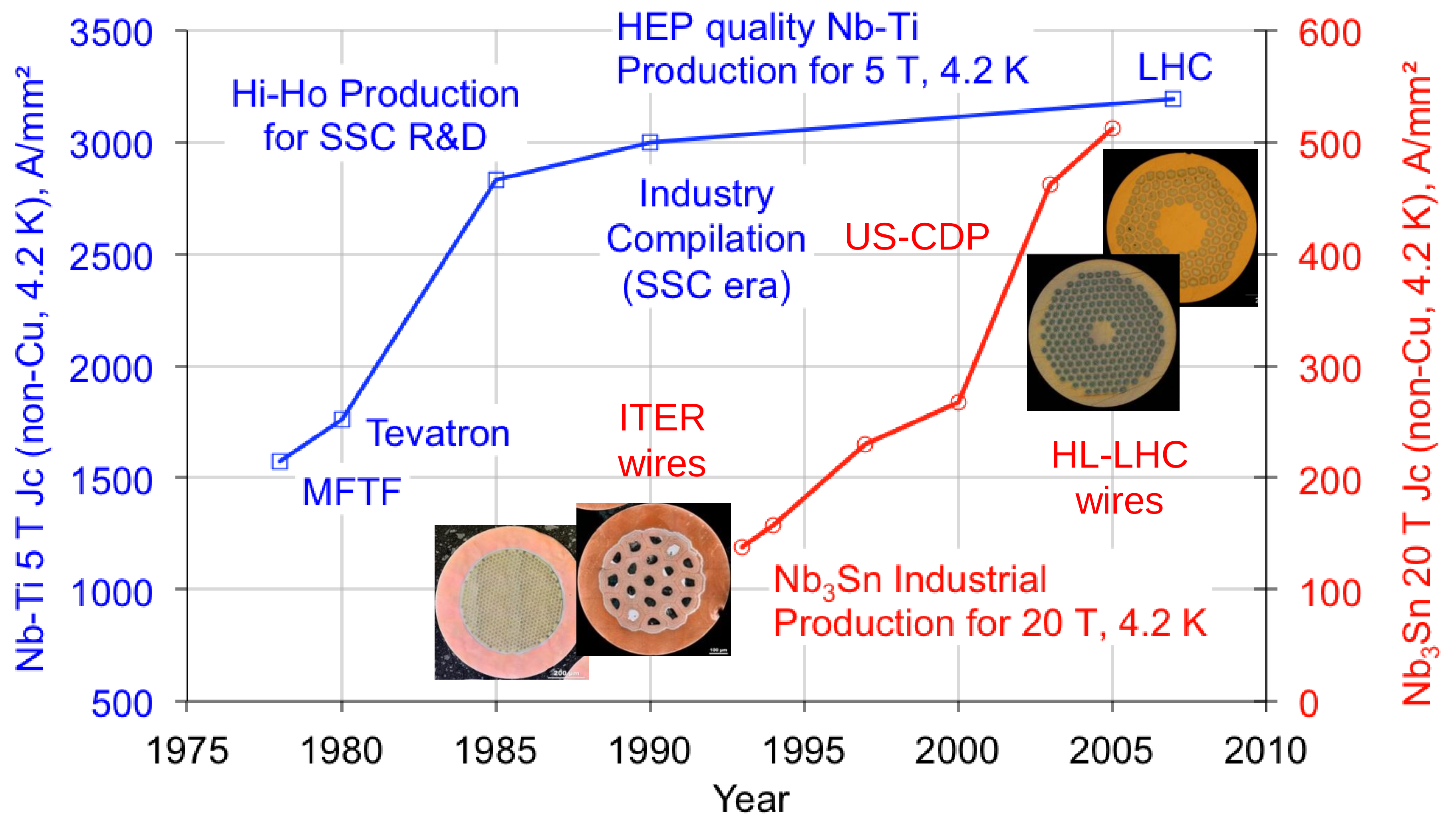
V. Shiltsev

HL-LHC/FCC technology change: *Nb-Ti* →*Nb_3Sn*



O. Bruning

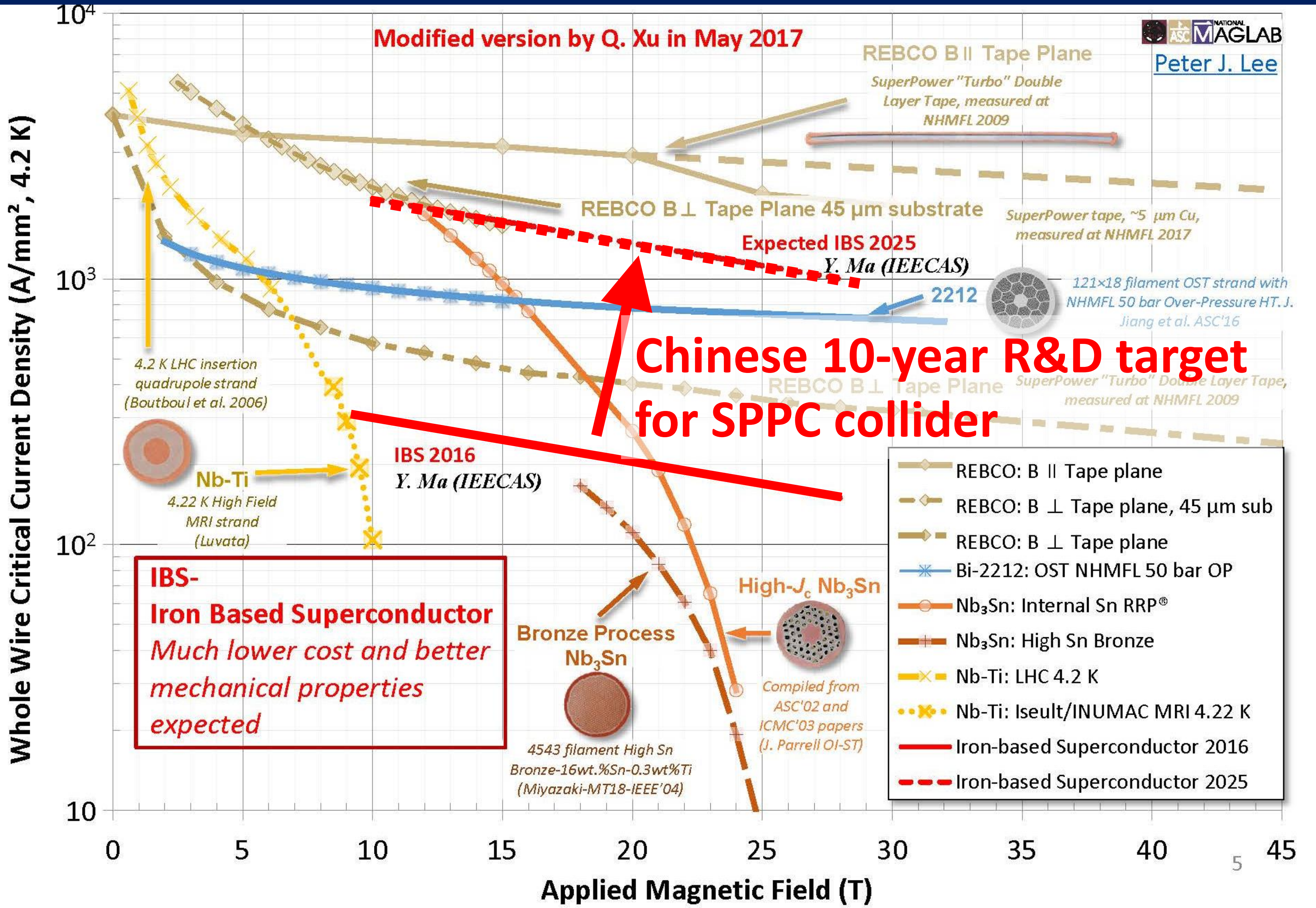
SC wire production: *Nb-Ti* and *Nb_3Sn*



B. Strauss, data by courtesy of J. Parrell (US DOE OST)

wire from Fe-based HTS*

*discovered at TIT/Japan in 2008



Modified version by Q. Xu in May 2017

Chinese 10-year R&D target for SPPC collider

IBS-
Iron Based Superconductor
Much lower cost and better mechanical properties expected

3 steps to lower the cost of future highest-energy circular colliders

- reduce SC/magnet cost
- build on a site with existing injector complex
- consider staging

(e$^+$e$^-$ 1st, *pp* 2nd, and $\mu^+\mu^-$ 3rd?)

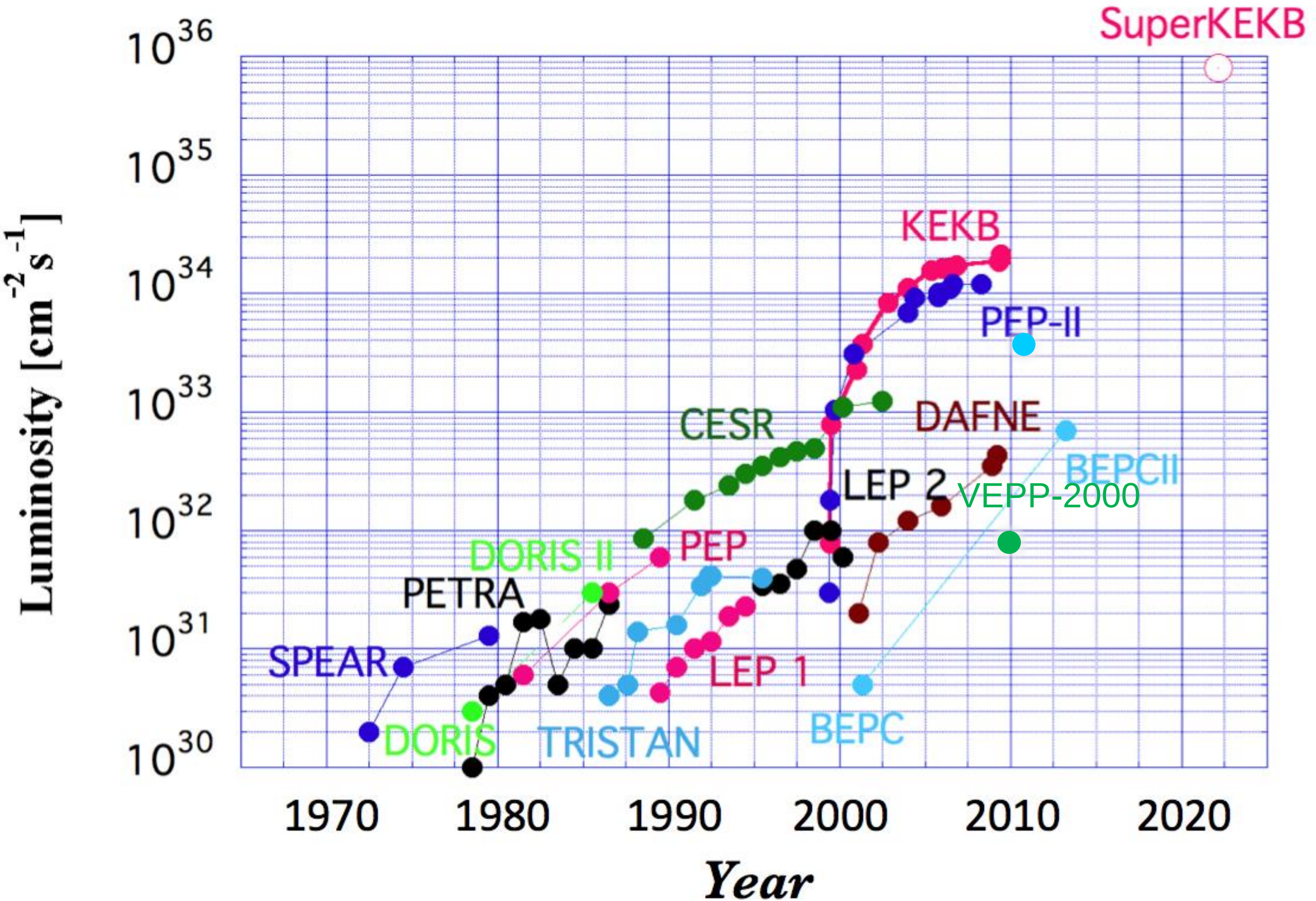
FCC-ee
CEPC

FCC-hh
SPPC

“FCC-μμ”?

