Summary of Open Symposium on European Strategy Upgrade: Accelerators

Moses Chung (Dept. of Physics, UNIST)

KAIST-KAIX Workshop for Future Particle Accelerators

July 8-19, 2019, Daejeon, Korea

Accelerators summary

Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann

Open Symposium towards updating the European Strategy for Particle Physics

May 13-16, 2019, Granada, Spain

Accelerators related inputs

About 60 different inputs + national inputs which include accelerators

- e+e- colliders
- hh colliders
- ep colliders
- FCC
- Gamma factories
- Plasma acceleration
- Muon colliders
- Beyond colliders
- Technological developments

Input to speakers:

- Contributions of the community
- Coherent parameters (Integrated luminosity, duty cycle, readiness definition, …)
- What about costs and time schedule?

Output from speakers

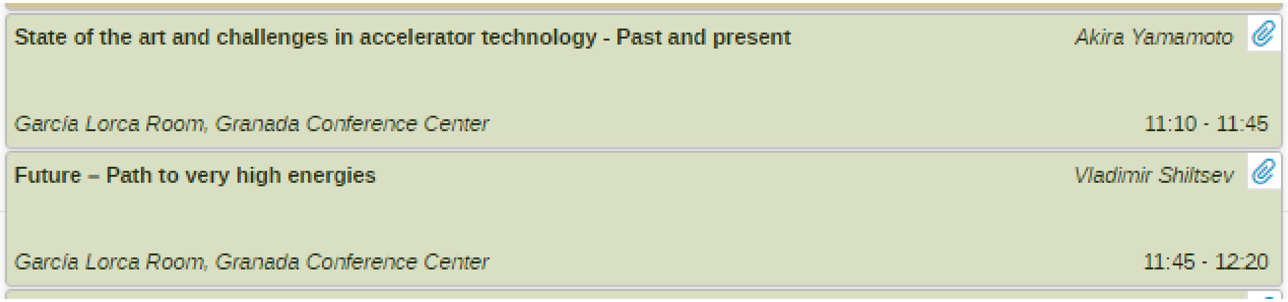
- comprehensive summary of 2-3 slides, including open questions, challenges, opportunities and objectives.

Big Questions

In particular for the Accelerator Science and Technology

- What is the best implementation for a Higgs factory? Choice and challenges for accelerator technology: linear vs. circular?
- Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
- How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
- Energy management in the age of high-power accelerators?

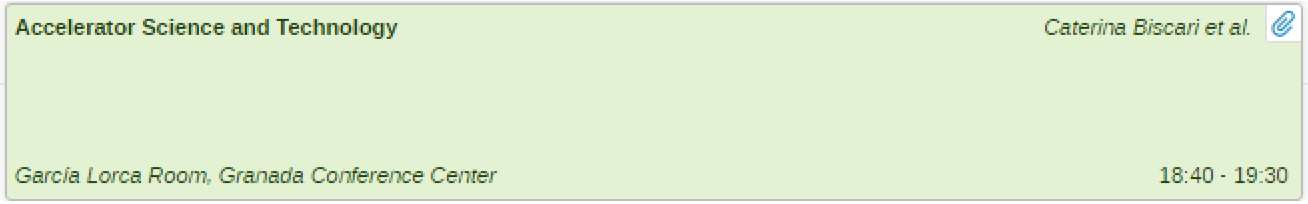
Mon 13/5


State of the art and challenges in accelerator technology - Past and present *Akira Yamamoto*
García Lorca Room, Granada Conference Center 11:10 - 11:45

Future – Path to very high energies *Vladimir Shiltsev*
García Lorca Room, Granada Conference Center 11:45 - 12:20

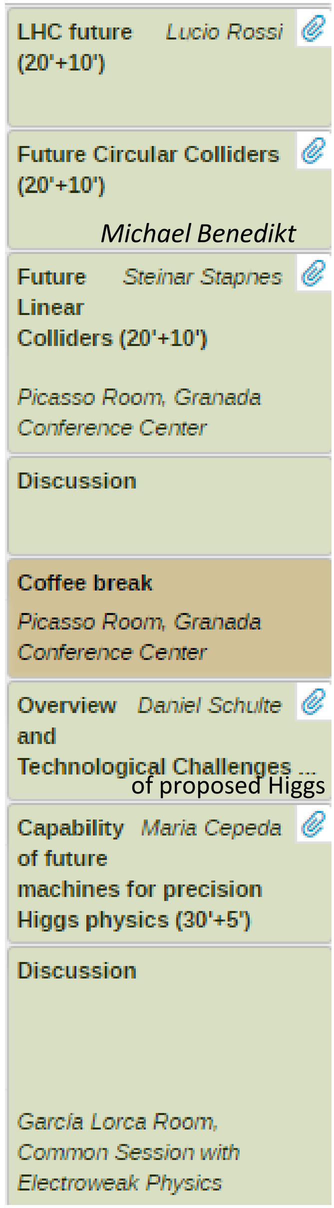
2 plenary

Wed 15/5


Accelerator Science and Technology *Caterina Biscari et al.*
García Lorca Room, Granada Conference Center 18:40 - 19:30

1 summary

Mon 13/5


LHC future (20'+10') *Lucio Rossi*

Future Circular Colliders (20'+10')
Michael Benedikt

Future Linear Colliders (20'+10') *Steinar Stapnes*
Picasso Room, Granada Conference Center

Discussion

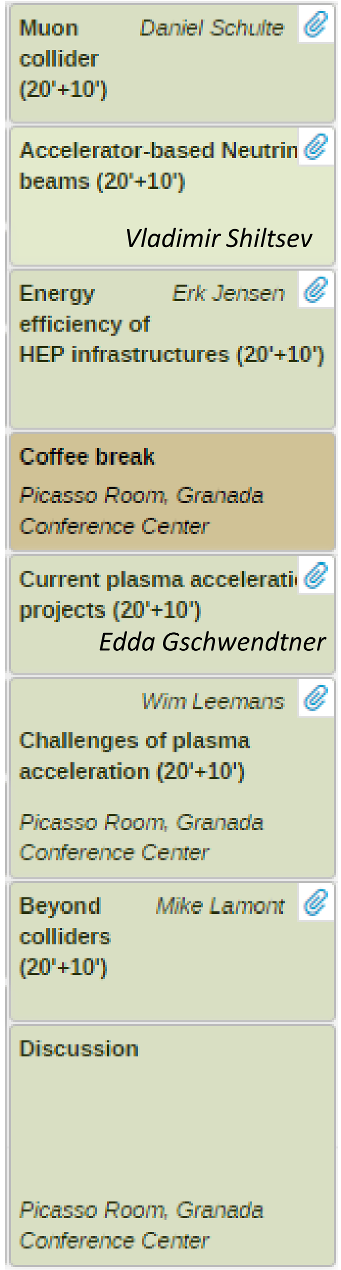
Coffee break
Picasso Room, Granada Conference Center

Overview and Technological Challenges ... *Daniel Schulte*
of proposed Higgs Factories

Capability of future machines for precision Higgs physics (30'+5') *Maria Cepeda*

Discussion
García Lorca Room, Common Session with Electroweak Physics

Tue 14/5


Muon collider (20'+10') *Daniel Schulte*

Accelerator-based Neutrin beams (20'+10')
Vladimir Shiltsev

Energy efficiency of HEP infrastructures (20'+10') *Erk Jensen*

Coffee break
Picasso Room, Granada Conference Center

Current plasma accelerati projects (20'+10')
Edda Gschwendtner

Wim Leemans
Challenges of plasma acceleration (20'+10')
Picasso Room, Granada Conference Center

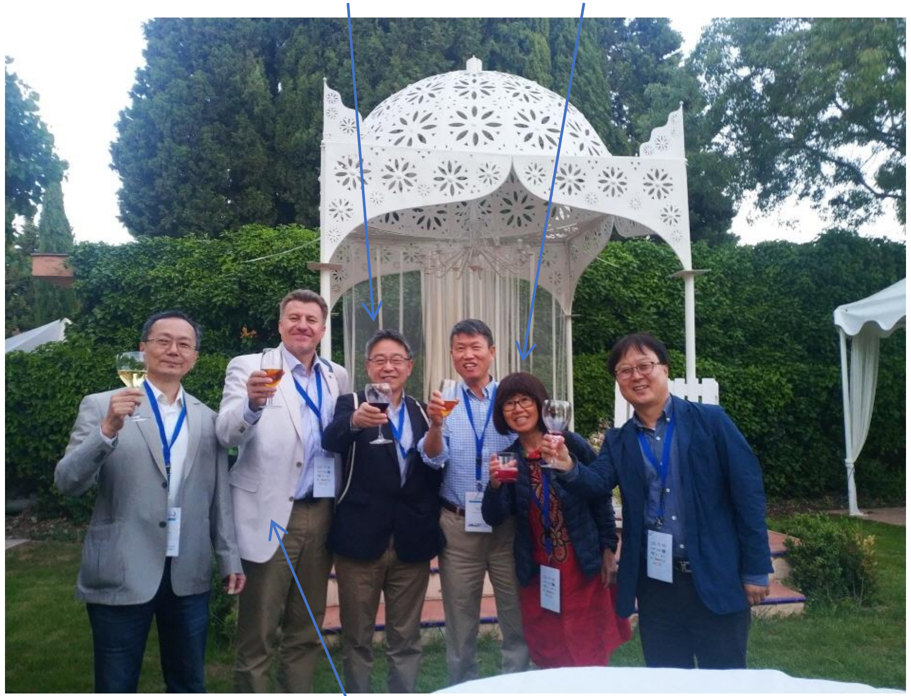
Beyond colliders (20'+10') *Mike Lamont*