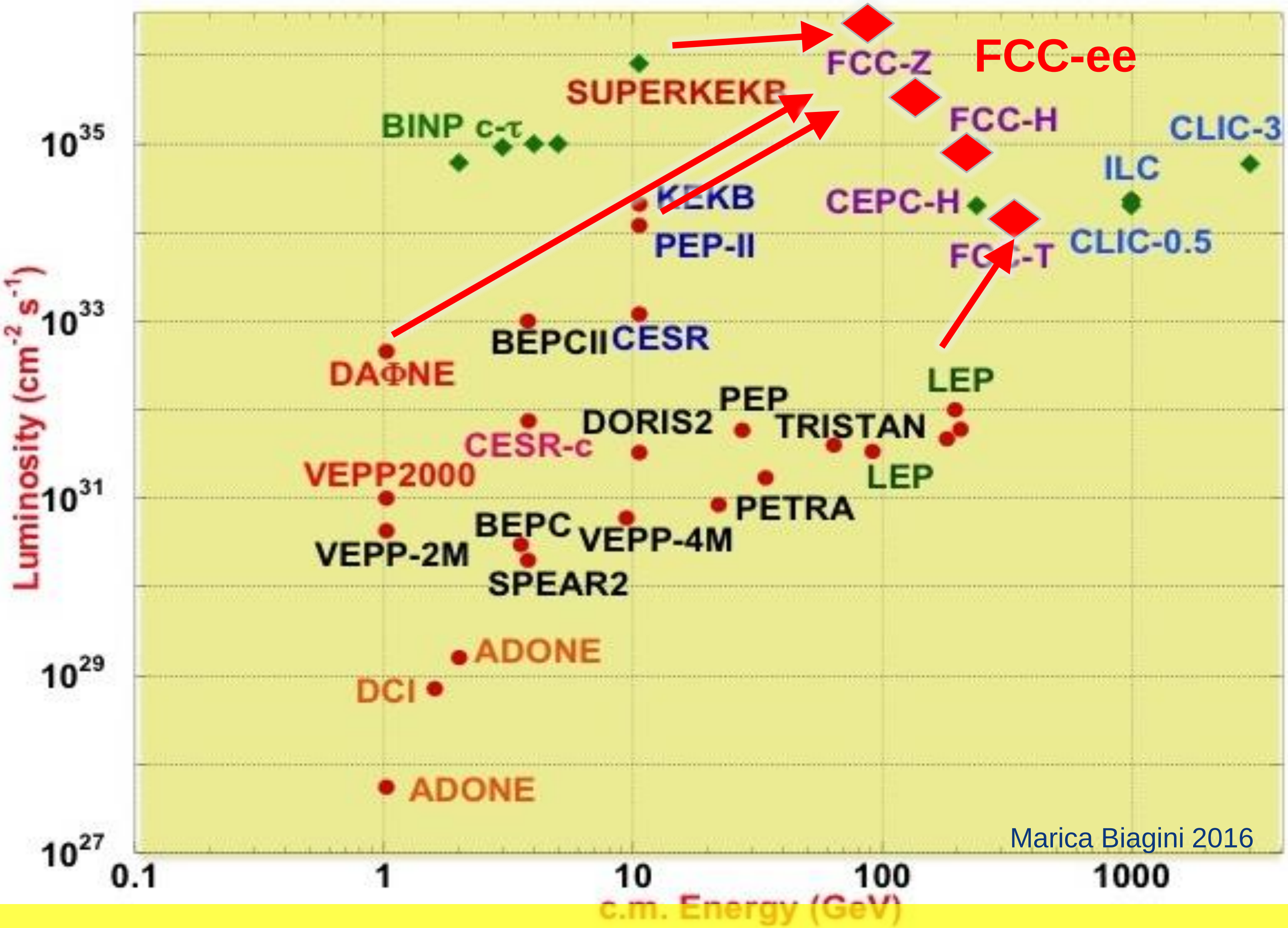
1st stage e^+e^- collider?

luminosity history of circular e^+e^- colliders



source: Y. Funakoshi

FCC-ee & CEPC exploit lessons & recipes from past & present e^+e^- and *pp* colliders



Marica Biagini 2016

LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam currents
top-up injection

DAFNE: crab waist

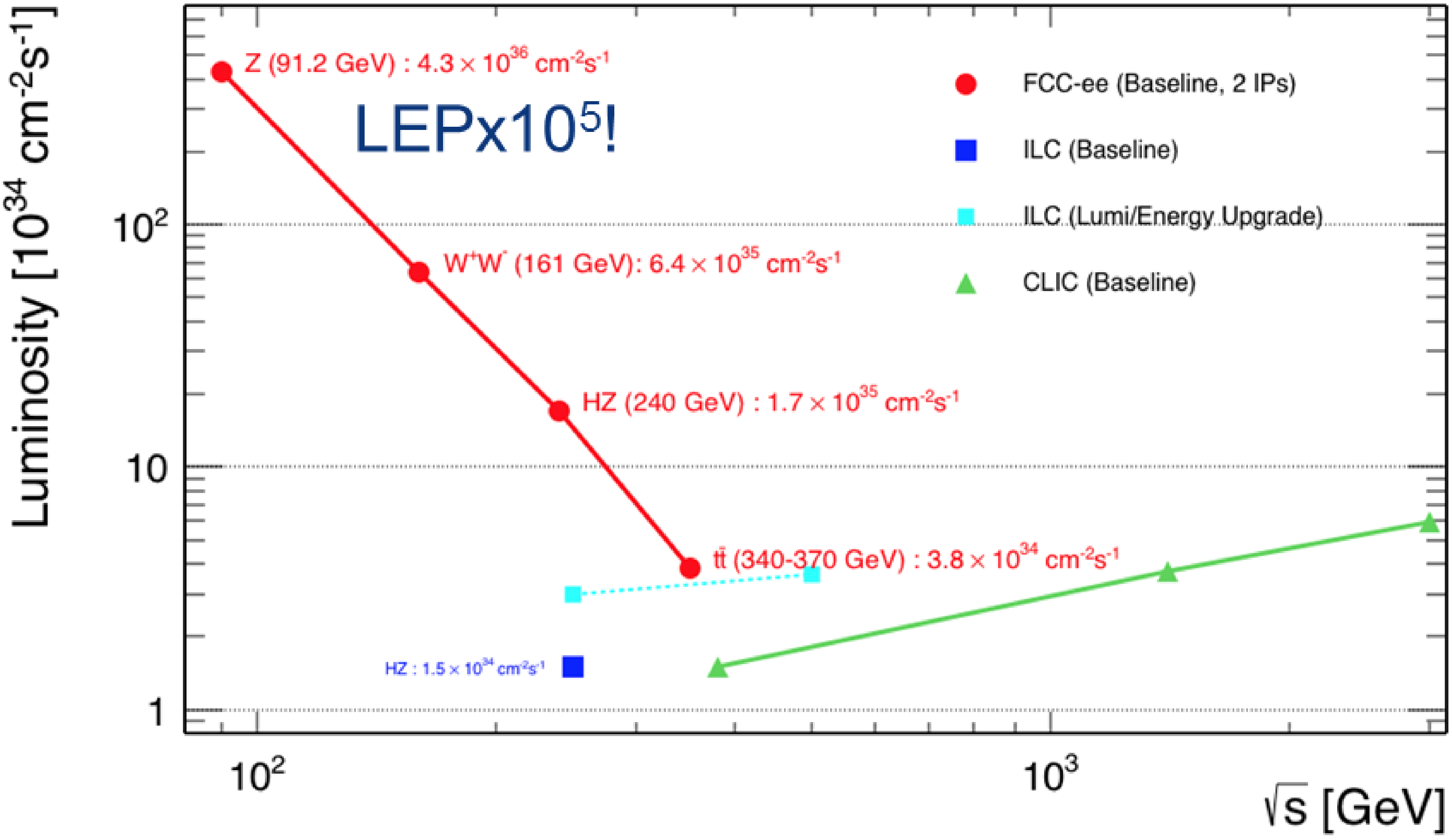
Super B-factories
S-KEKB: low β_y*

KEKB: *e^+* source

HERA, LEP, RHIC:
spin gymnastics

combining successful ingredients of recent colliders → extremely high luminosity at high energies

total luminosity of proposed future e^+e^- colliders

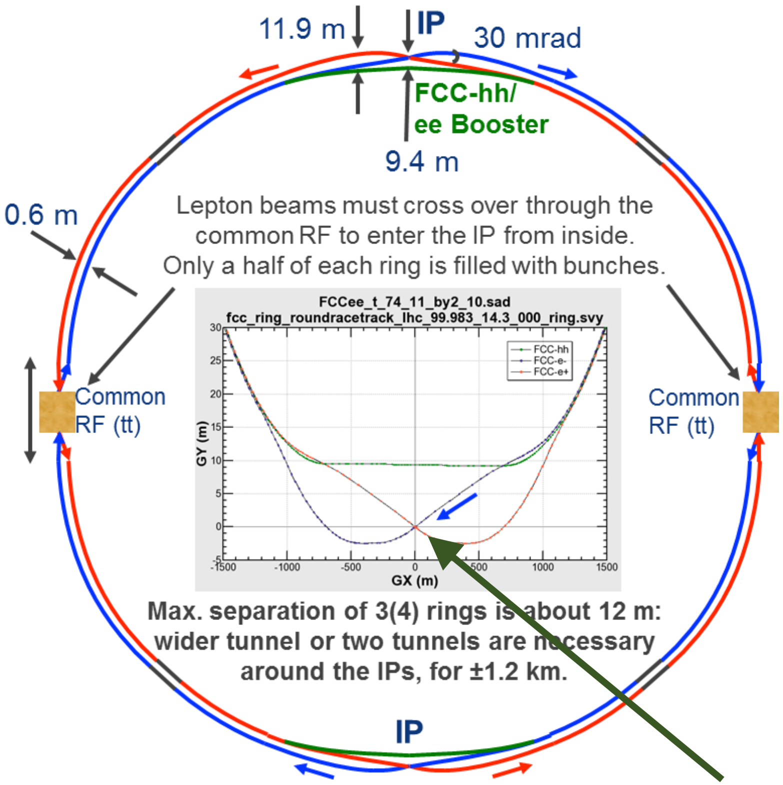


A. Blondel, Lepton-Photon 2017

designs for future circular e^+e^- colliders are converging

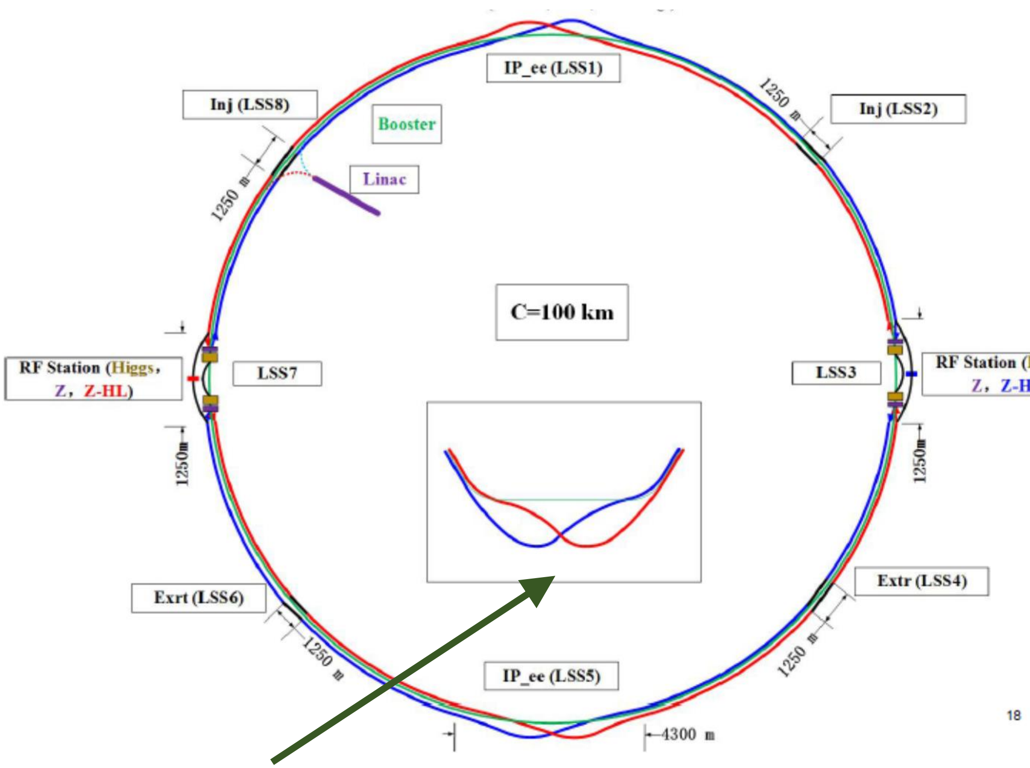
FCC-ee design

CEPC design



Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.



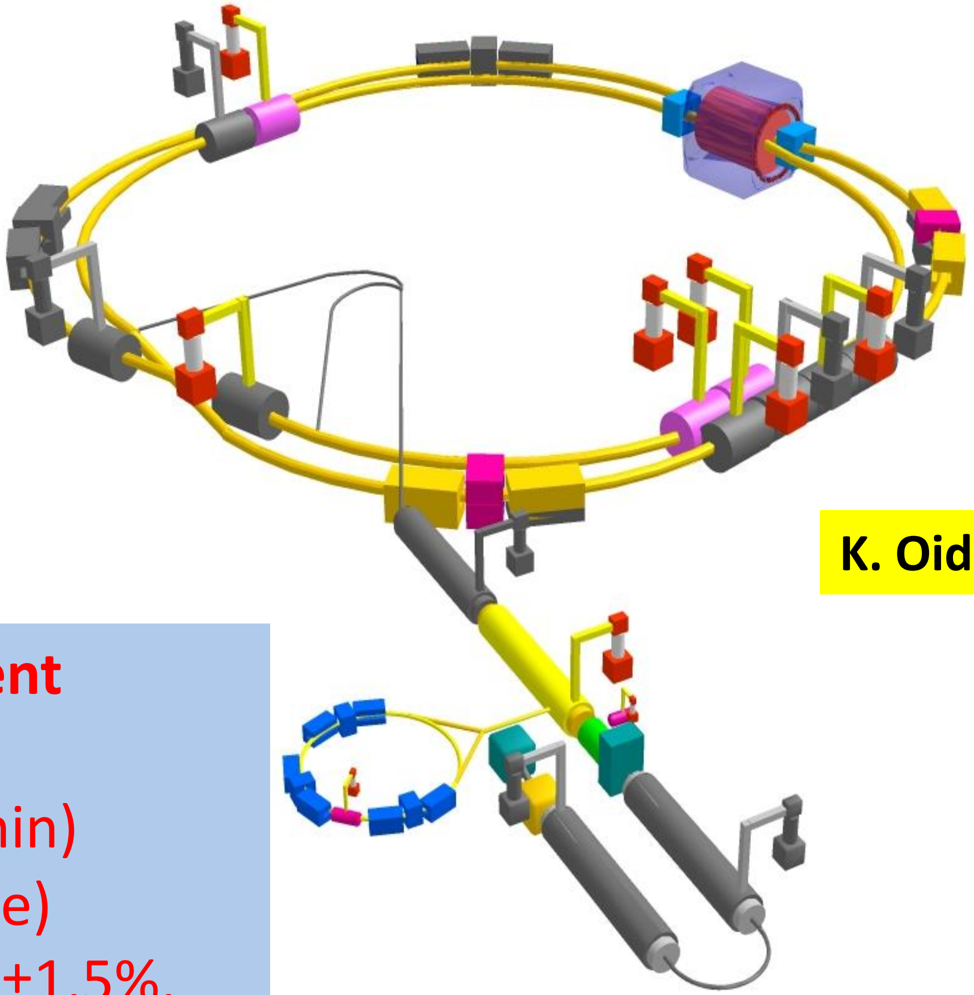
C=97.75 km

“bowtie” final focus (M. Koratzinos, A. Blondel, K. Oide)

C=100 km

SuperKEKB = *FCC-ee* demonstrator

beam commissioning started in 2016



K. Oide et al.

top up injection at high current

β_y* =300 μm (FCC-ee: 2 mm)

lifetime 5 min (FCC-ee: ≥60 min)

$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)

off momentum acceptance (±1.5%, similar to FCC-ee)

***e*⁺ production rate** (2.5x10^{12}/s, FCC-ee: <1.5x10^{12}/s (*Z* crab waist)

SuperKEKB goes beyond *FCC-ee*, testing all concepts

synchrotron radiation

energy loss $\propto E^4$

FCC-ee: maximum energy $\sim$400 GeV (RF voltage)

FCC-hh: power consumption dominated by SR (heat extraction from beam screen and cold bore, RF power)

can we remove or reduce the synchrotron radiation?

possible approaches

1. suppression of synchrotron radiation for circular e^+e^- and/or pp colliders?

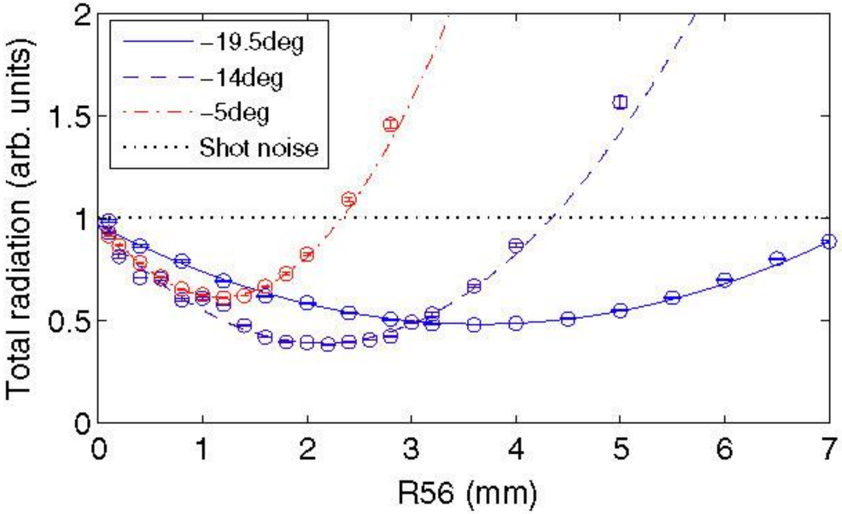
2. linear collider?

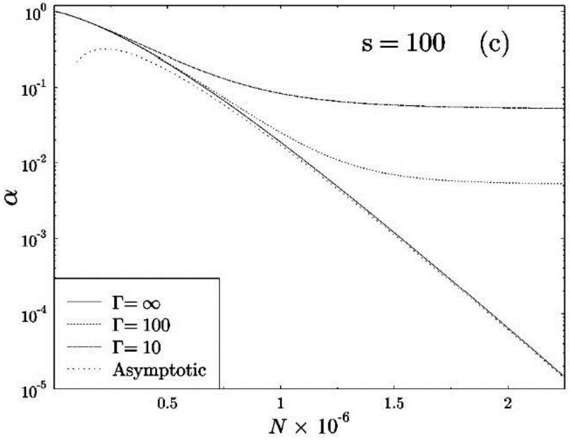
3. muon collider?

suppressing synchrotron radiation 1

shaping the beam

- DC beam does not radiate
- suppression of shot noise and reduced radiation demonstrated at SLAC NLCTA, D. Ratner et al., PRST-AB 18, 050703 (2015)
- 1 D crystalline beam (acceleration by induction acceleration)?





N~10^6 particles uniformly distributed → factor 50 reduction in total SR power

Synchrotron radiation of crystallized beams, Harel Primack and Reinhold Blümel, Phys. Rev. E 60, 957 (1999)

suppressing synchrotron radiation 2

tailoring the boundary

- large bending radius + small chamber size provide shielding
  - *effect seen at RHIC*
- HTS coating for small (mm/micro/nano-) chamber?
- hollow channel shield?

$$\lambda \geq 2\sqrt{h^2\, w/\rho}$$

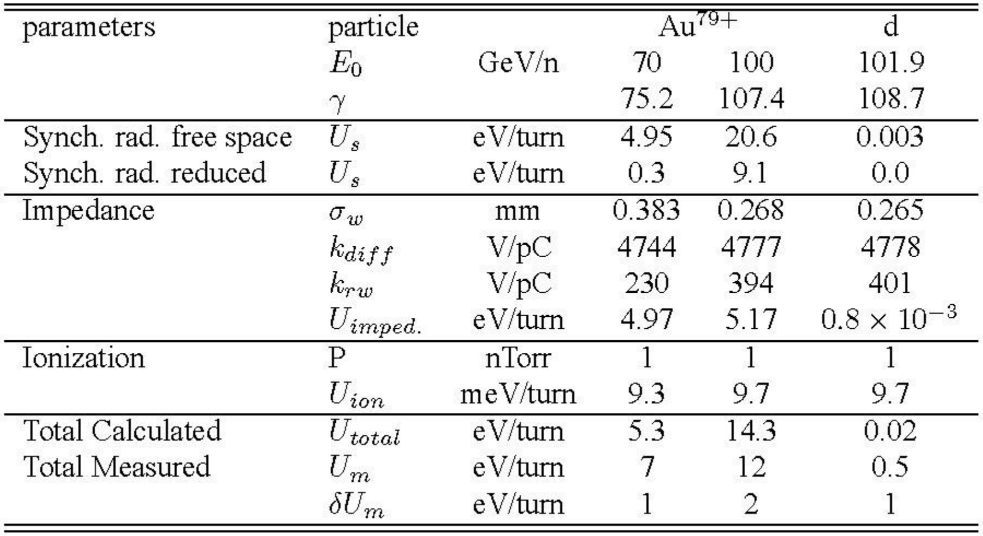
h: full chamber height
w: full chamber width
ρ: bending radius

Examples:

h=*w*=1 cm, ρ=1 km →
λ >600 nm (2 eV)