Discussion
Picasso Room, Granada Conference Center

11 WG

Jie: CepC

Young-Kee: Colliders



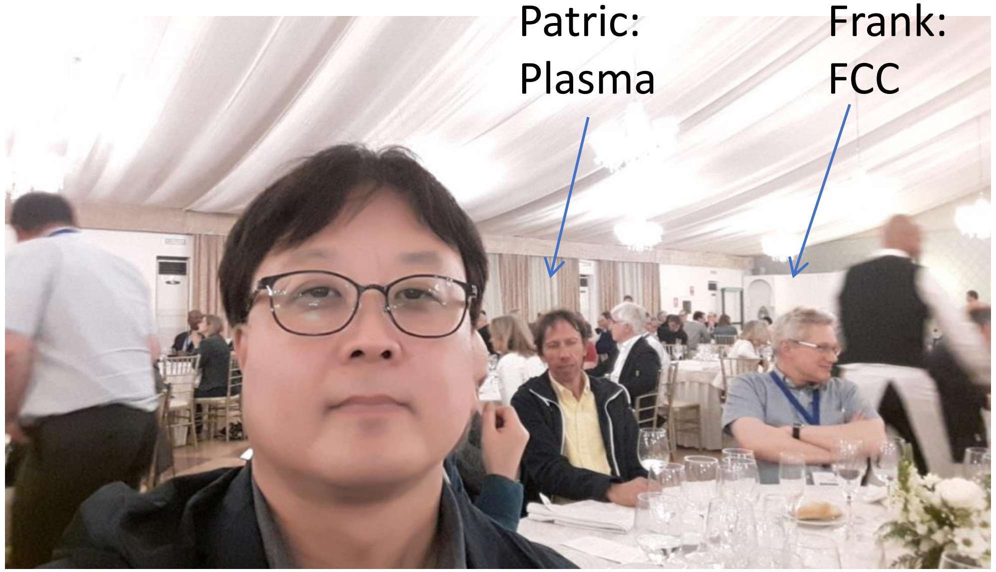
Ken:
Muon
collider

Vladimir:
Colliders

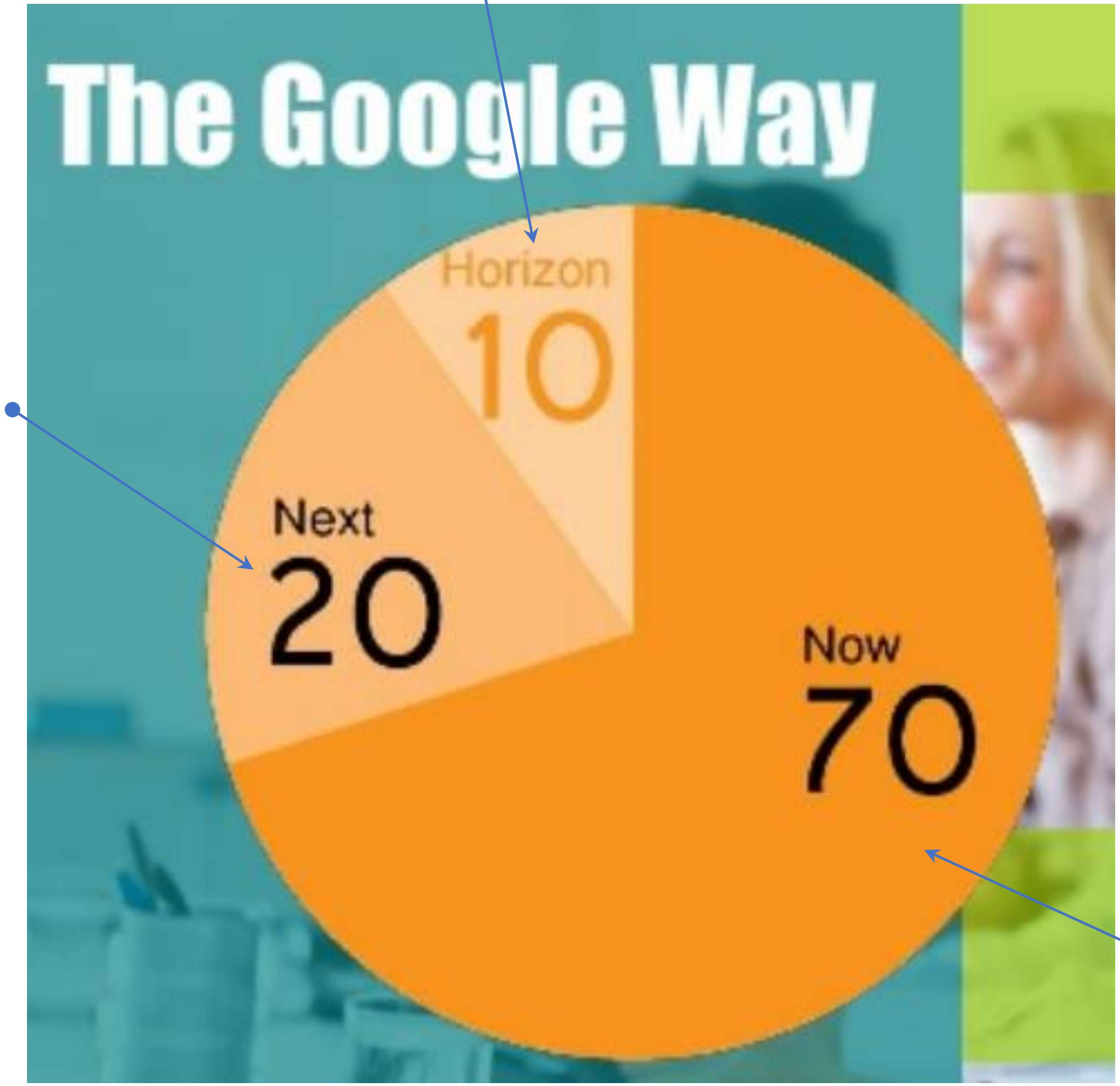
Edda:
Plasma

Patric:
Plasma

Frank:
FCC

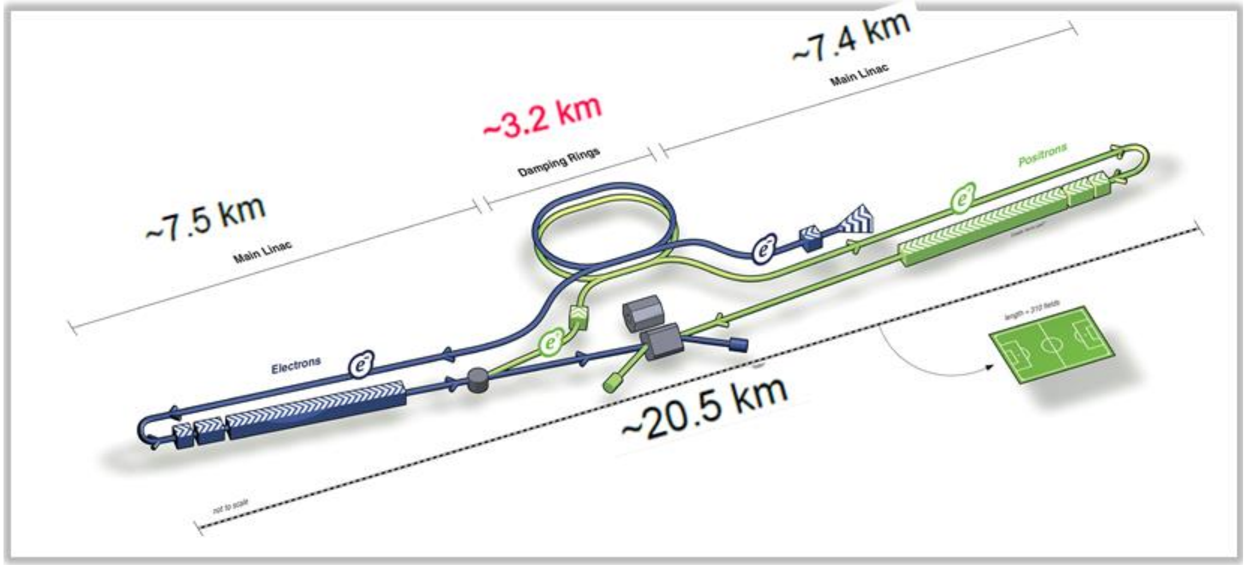


Plasma/Muon



ILC/CLIC
CEPC/FCC

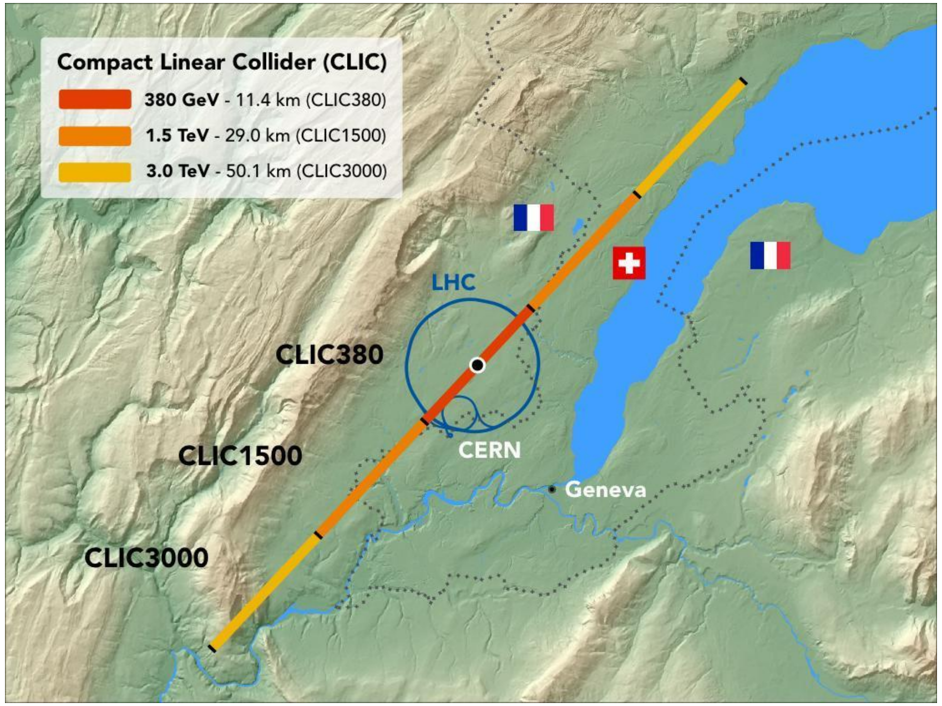
LHC