***h*=*w*=1 mm, ρ=10 km**
→ λ >0.6 nm (2 keV)

***h*=*w*=0.1 mm, ρ=10 km**
→ λ >2 pm (600 keV)

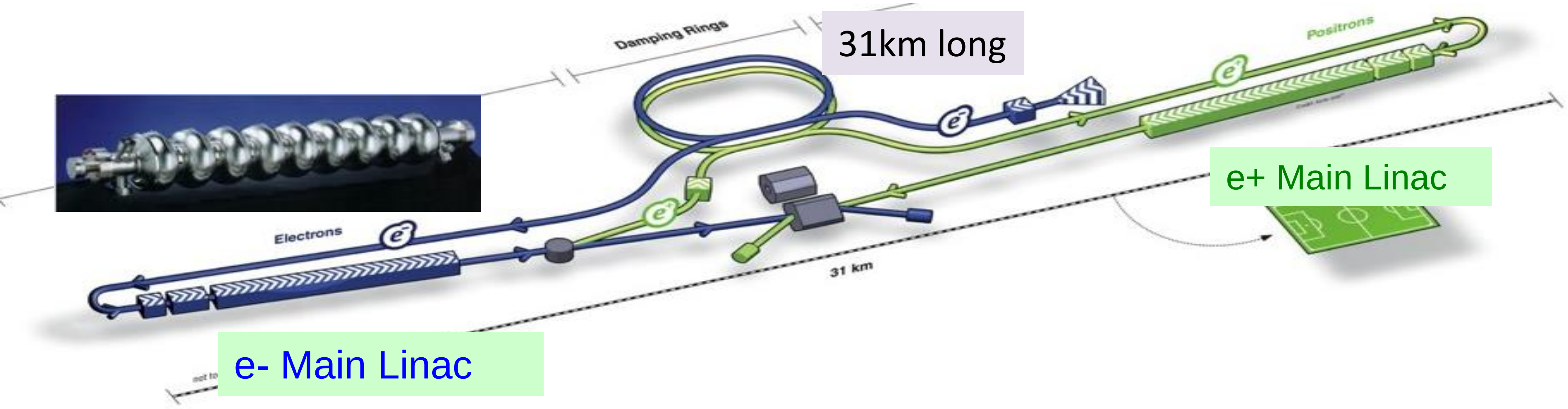


parameters	particle		Au^{79+}		d
	E_0	GeV/n	70	100	101.9
	γ		75.2	107.4	108.7
Synch. rad. free space	U_s	eV/turn	4.95	20.6	0.003
Synch. rad. reduced	U_s	eV/turn	0.3	9.1	0.0
Impedance	σ_w	mm	0.383	0.268	0.265
	k_{diff}	V/pC	4744	4777	4778
	k_{rw}	V/pC	230	394	401
	$U_{imped.}$	eV/turn	4.97	5.17	0.8×10^{-3}
Ionization	P	nTorr	1	1	1
	U_{ion}	meV/turn	9.3	9.7	9.7
Total Calculated	U_{total}	eV/turn	5.3	14.3	0.02
Total Measured	U_m	eV/turn	7	12	0.5
	δU_m	eV/turn	1	2	1

first experimental evidence for suppression of incoherent synchrotron radiation,
N. P. Abreu et al., EPAC'08

linear accelerators

ILC



31km long

e+ Main Linac

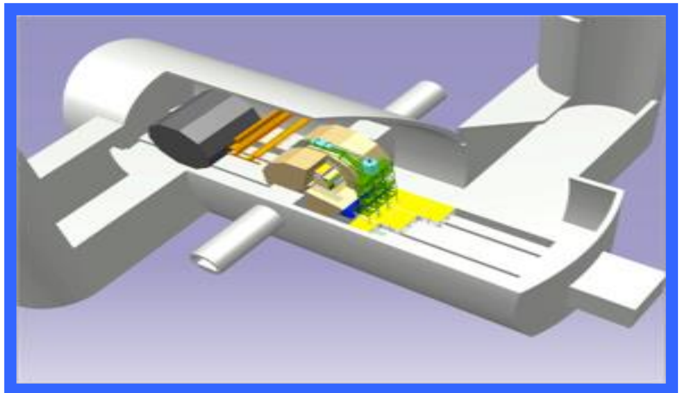
e- Main Linac

TDR exists

Aim for cost reduction

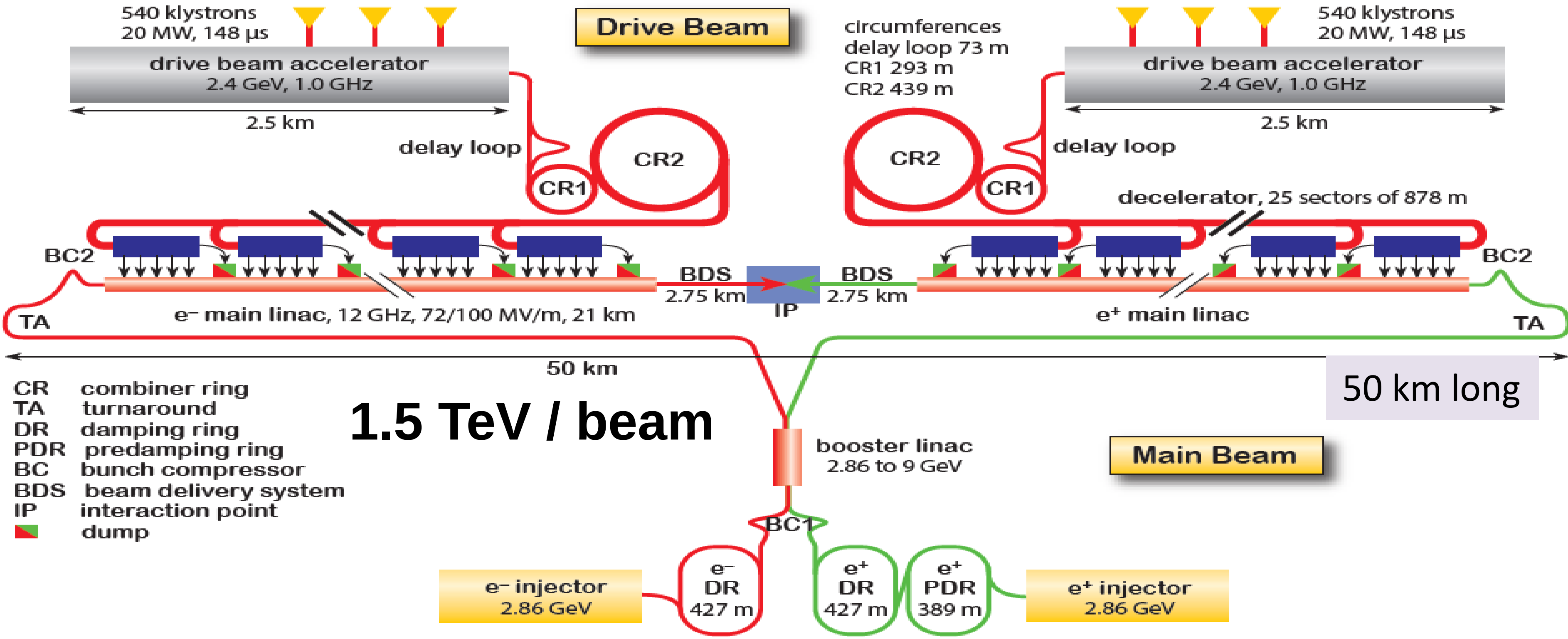
Political process in Japan ongoing

Parameters	**Value**
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	**31.5** MV/m +/-20% Q_0 = 1E10



D. Schulte,
EPS-HEP 2017

CLIC (3 TeV)



1.5 TeV / beam

50 km long

one problem:

3 TeV collider: 50 km long

100 TeV linear pp collider > 1000 km

D. Schulte,
EPS-HEP 2017

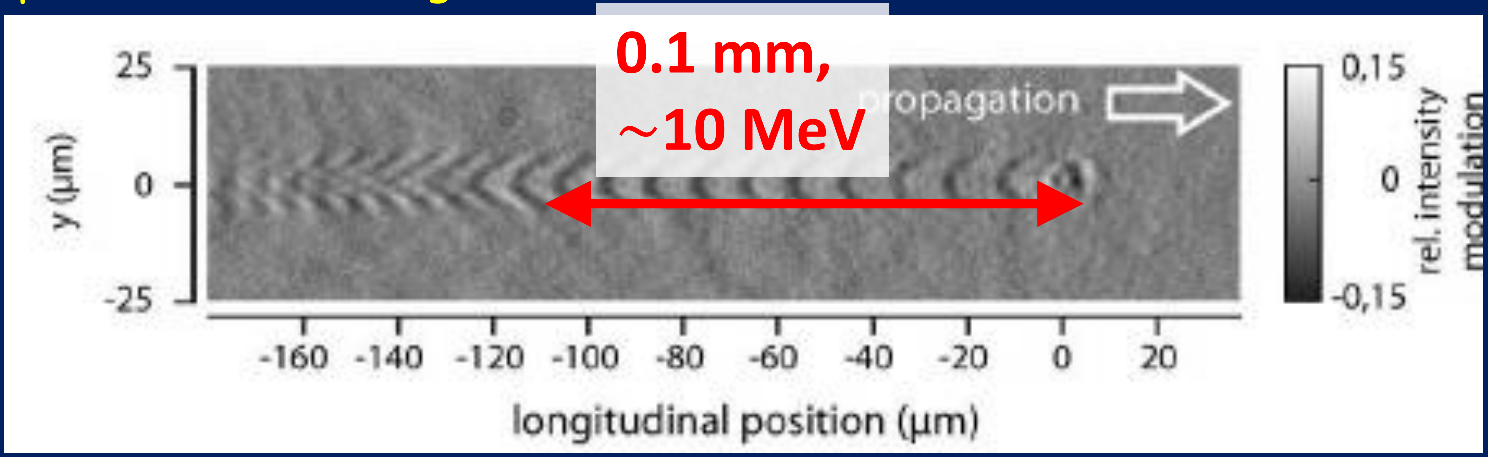
much higher accelerating fields?

"conventional"
SC accelerating
structure, ~10-30 MV/m

~1 m,
~10 MeV

credit: CERN

plasma accelerating structure, field ~100 GV/m

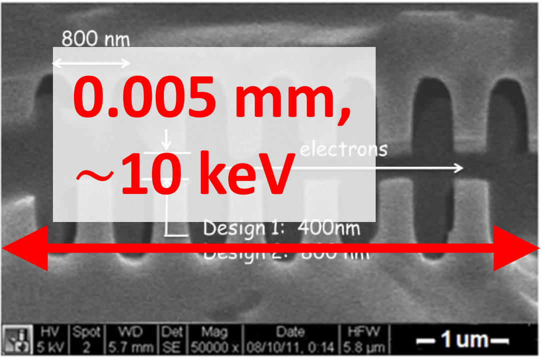


0.1 mm,
~10 MeV

Fourier
Domain
Holography

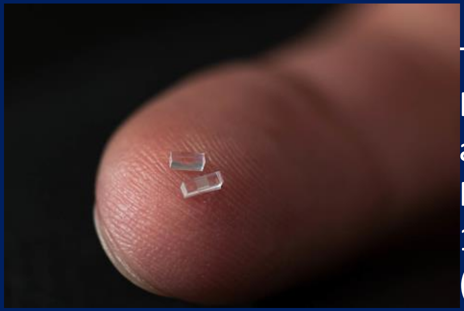
A. Sävert et al., arXiv: 1402.3052,
N.H. Matlis et al., Nature Physics 2, 2006

dielectric
accelerating,
structure
~2 GV/m



0.005 mm,
~10 keV

electron-
microscope
image



T. Plettner,
R. Byer et
al. ,
PRST-AB 9,
111301
(2006)

example: compact X-ray Free Electron Laser

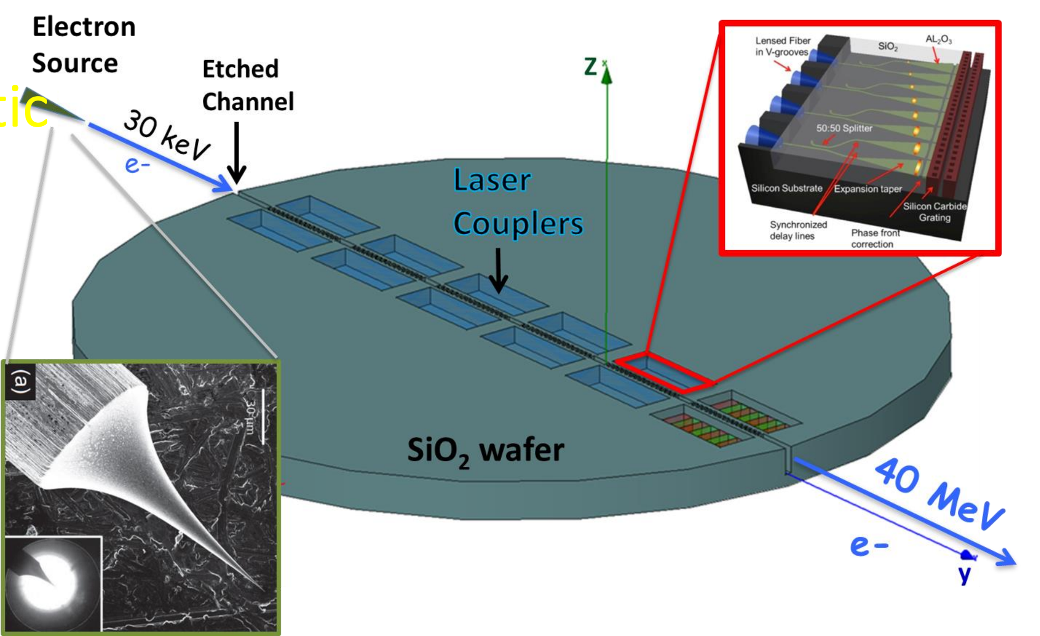
European XFEL
in Hamburg,
SC RF 1.3 GHz

H. Weise,
FCC Week 2017

1.9 km,
17.5 GeV,
40 mm
undulator
period

"XFEL on a chip" - laser driven dielectic accelerator with integrated source and undulator on SiO_2 wafer

R. Byer, ICHEP'14



~0.1 m,
40-100
MeV,
1 µm
undulator
period

linac technology cost drivers

"SRF is the most expensive technology ever invented"

$\beta \approx$ **10 B$/sqrt(*E*/TeV)**

"only plasma acceleration is even more expensive"

$\beta \approx$ **XX B$/sqrt(*E*/TeV)**

V. Shiltsev

efficiency: two figures-of-merit

1. beam power at collision point(s) divided by total electrical power of the facility
2. luminosity per electrical input power

collider	c.m. energy [TeV]	P_{el}: tot. el. power [MW]	P_b: IP beam power [GW]	luminosity L [$nb^{-1}s^{-1}$]	P_b/P_{el}	L/P_{el} (/IP) $b^{-1}s^{-1}$/MW]
CEPC	0.24	~500	4.0	20		
FCC-ee	0.091	276	132			
FCC-ee	0.24	308	7.2			
FCC-ee	0.35	364				
LHeC	1.3					
LHeC-HF	1.3					**0.16**
ILC					**0.05**	**0.06**
ILC					**0.06**	**0.11**
CLIC				23	**0.03**	**0.08**
CLIC			0.028	59	**0.05**	**0.10**
laser-plasma			0.045	100**	**0.05??**	**??**
LHC	13.0	~150	8000	10	**50000**	**0.07**
FCC-hh	100.0	500 (target)	50000	300 (phase 2)	**100000**	**0.6**
SPPC	70.2	600 (guess)	53000	100	**90000**	**0.2**

circular colliders more efficient than linear ones

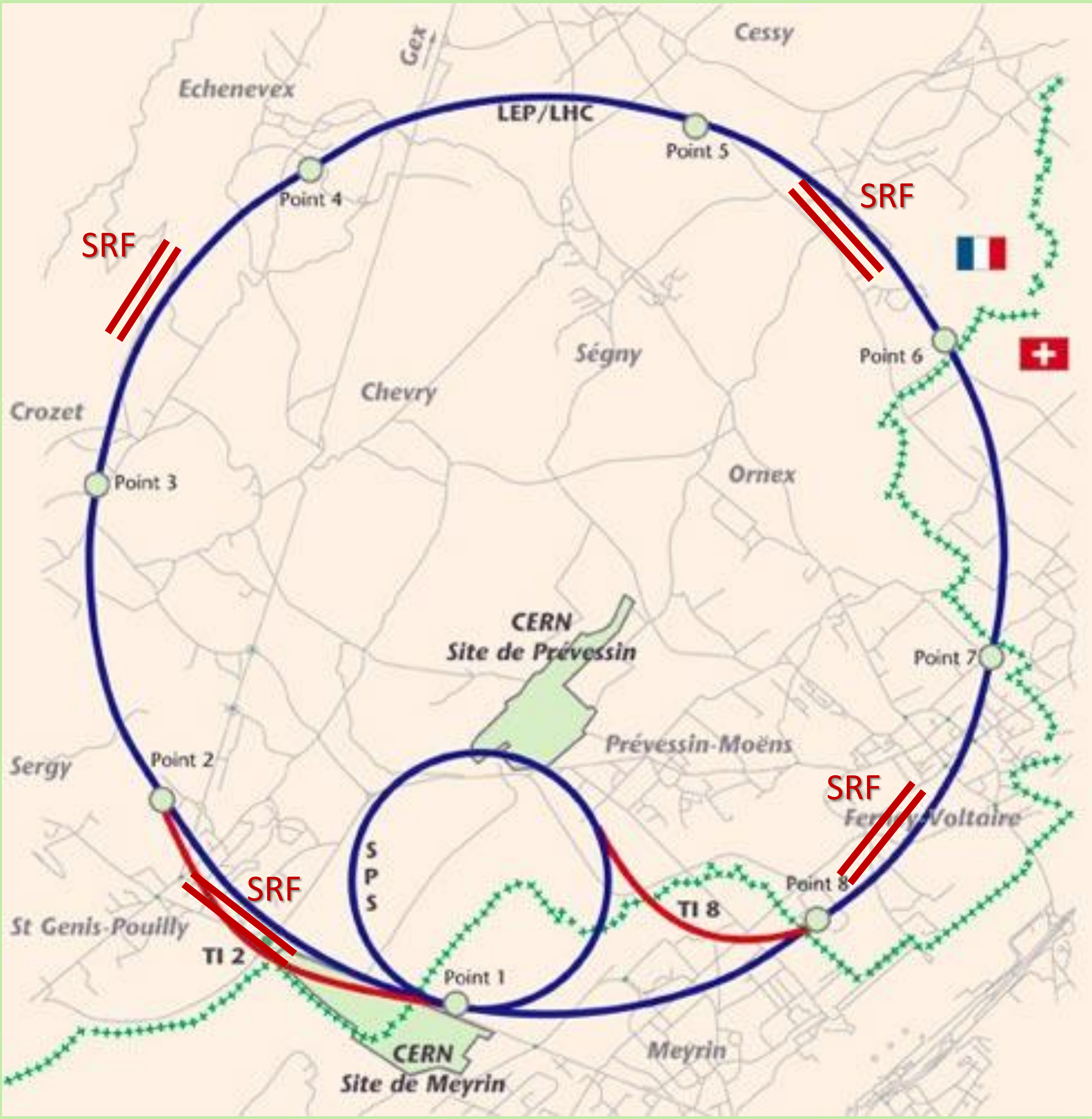
$\mu^+\mu^-$ collider?

e.g. CMC

CERN
Muon
Collider

- *14 TeV cm*
- *LHC tunnel*
- *SPS tunnel and mb PS*
- *~7GeV SRF*
- *pulsed magnets*
- ***cost ~LHC***

V. Shiltsev



recent intriguing approach(es) to muon collider: produce muon beam with low emittance

- no need for ionization cooling
- ideally already with muons at high energy!!

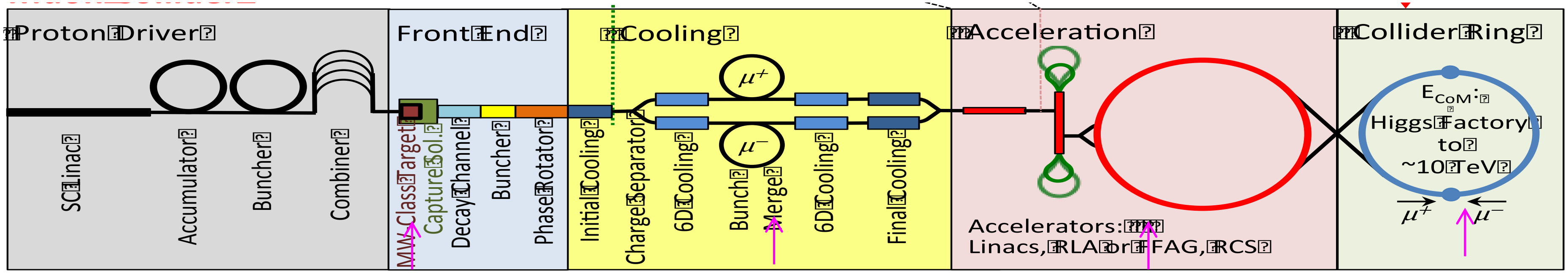
various schemes proposed

1) e^+ annihilation (10^{15} e^+/s → 10^{11} μ/s)
   P. Raimondi et al.

2) π/μ production from γ-p collision at LHC or FCC (~10^{11} μ/s) L. Serafini et al.

3) $e^\pm$ and μ production in γ-PSI collisions at LHC or FCC –“Gamma Factory” – (10^{17} e^+/s, 10^{12} μ/s) W. Krasny

from US-MAP (2015) to Italian μ-collider (2017)