HL-LHC

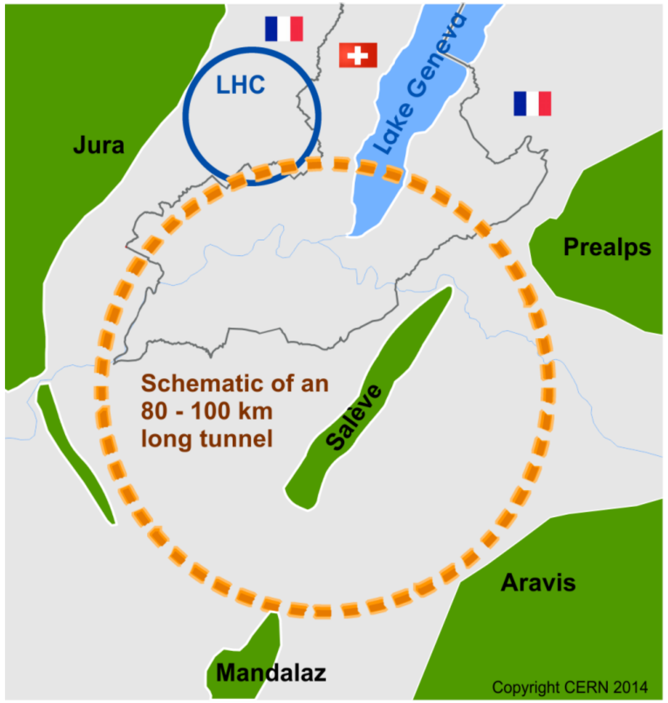


easy access
300 km east
from Beijing
3h by car
1h by train

Yifang Wang

"Chinese Toscana"





Schematic of an 80 - 100 km long tunnel

Copyright CERN 2014

Q1: What is the best implementation for a Higgs factory?

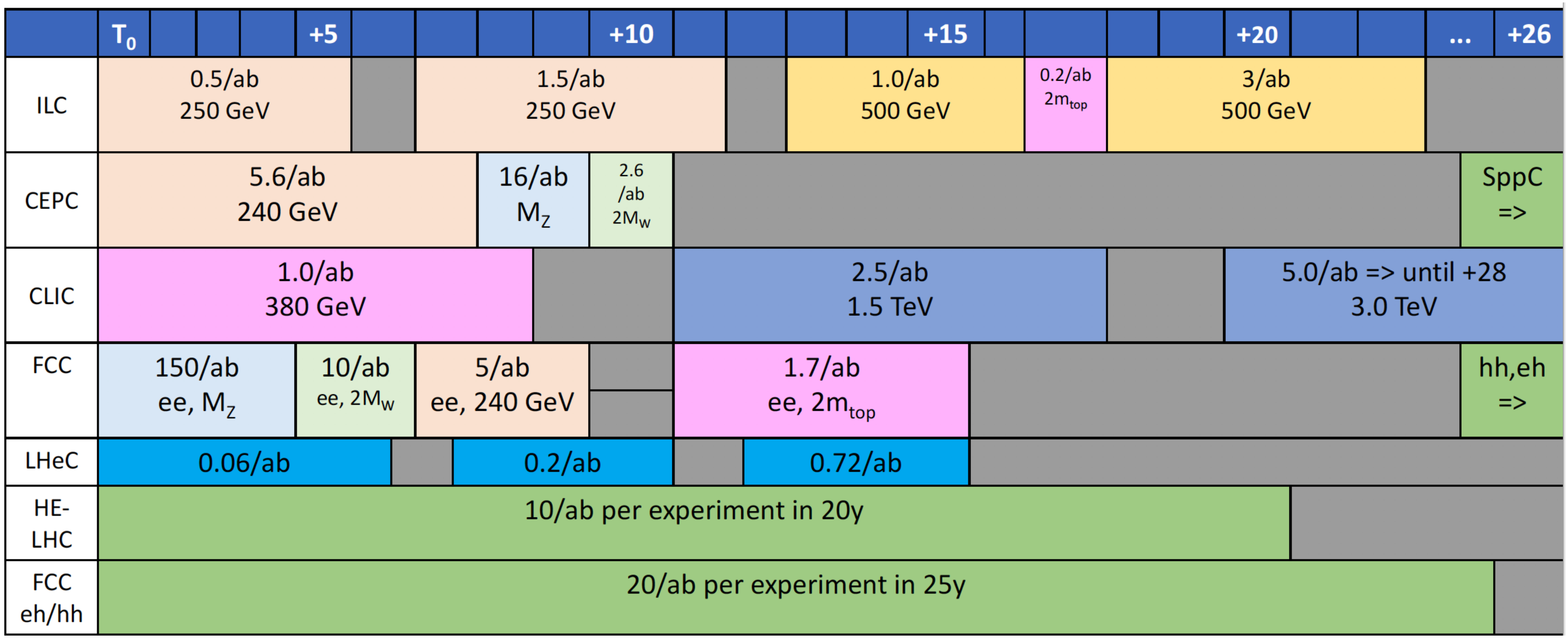
Choice and challenges for accelerator technology: linear vs. circular?

Comparisons

1 G = 1 Billion = 1,000,000,000
“ILCU” as the United States dollar as in January 2012
CHF ~ US$

Project	Type	Energy [TeV]	Int. Lumi. $[a^{-1}]$	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Proposed Schedules and Evolution



T_0 +5 +10 +15 +20 … +26

ILC: 0.5/ab 250 GeV; 1.5/ab 250 GeV; 1.0/ab 500 GeV; 0.2/ab $2m_{top}$; 3/ab 500 GeV

CEPC: 5.6/ab 240 GeV; 16/ab M_Z; 2.6 /ab $2M_W$; SppC =>

CLIC: 1.0/ab 380 GeV; 2.5/ab 1.5 TeV; 5.0/ab => until +28 3.0 TeV

FCC: 150/ab ee, M_Z; 10/ab ee, $2M_W$; 5/ab ee, 240 GeV; 1.7/ab ee, $2m_{top}$; hh,eh =>

LHeC: 0.06/ab; 0.2/ab; 0.72/ab

HE-LHC: 10/ab per experiment in 20y

FCC eh/hh: 20/ab per experiment in 25y

Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

Luminosity Challenge

*beamstrahlung (the energy loss caused by radiation of gamma quanta by the incoming electron due to its interaction with the EM field electron (positron) bunch moving in the opposite direction) during the very moment of collision of short bunches

Luminosity cannot be fully demonstrated before the project implementation

- Luminosity is a feature of the facility not the individual technologies
- Have to rely on experiences, theory and simulations
- Foresee margins

FCC-ee and CEPC are based on experience from LEP, DAPHNE, KEKB, PEP II, superKEKB, …

- Gives confidence that we understand performance challenges
- New beam physics occurs in the designs,
    - e.g. beamstrahlung* is unique feature of FCC-ee and CEPC
        - Identified and anticipated in the design, should be able to trust simulations
- The technologies required are improved versions of those from other facilities

Linear colliders are based on experiences from SLC, FELs, light sources, …

- Gives confidence that we understand the performance challenges
- Gives us confidence that we can do better than SLC
- Still performance goal more ambitious, e.g. beam size of nm scale
    - Creates additional challenges and requires additional technologies, e.g. stabilisation
- A part of the technologies are improved versions of those from other facilities
- Some had to be purpose-developed for linear colliders

All studies prioritised their work because of limited resources

- Depending on your preference you will see holes in any of them that you find are unacceptable
- Or you will be convinced that this very issue is a mere detail …

Maturity

- CEPC and FCC-ee, LHeC
  - Do not see a feasibility issue with technologies or overall design
  - But more hardware development and studies essential to ensure that the performance goal can be fully met
    - E.g. high power klystrons, strong-strong beam-beam studies with lattice with field errors, …

- ILC and CLIC
  - Do not see a feasibility issue with technology or overall design
  - Cutting edge technologies developed for linear colliders
    - ILC technology already used at large scale
    - CLIC technology in the process of industrialisation
  - More hardware development and studies required to ensure that the performance goal can be full met
    - e.g. undulator-based positron source, BDS (Beam Delivelry System) tuning, …

- Do not anticipate obstacle to commit to either CEPC, FCC-ee, ILC or CLIC
  - But a review is required of the chosen candidate(s)
  - More effort required before any of the projects can start construction

- Guidance on project choice is necessary
  - Physics potential
  - Strategic considerations

Higgs Factories

- e+e- linear
  - ILC **Input #77**
  - CLIC **Input #146**
- e+e- circular
  - FCC-ee **Input #132**
  - CepC **Input #51**
- μ+μ- circular
  - μ-HF **Input #120**

Requirement: high luminosity $O(10^{34})$ at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine :

- 27 km long
- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost "1 LHC Unit" *

Fermilab

** as a project, i.e. w/o existing tunnel and injectors*

Finding *Common Denominators* * – Three Factors

** to be further discussed in the Symposium's accelerator sessions*

- ***F1*** **"Technology Readiness" :**

Green - TDR
Yellow - CDR
Red - R&D

- ***F2*** **"Energy Efficiency"**

Green : 100-200 MW
Yellow : 200-400 MW
Red : > 400 MW

- ***F3*** **"Cost" :**

Green : < LHC
Yellow : 1-2 x LHC
Red : > 2x LHC

Higgs Factories	**Readiness**	**Power-Eff.**	**Cost**
ee Linear *250 GeV*	🟩	🟩	🟩🟨
ee Rings *240GeV/tt*	🟨🟩	🟨	🟨
μμ Collider *125 GeV*	🟥	🟨	🟩 *
Highest Energy			
ee Linear *1-3TeV*	🟨🟩	🟨🟥	🟥
pp Rings *HE-LHC*	🟥🟨	🟩	🟨
FCC-hh/SppC	🟥🟨	🟥	🟥
μμ Coll. *3-14 TeV*	🟥	🟨	🟩🟨 *

7-10 YEARS FROM NOW

WITH PROPOSED ACTIONS / R&D DONE / TECHNICALLY LIMITED

- ***ILC:***
  - Some change in cost (~6-10%)
  - All agreements by 2024, then
  - **Construction** (2024-2033)
- ***CLIC:***
  - TDR & preconstr. ~2020-26
  - **Construction** (2026-2032)
  - 2 yrs of commissioning
- ***CepC:***
  - Some change in cost & power
  - TDR and R&D (2018-2022)
  - **Construction** (2022-2030)
- ***FCC-ee:***
  - Some change in cost & power
  - **Preparations** 2020-2029
  - Construction 2029-2039
- ***HE-LHC:***
  - **R&D and prepar'ns** 2020-2035
  - Construction 2036-2042
- ***FCC-hh*** (w/o FCC-ee stage)***:***
  - **16T magnet prototype** 2027
  - Construction 2029-2043
- ***μ^+-μ^- Collider :***
  - **CDR completed** 2027, cost known
  - Test facility constructed 2024-27
  - Tests and TDR 2028-2035

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	[illegible]	(to be filled)	[illegible] 120	[illegible]	[illegible]	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	[illegible]	[illegible] 0.37	[illegible]60 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - [illegible] (0.37)	32~ 5	150 – 270	5 [B$]		20 (40)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8 - 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	[illegible]	[illegible] (-3)	[illegible] (-6)	160 (-580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

Major Technical Challenges:

Hadron Colliders:

- High-field magnet
- Energy management

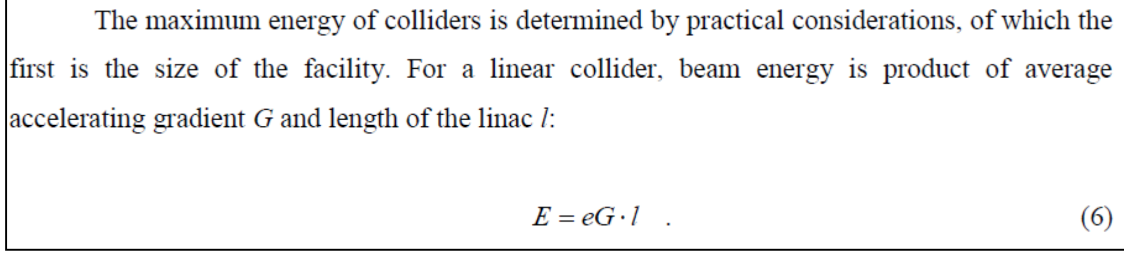
Lepton Colliders:

- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

A. Yamamoto, 190513b

*Cost estimates are commonly for "**Value**" (material) only.

RF technology


The maximum energy of colliders is determined by practical considerations, of which the first is the size of the facility. For a linear collider, beam energy is product of average accelerating gradient G and length of the linac l:

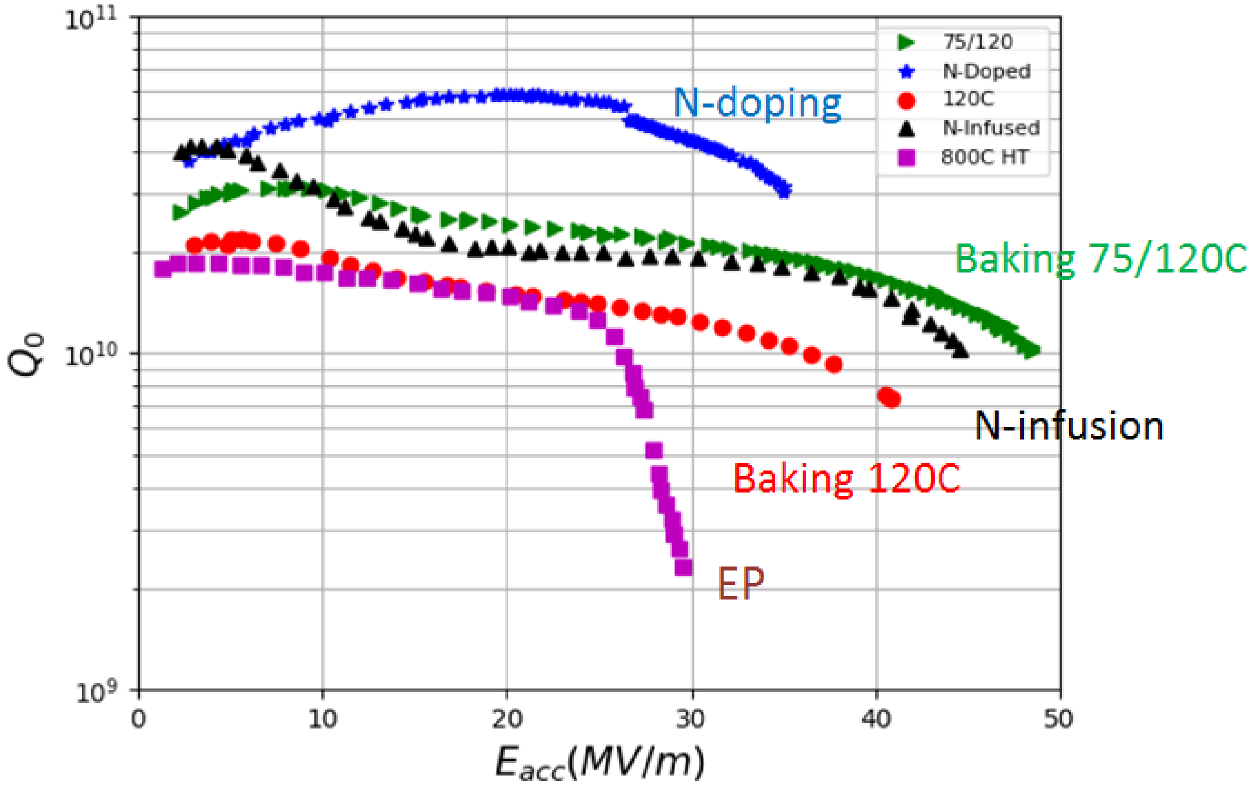
$$E = eG \cdot l \quad . \qquad (6)$$

- Accelerator Technologies are ready to go forward for **lepton colliders** (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory **construction to begin in > ~5 years.**
- SRF accelerating technology is well **matured** for the realization including cooperation with industry.