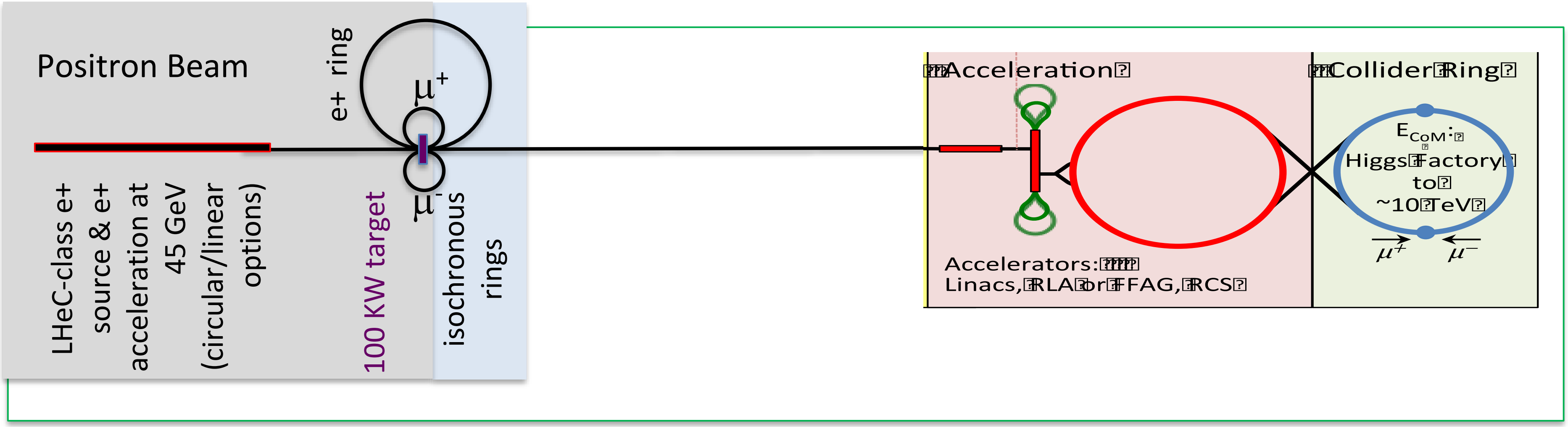
key challenges

~10^{13}-10^{14} μ / sec tertiary particle $p\rightarrow\pi\rightarrow\mu$:

fast cooling (τ=2μs) by 10^6 (6D)

fast acceleration mitigating μ decay

background from μ decay



key challenges

~10^{11} μ / sec from $e^+e^-\rightarrow\mu+\mu-$

key R&D

10^{15} e+/sec, 100 kW class target, NON destructive process in e+ ring

M. Boscolo

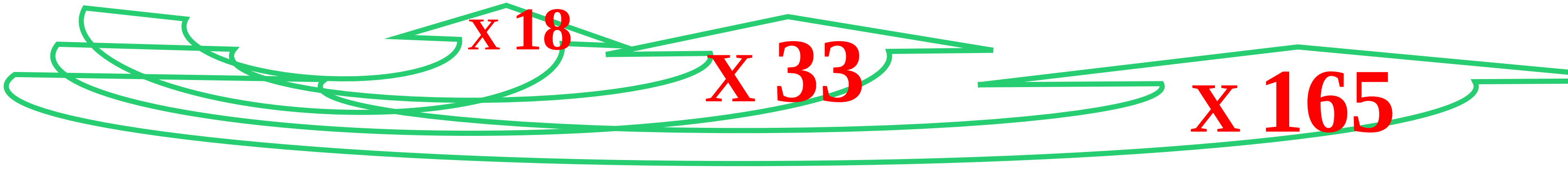
threshold e^+ energy for μ production in e^+ annihilation on static e^-:

$$E_{e^+,\text{thr}} = \frac{4m_\mu^2c^4 - 2m_e^2c^4}{2m_ec^2} = 43.7\ \text{GeV}$$

→ we could use the FCC-ee e^+ ring (or the FCC-ee top-up booster, or a LEP3,…) as μ accumulation & internal target ring!

e^+ production rates achieved (SLC) or needed

	S-KEKB	**SLC**	**CLIC (3 TeV)**	**ILC (*H*)**	**FCC-ee (*Z*)**	**Italian μ collider**
10^{12} e^+ / s	**2.5**	**6**	**110**	**200**	**5**	**1000**


x 18

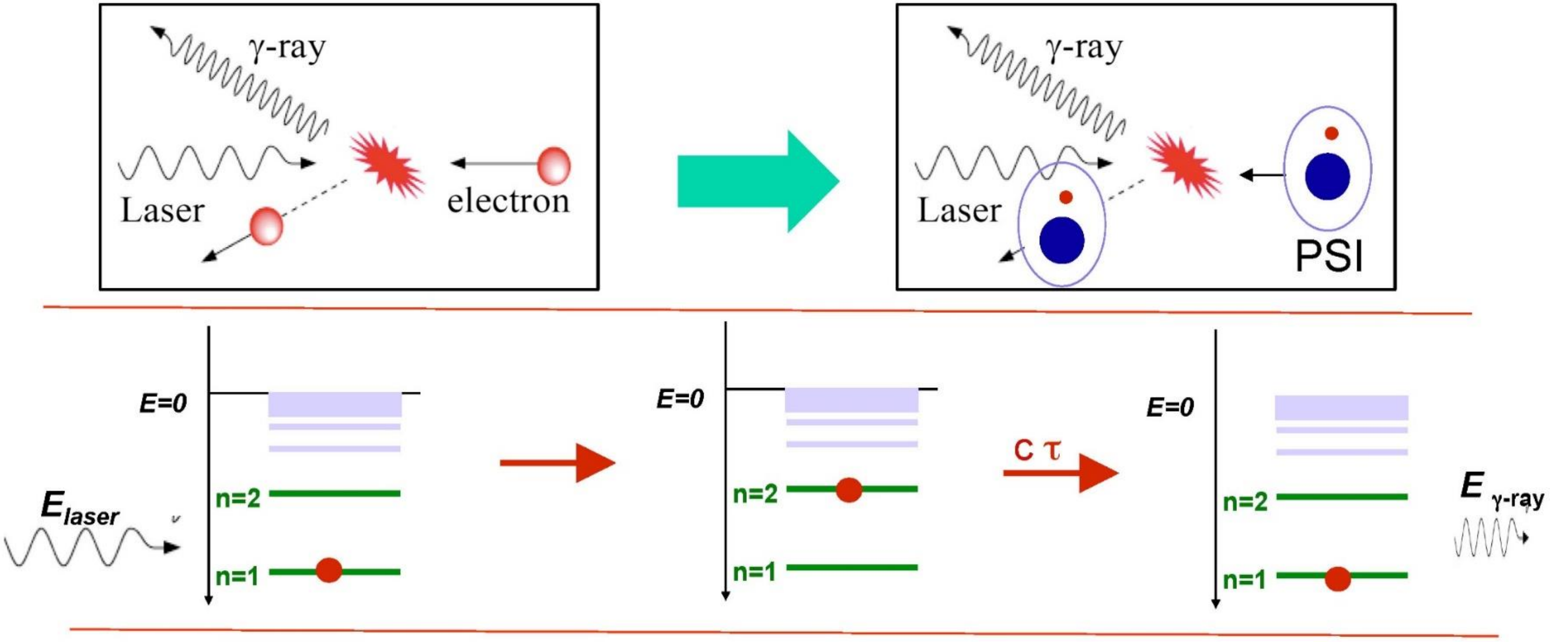
x 33

x 165

LHC based Gamma Factory could provide 100x more e^+/s than needed

"Gamma Factory" based on "PSI" Compton back scattering at LHC or FCC

Simple Idea: replace an Electron beam by a Partially Stripped Ion (PSI) beam



$E_{laser} = 1Ry\,(Z^2 - Z^2/n^2)/2\gamma_L$ → $E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^2/(1+(\gamma_L\theta)^2)$

Note: $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

high photon energies,
high cross section

W. Krasny

muon decay during acceleration ☹

#turns a muon survives in a ring:

$$n_{surv} = \frac{F}{2\pi} \frac{\tau_{\mu,0} c^2 e B}{m_\mu c^2} \approx 209\ B[T]$$

G.I. Budker, High Energy Phys. Conf. (Kiev, 1970)

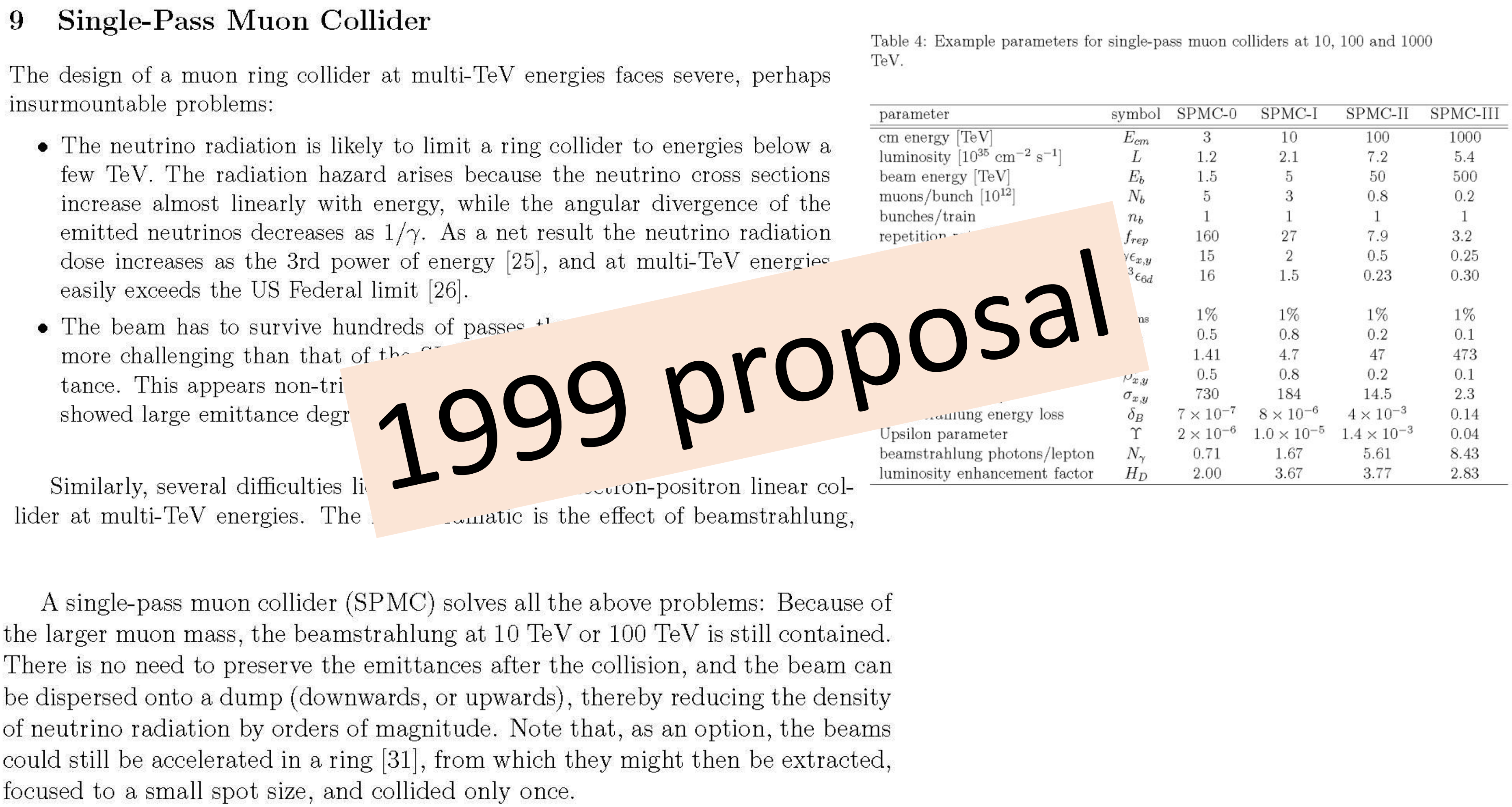
F=0.7 (dipole filling factor) & B=20 T → $n_{surv} = $ 4000 turns; in a 100-km ring this corresponds to ~1.3 seconds

several problems, e.g.:

- how do we accelerate to 50 TeV in less than a few thousand turns?
- how do we accumulate a significant charge?

one possibility: linear muon collider

F. Zimmermann, “Final Focus Challenges for Muon Colliders at Highest Energies,” CERN-SL-99-077-AP.- AIP Conf. Proc.: 530 (1999) , pp. In : Colliders and Collider Physics at the Highest Energies : Muon Colliders at 10 TeV to 100 TeV, Montauk, NY, USA, 27 Sep - 1 Oct 1999, pp.347-367



9 Single-Pass Muon Collider

The design of a muon ring collider at multi-TeV energies faces severe, perhaps insurmountable problems:

- The neutrino radiation is likely to limit a ring collider to energies below a few TeV. The radiation hazard arises because the neutrino cross sections increase almost linearly with energy, while the angular divergence of the emitted neutrinos decreases as $1/\gamma$. As a net result the neutrino radiation dose increases as the 3rd power of energy [25], and at multi-TeV energies easily exceeds the US Federal limit [26].
- The beam has to survive hundreds of passes [illegible] more challenging than that of th[illegible] tance. This appears non-tri[illegible] showed large emittance degr[illegible]

Similarly, several difficulties li[illegible] electron-positron linear collider at multi-TeV energies. The [illegible] dramatic is the effect of beamstrahlung,

A single-pass muon collider (SPMC) solves all the above problems: Because of the larger muon mass, the beamstrahlung at 10 TeV or 100 TeV is still contained. There is no need to preserve the emittances after the collision, and the beam can be dispersed onto a dump (downwards, or upwards), thereby reducing the density of neutrino radiation by orders of magnitude. Note that, as an option, the beams could still be accelerated in a ring [31], from which they might then be extracted, focused to a small spot size, and collided only once.