- Continuing R&D effort for higher performance is very important for future project upgrades.
  - **Nb-bulk, 40 – 50 MV/m**: ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities statistics to be integrated. Ready **for the upgrade**, **10 ~ 15 years.**

State of the Art in High-Q and High-G (1.3 GHz, 2K)

Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019



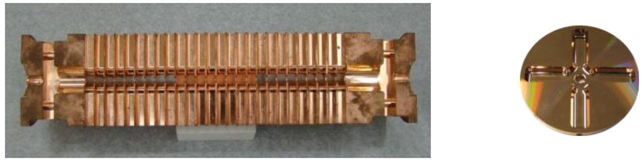
- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- **High-Q** by **N-Doping** well established, and
- **High-G** by N-infusion and **Low-T baking** still to be understood and reproduced, worldwide.

Courtesy: W. Wuensch

Features of Normal conducting and Superconducting RF

Normal conducting (CLIC)	Superconducting (ILC)
Gradient: 72 to 100 MV/m - Higher energy reach, shorter facility	Gradient: 31.5 to 35 (to 45) MV/m, - Higher efficiency, steady state beam power from RF input
RF Frequency: 12 GHz - High efficiency RF peak power - Precision alignment & stabilization to compensate wakefields	RF Frequency: 1.3 GHz - Large aperture gives low wakefields
Q_0: order $< 10^5$, - Resistive copper wall losses compensated by strong beam loading – 40% steady state rf-to-beam efficiency	Q_0: order 10^{10}, - High Q - losses at cryogenic temperatures
Pulse structure: 180 ns / 50 Hz	Pulse structure: 700 µs / 5 Hz
Fabrication: - driven by micron-level mechanical tolerances	Fabrication - driven by material (purity) & clean-room type chemistry
- High-efficiency RF peak power production through long-pulse, low freq. klystrons and two-beam scheme	- High-efficiency RF also from long-pulse, low-frequency klystrons



A. Yamamoto, 190513b

Q2: Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
		(to be filled)	75 - 120			TBD	12 -		High-field SCM - IBS: Jcc and mech. stress Energy management
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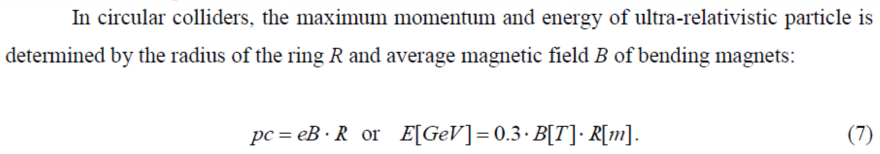


In circular colliders, the maximum momentum and energy of ultra-relativistic particle is determined by the radius of the ring R and average magnetic field B of bending magnets:

$$pc = eB \cdot R \quad \text{or} \quad E[GeV] = 0.3 \cdot B[T] \cdot R[m]. \qquad (7)$$

Lepton Colliders:

- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

A. Yamamoto, 190513b

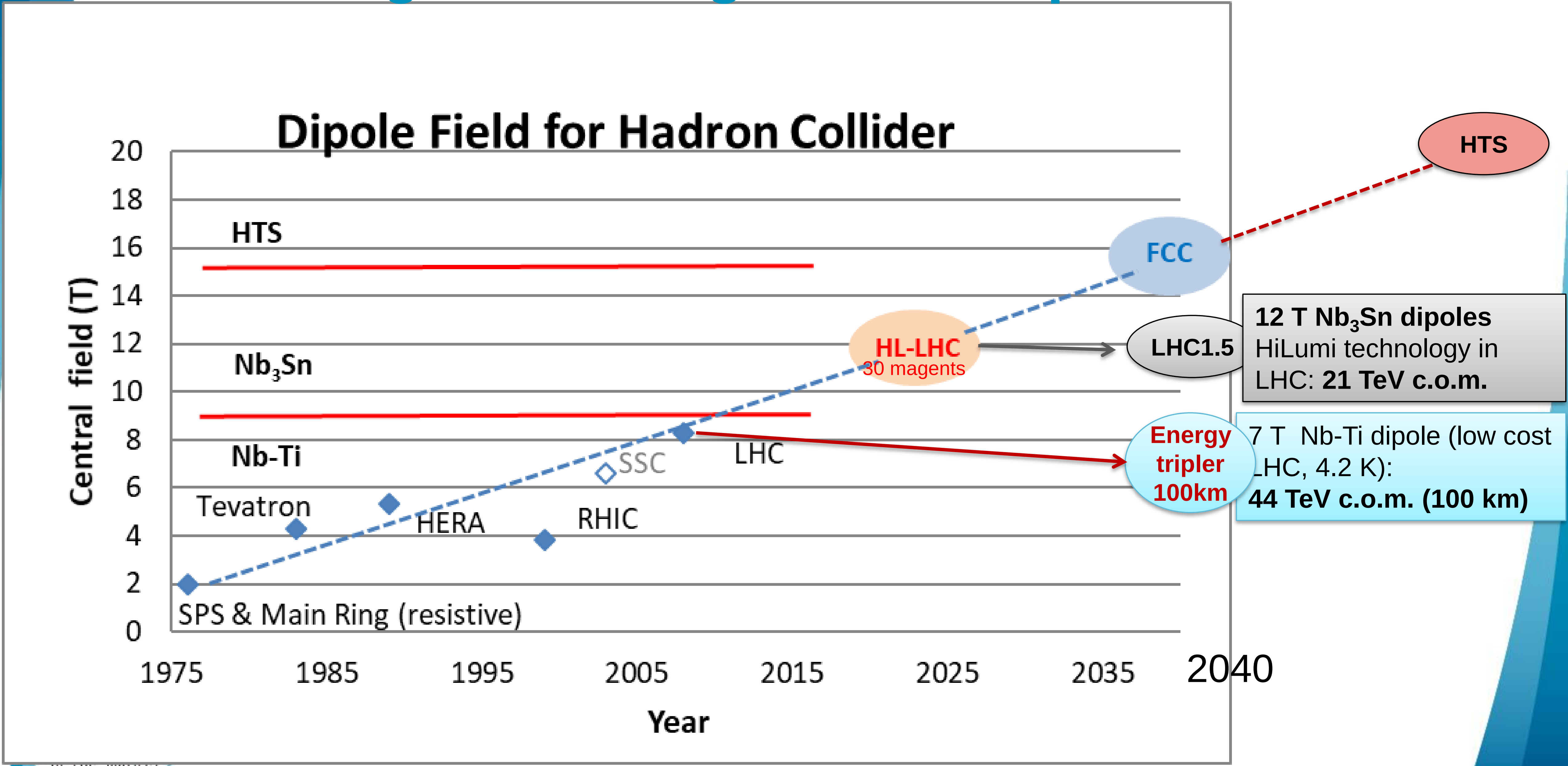
*Cost estimates are commonly for "**Value**" (material) only.

Lucio Rossi – CERN
HL-LHC Project Leader

p-p machine CERN

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.1	1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.4	0.7	0.36

High field magnet development



12 T Nb$_3$Sn dipoles
HiLumi technology in
LHC: **21 TeV c.o.m.**

7 T Nb-Ti dipole (low cost
LHC, 4.2 K):
44 TeV c.o.m. (100 km)

Conclusions

- HiLumi will allow LHC to continue to produce top class HEP till 2035-2040; it is technology drivers and buys time for next project
- A HE-LHC of 27 TeV (16 T dipoles) is probably for 2050…
- **A new HEP hadron collider to start in 2040 can be – with realism – a LHC1.5 @ 21 TeV, based on 12 T magnets of HiLumi technology and SC.** If treated as un upgrade (and not as a full new project, may save time&money (cryogenics and T.I. …)
- The LHeC machine may be a mid-size project to fill the gap to a very large project (like FCC-hh) **or a very appealing complement** in case of:
  - LHC used as Injector for FCC-hh (today baseline of FCC study)
  - LHC1.5 at 10.5 TeV/beam (from 2040)
  - HE-LHC at 13.5 TeV/beam (from 2050)

s.c. magnet technology

- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, and 16 T**.
- It would require the following **time-line** (in my personal view):
  - **Nb_3Sn, 12~14 T:** 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn, 14~16 T:** 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral time line).
  - **NbTi , 8~9 T:** proven by LHC and **Nb_3Sn, 10 ~ 11 T** being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.
- **Continuing R&D effort** for high-field magnet, present to future, should be critically **important**, to realize highest energy frontier hadron accelerators in future.

Intensify HTS accelerator magnet development

Personal (A. Yamamoto) View on Relative Timelines

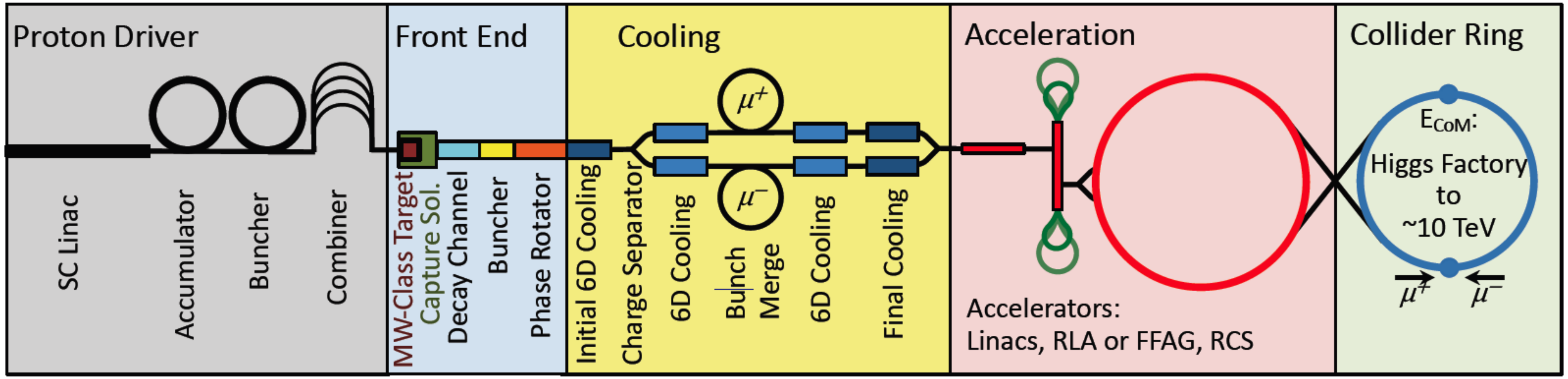
Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	**Construction**		**Operation**		**Upgrade**	
NRF—LC	Proto/pre-series	**Construction**		**Operation**		**Upgrade**	
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	**Construction**		**Operation**			**Upgrade**
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		**Construction**		**Operation**	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			**Construction**	

Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> **(8.3 T)** Production started in late 1990's, in **~ 15 years**

A. Yamamoto, 190512b

Proton-driven Muon Collider Concept

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

As a Higgs factory:

Key facts:

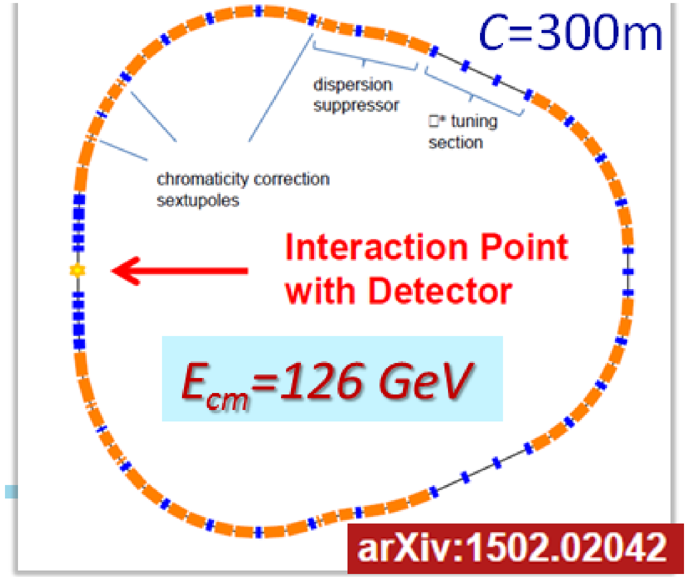
1/100 luminosity requirements (large cross-section in ***s*-channel**)

Half the energy 2 x 63 GeV $\mu+\mu- \rightarrow H_0$

Small footprint (<10 km) and low cost

Small(est) energy spread ~3 MeV

Total site power ~200MW (tbd)



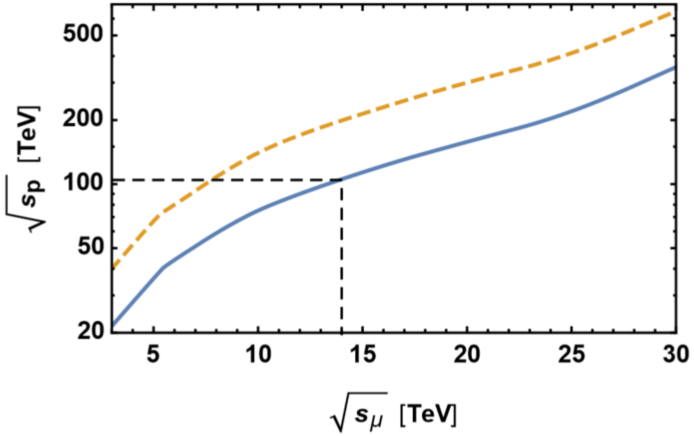
arXiv:1502.02042

As a High Energy Collider:

***Advantages*:**

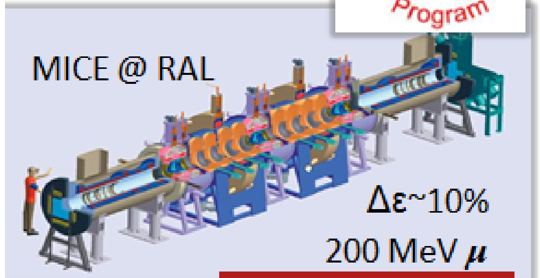
- ***μ***'s do not radiate / no beamstrahlung→ acceleration in rings → *low cost & great power efficiency*
- ~ *x7* energy reach vs *pp*

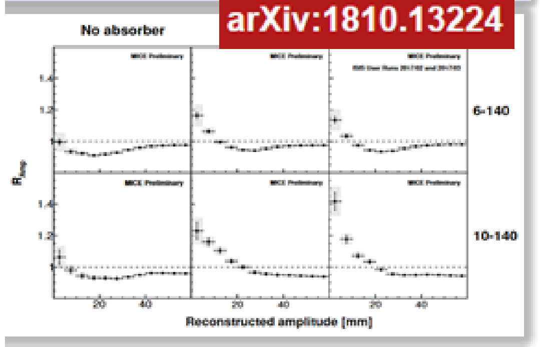
Offer *"moderately conservative - moderately innovative"* path **to cost affordable** energy frontier colliders:

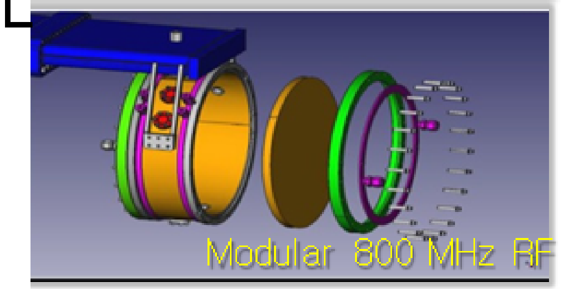


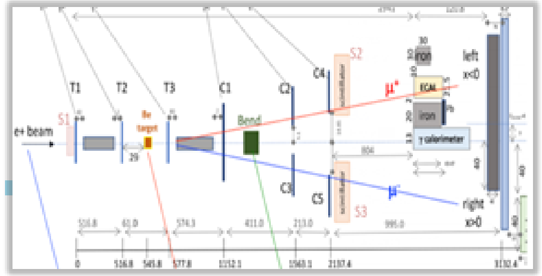
Recent progress: *μ+μ- Colliders*

- Ionization cooling of muons:
  - Demonstrated in MICE @ RAL
  - 4D emittance change *O*(10%)
- NC RF 50 MV/m in 3 T field
  - Developed and tested at Fermilab
- Rapid cycling HTS magnets
  - Record 12 T/s – built and tested at FNAL
- First RF acceleration of muons
  - J-PARC MUSE RFQ 90 KeV
- US MAP Collaboration → Int'l
- Low emittance (no cool) concept
  - 45 GeV $e^+ + e^- \rightarrow \mu^+\mu^-$: CERN fixed target




arXiv:1810.13224





Answers to the Key Questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - **Should not miss this opportunity?**

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source
  - **R&D in a strongly coordinated global effort**