Table 4: Example parameters for single-pass muon colliders at 10, 100 and 1000 TeV.

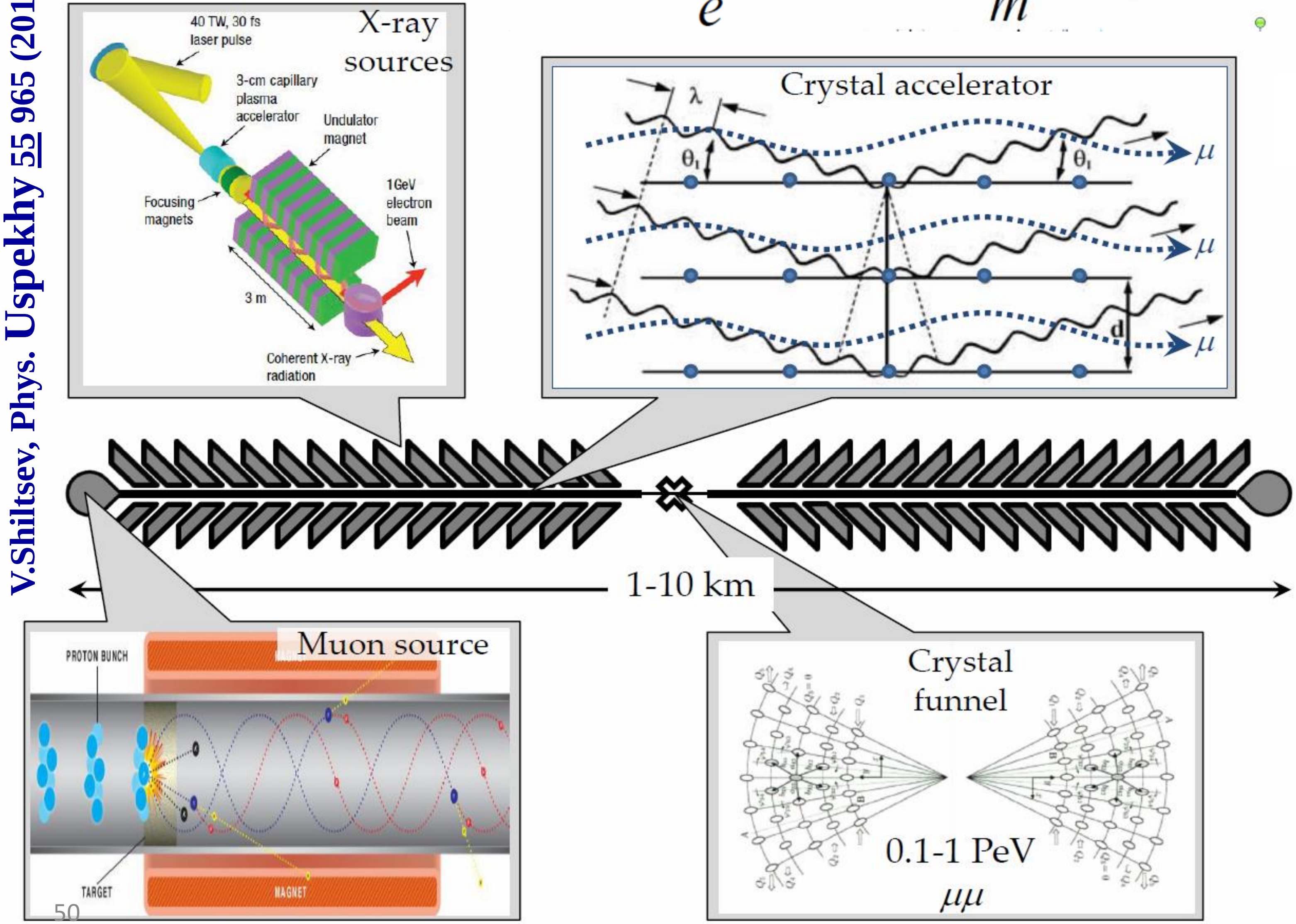
parameter	symbol	SPMC-0	SPMC-I	SPMC-II	SPMC-III
cm energy [TeV]	E_{cm}	3	10	100	1000
luminosity [10^{35} cm^{-2} s^{-1}]	L	1.2	2.1	7.2	5.4
beam energy [TeV]	E_b	1.5	5	50	500
muons/bunch [10^{12}]	N_b	5	3	0.8	0.2
bunches/train	n_b	1	1	1	1
repetition [illegible]	f_{rep}	160	27	7.9	3.2
[illegible]	$\gamma\epsilon_{x,y}$	15	2	0.5	0.25
[illegible]	$^3\epsilon_{6d}$	16	1.5	0.23	0.30
[illegible]	[illegible]	1%	1%	1%	1%
[illegible]	[illegible]	0.5	0.8	0.2	0.1
[illegible]	[illegible]	1.41	4.7	47	473
[illegible]	$\beta_{x,y}$	0.5	0.8	0.2	0.1
[illegible]	$\sigma_{x,y}$	730	184	14.5	2.3
[illegible]ahlung energy loss	δ_B	7×10^{-7}	8×10^{-6}	4×10^{-3}	0.14
Upsilon parameter	Υ	2×10^{-6}	1.0×10^{-5}	1.4×10^{-3}	0.04
beamstrahlung photons/lepton	N_γ	0.71	1.67	5.61	8.43
luminosity enhancement factor	H_D	2.00	3.67	3.77	2.83

1999 proposal

much higher acceleration? muon crystal linac?

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

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



n~10^{22} cm^{-3},
10 TeV/m →

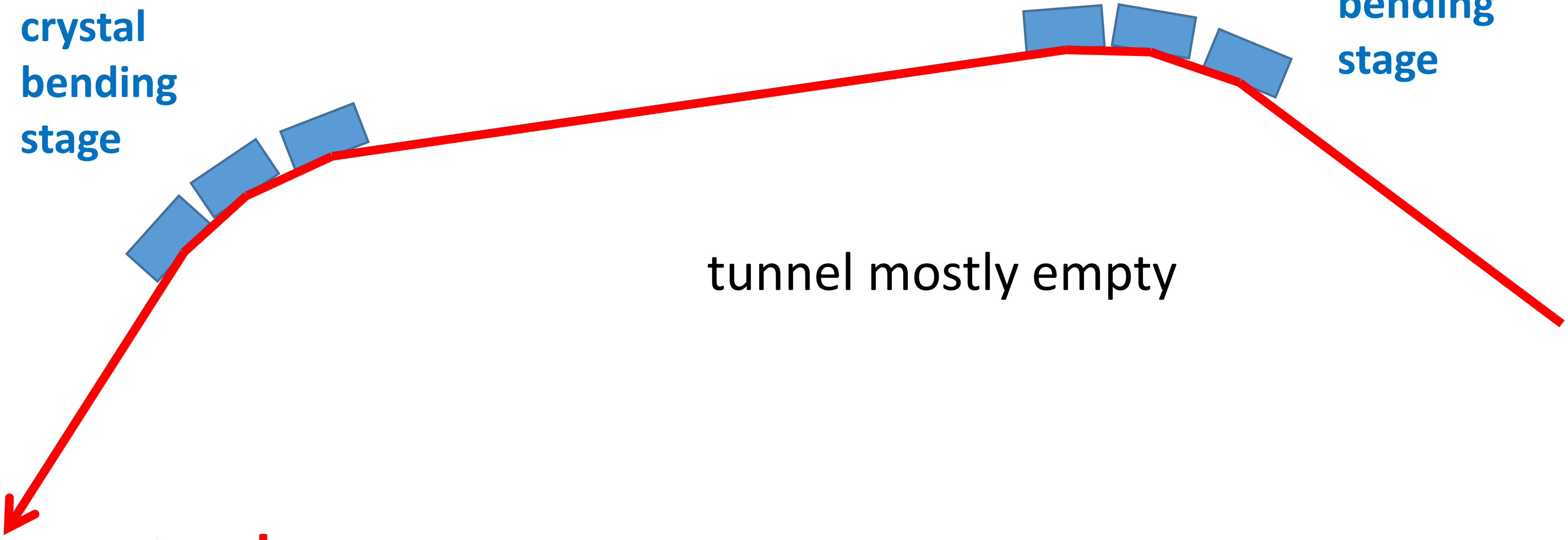
1 PeV =
1000 TeV

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

V. Shiltsev

and/or much higher bending fields?

circular crystal (or nanotube) collider?



cryogenic crystal bending stage

cryogenic crystal bending stage

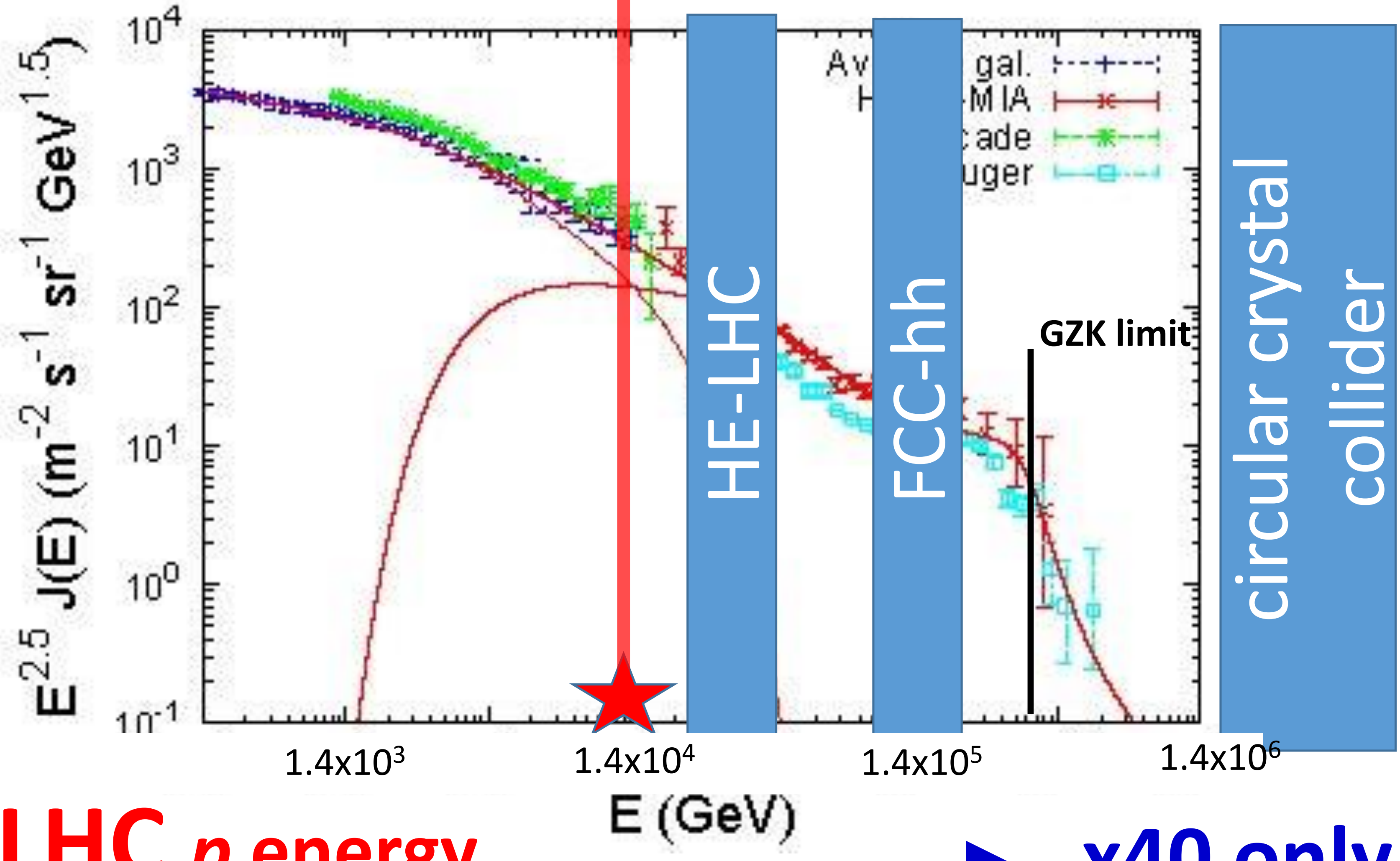
tunnel mostly empty

proton beam

energy ramp using induction acceleration

$10^{45}\ m^{-2}s^{-1}sr^{-1}GeV^{1.5}$!