Plasma Wakefield Accelerators

Input #7 Input #109
Input #58 Input #95

Tajima & Dawson
(1979)

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

Key facts:

Three ways to excite plasma (drivers)

laser *dE* ~ 4.3 GeV (10^{18} cm^{-3} 9cm)

e- bunch *dE* ~ 9 GeV (~10^{17} cm^{-3} 1.3m)

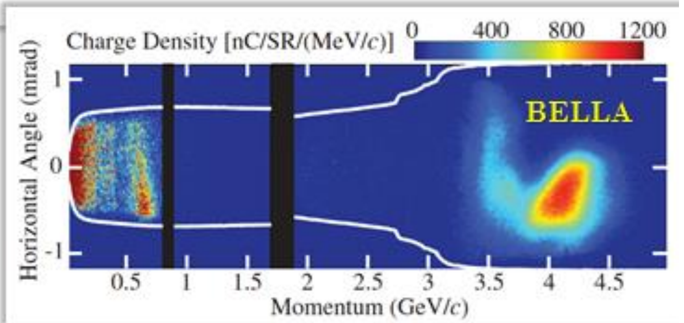
p+ bunch *dE* ~ 2 GeV (~10^{15} cm^{-3} 10m)

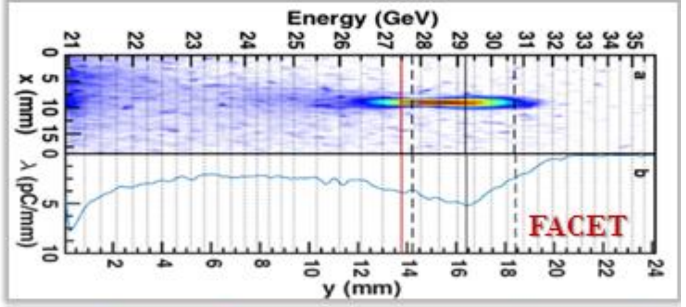
Impressive proof-of-principle demos

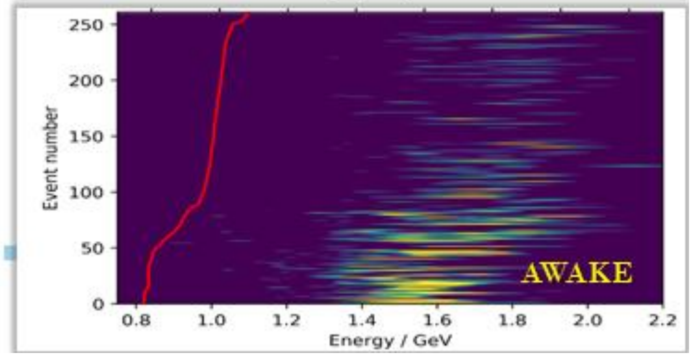
In principle, feasible for e+e- collisions

Collider cost and power will greatly depend on the driver technology:

- lasers, super-beams of electrons or protons







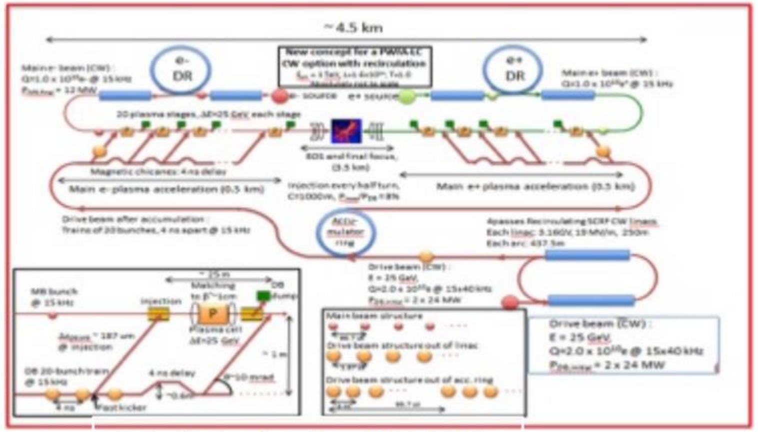
Plasma acceleration based colliders

Drive beams

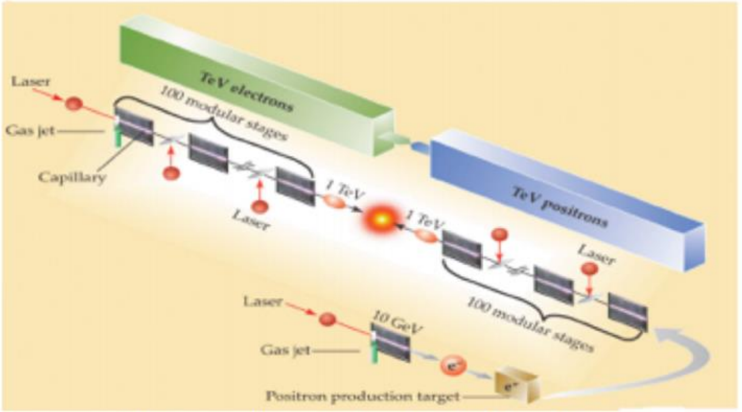
Lasers: ~40 J/pulse
Electrons: 30 J/bunch
Protons: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams

Electrons: 1010 particles @ 1 TeV ~few kJ



E. Adli et. al.,arXiv:1308.1145



Leemans & Esarey, Phys. Today 63 #3 (2009)

Key achievements in last 15 years in plasma based acceleration using lasers, electron and proton drivers

- Focus is now **on high brightness beams, tunability, reproducibility, reliability, and high average power**

The road to colliders passes through **applications** that need compact accelerators (Early HEP applications, FELs, Thomson scattering sources, medical applications, injection into next generation storage rings …)

Many key challenges remain as detailed in community developed, consensus based roadmaps (ALEGRO, AWAKE, Eupraxia, US roadmap,…)

Strategic investments are needed:

- **Personnel** – advanced accelerators attract large numbers of students and postdocs
- Existing **facilities** (with upgrades) and a few new ones (High average power, high repetition rate operation studies; fully dedicated to addressing the challenges towards a TDR for a plasma based collider)
- **High performance computing** methods and tools

Status of Today and Goals for Collider Application

	Current	Goal
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	$<10^{-1}$
Staging	single, two	multiple
Efficiency (%)	20	40
Rep Rate (Hz)	1-10	10^{3-4}
Acc. Distance (m)/stage	1	1-5
Positron acceleration	acceleration	emittance preservation
Proton drivers	SSM, acceleration	Emittance control
Plasma cell (p-driver)	10 m	100s m
Simulations	days	Improvements by 10^7

Achieved
Individually
And
Not
Simultaneously

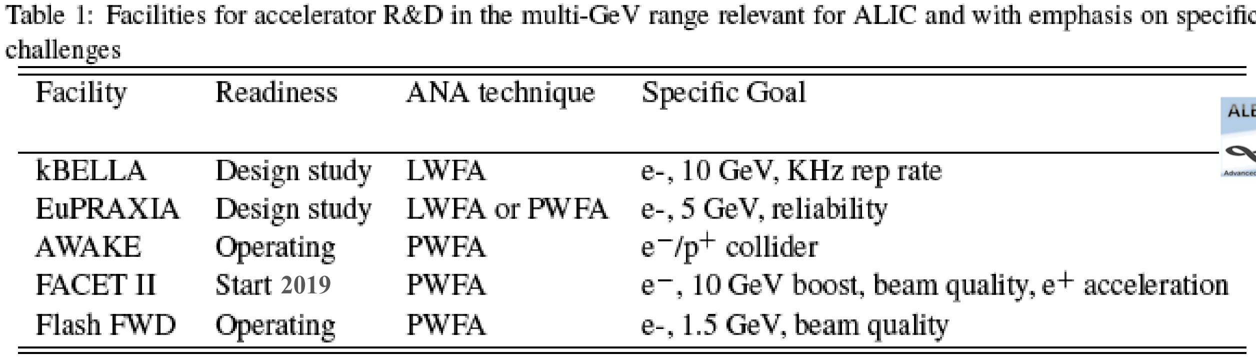


Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges

Facility	Readiness	ANA technique	Specific Goal
kBELLA	Design study	LWFA	e-, 10 GeV, KHz rep rate
EuPRAXIA	Design study	LWFA or PWFA	e-, 5 GeV, reliability
AWAKE	Operating	PWFA	e^-/p^+ collider
FACET II	Start 2019	PWFA	e^-, 10 GeV boost, beam quality, e^+ acceleration
Flash FWD	Operating	PWFA	e-, 1.5 GeV, beam quality

Beam-Driven Plasma Acceleration Facilities span a broad range in beam energy, particle species and average power