cosmic-ray **c.m. energy** spectrum



LHC *p* energy

x40 only

“ultimate limit” of electromagnetic acceleration

$E_{\mathrm{cr}} \approx 10^{18}$ V/m

Sauter-Schwinger critical field for e^+e^- pair creation - $\hbar/(m_e c)\, \mathrm{e}\, E_{\mathrm{cr}} \sim m_e c^2$

“ultimate limit” of magnetic bending

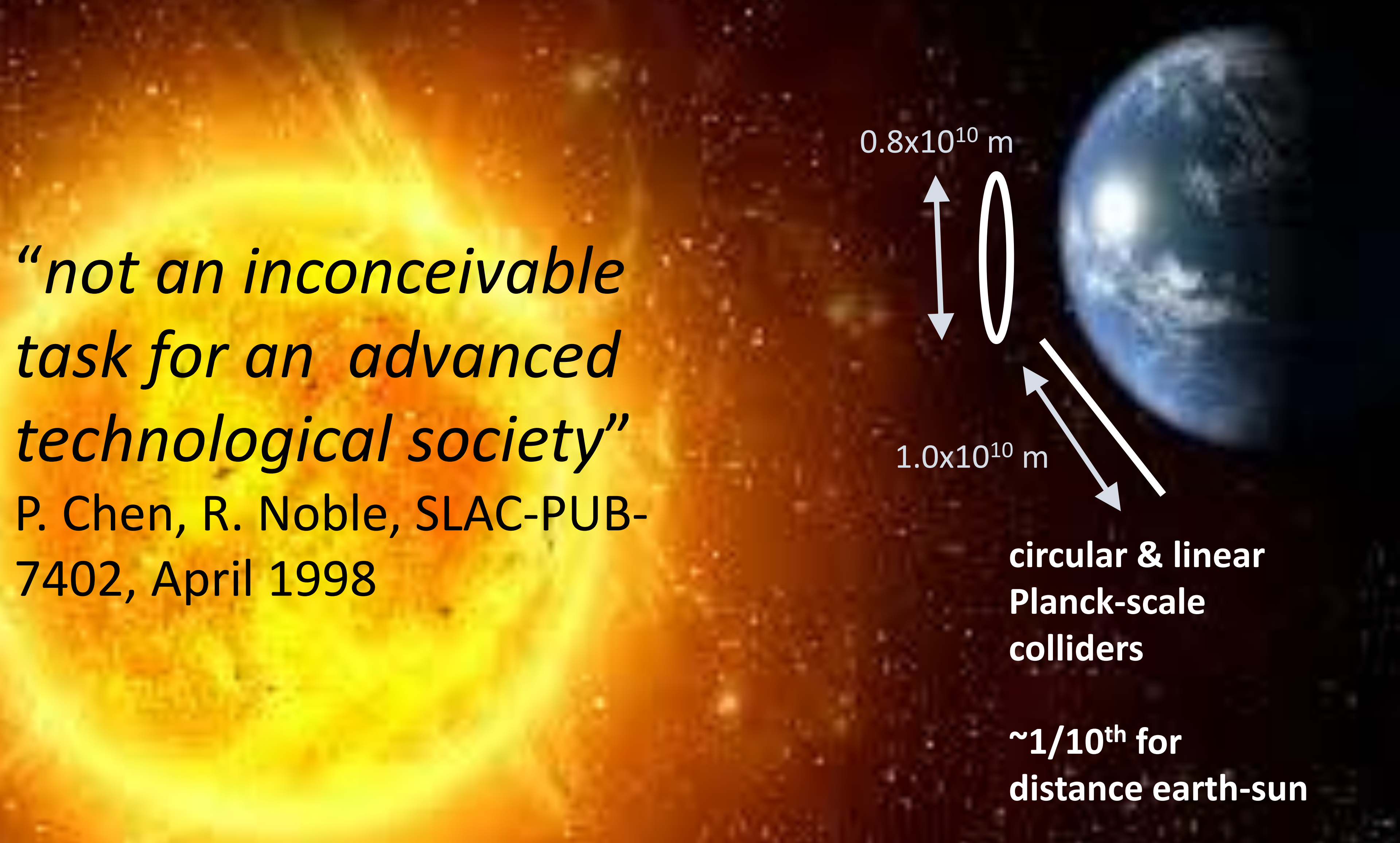
$B_{\mathrm{cr}} \approx 4\mathrm{x}10^9$ T

Sauter-Schwinger critical field for e^+e^- pair creation - $\hbar/(m_e c)\, \mathrm{ec}\, B_{\mathrm{cr}} \sim m_e c^2$

ultimate limit on electromagnetic acceleration

Schwinger critical fields $E_{cr} \approx 10^{12}$ MV/m, $B_{cr} = 4.4 \times 10^{9}$ T

Planck scale: 10^{28} eV



"not an inconceivable task for an advanced technological society"

P. Chen, R. Noble, SLAC-PUB-7402, April 1998

circular & linear Planck-scale colliders

~1/10th for distance earth-sun

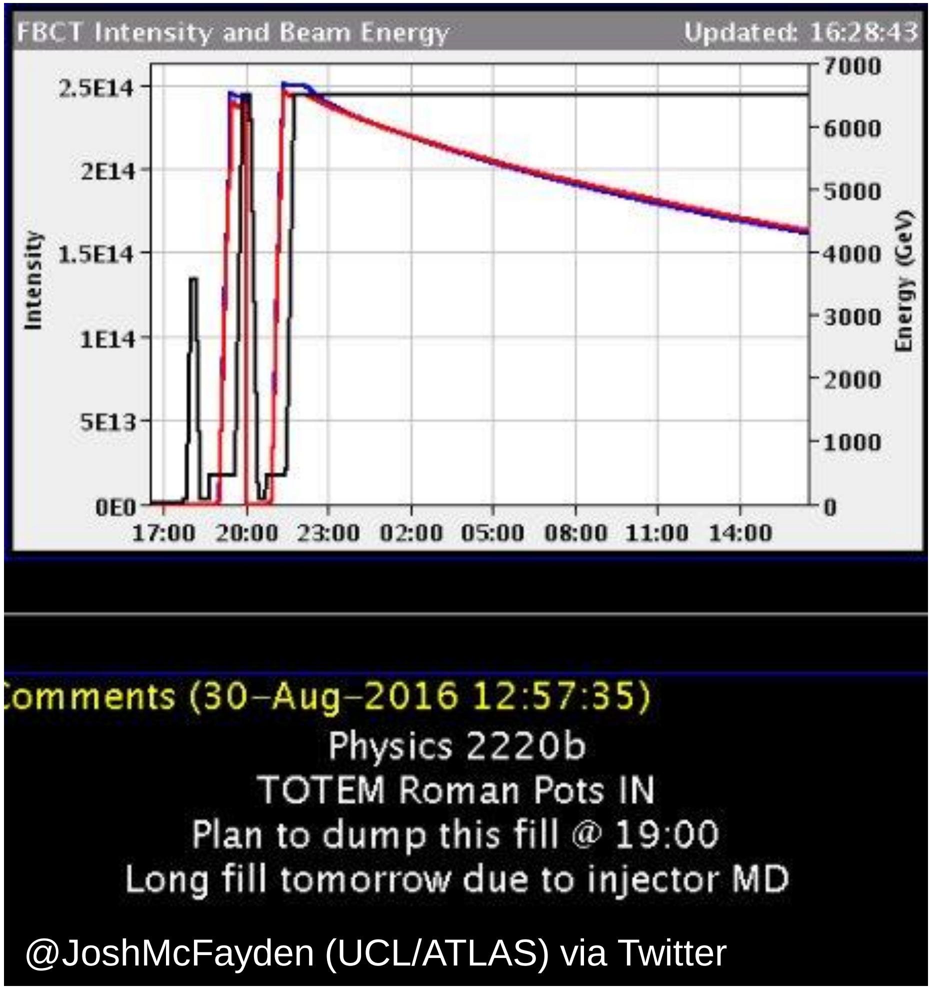
final challenges for the audience

can we use accelerators to detect or generate gravitational waves?

can crystal accelerators work (accel./bending)?

how could we approach the Planck scale?
can we accelerate beyond the Schwinger limit?
– "quantum plasma accelerator"??
– acceleration using a different force?
  (e.g. gravity / black holes ?)
– "cheating with entanglement"?

A Case for Optimism



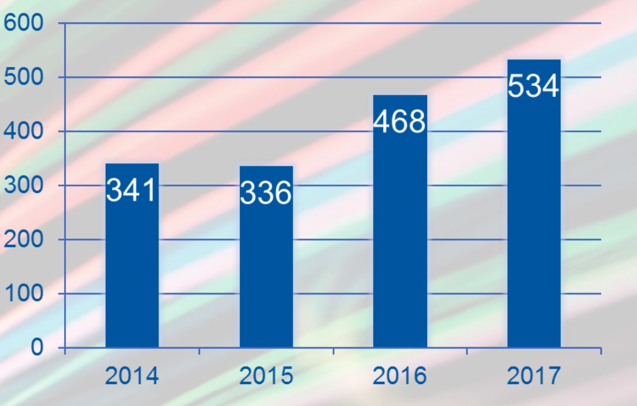
omments (30-Aug-2016 12:57:35)

Physics 2220b
TOTEM Roman Pots IN
Plan to dump this fill @ 19:00
Long fill tomorrow due to injector MD

@JoshMcFayden (UCL/ATLAS) via Twitter

- 2 * 2.5e14 * 6500 GeV
- = 521 MJ
- = 0.266 E_{Planck}

- Total energy is OK but it’s in too many particles



> 500 participants
147 institutes
a lot of young people
(>35% younger than 35)

FCCWEEK2017

Future Circular Collider Conference

BERLIN, GERMANY

29 MAY - 02 JUNE

fccw2017.web.cern.ch

FCC WEEK 2018

AMSTERDAM, 9-13 April 2018

also: 2018 FCC Physics Workshop, 15-19 January 2018, CERN