Courtesy B. Cros, LPGP, Paris, France

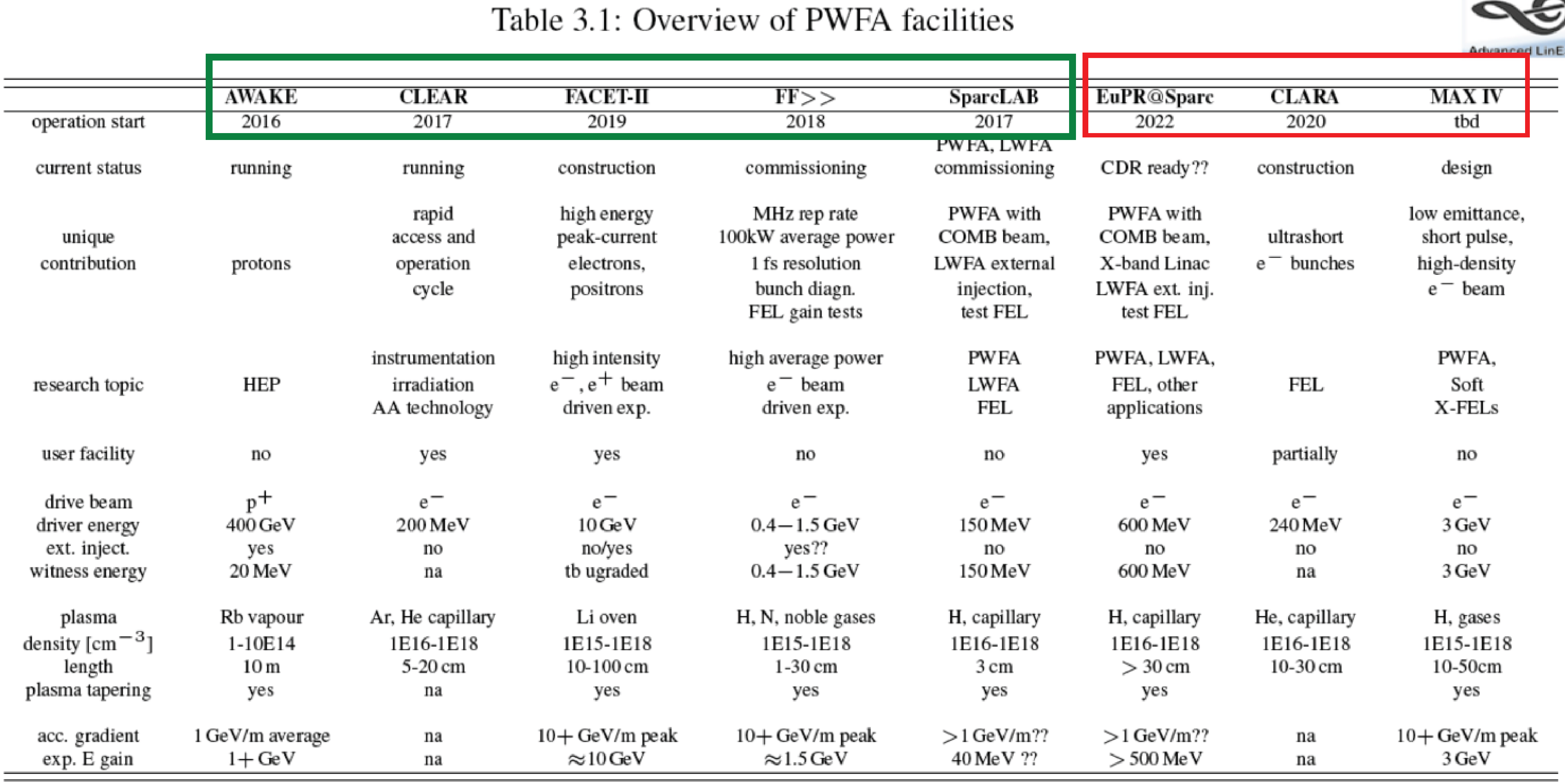
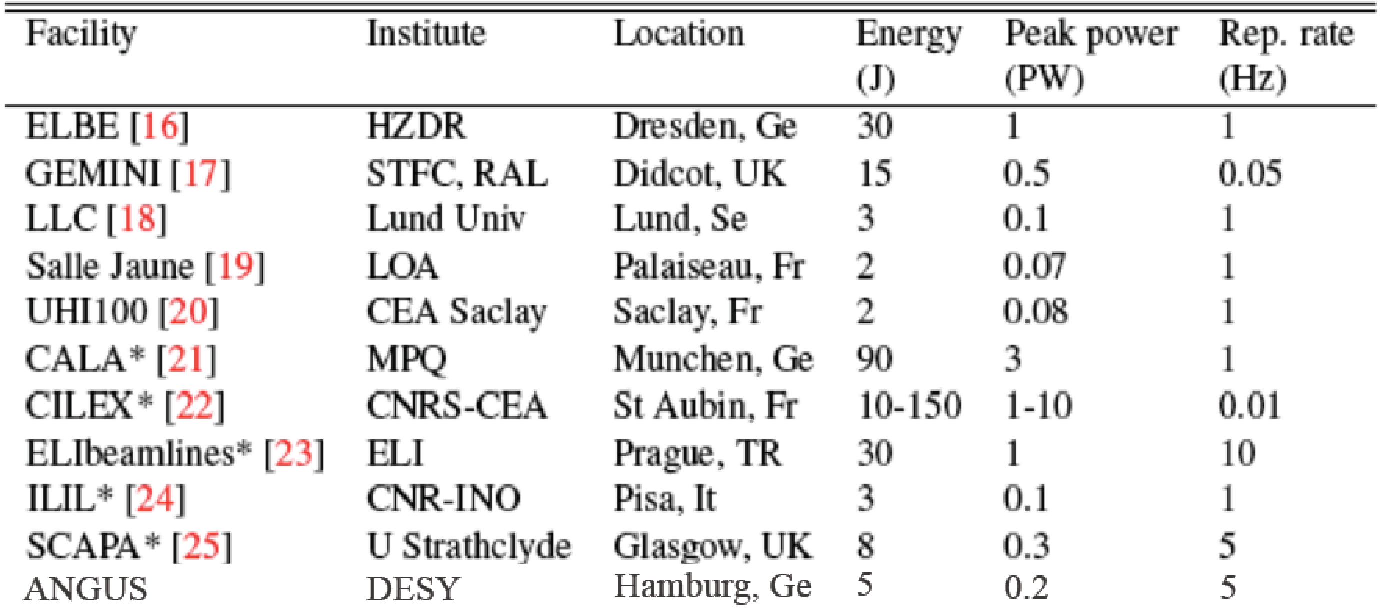


Table 3.1: Overview of PWFA facilities

	AWAKE	CLEAR	FACET-II	FF>>	SparcLAB	EuPR@Sparc	CLARA	MAX IV
operation start	2016	2017	2019	2018	2017	2022	2020	tbd
current status	running	running	construction	commissioning	PWFA, LWFA commissioning	CDR ready??	construction	design
unique contribution	protons	rapid access and operation cycle	high energy peak-current electrons, positrons	MHz rep rate 100kW average power 1 fs resolution bunch diagn. FEL gain tests	PWFA with COMB beam, LWFA external injection, test FEL	PWFA with COMB beam, X-band Linac LWFA ext. inj. test FEL	ultrashort e^- bunches	low emittance, short pulse, high-density e^- beam
research topic	HEP	instrumentation irradiation AA technology	high intensity e^-, e^+ beam driven exp.	high average power e^- beam driven exp.	PWFA LWFA FEL	PWFA, LWFA, FEL, other applications	FEL	PWFA, Soft X-FELs
user facility	no	yes	yes	no	no	yes	partially	no
drive beam	p^+	e^-	e^-	e^-	e^-	e^-	e^-	e^-
driver energy	400 GeV	200 MeV	10 GeV	0.4−1.5 GeV	150 MeV	600 MeV	240 MeV	3 GeV
ext. inject.	yes	no	no/yes	yes??	no	no	no	no
witness energy	20 MeV	na	tb ugraded	0.4−1.5 GeV	150 MeV	600 MeV	na	3 GeV
plasma	Rb vapour	Ar, He capillary	Li oven	H, N, noble gases	H, capillary	H, capillary	He, capillary	H, gases
density [cm^{-3}]	1-10E14	1E16-1E18	1E15-1E18	1E15-1E18	1E16-1E18	1E16-1E18	1E16-1E18	1E15-1E18
length	10 m	5-20 cm	10-100 cm	1-30 cm	3 cm	> 30 cm	10-30 cm	10-50cm
plasma tapering	yes	na	yes	yes	yes	yes		yes
acc. gradient	1 GeV/m average	na	10+ GeV/m peak	10+ GeV/m peak	>1 GeV/m??	>1 GeV/m??	na	10+ GeV/m peak
exp. E gain	1+ GeV	na	≈10 GeV	≈1.5 GeV	40 MeV ??	> 500 MeV	na	3 GeV

Present laser-Driven Plasma Acceleration Facilities can operate at up to 10 PW but lack high average power, high repetition rate capabilities

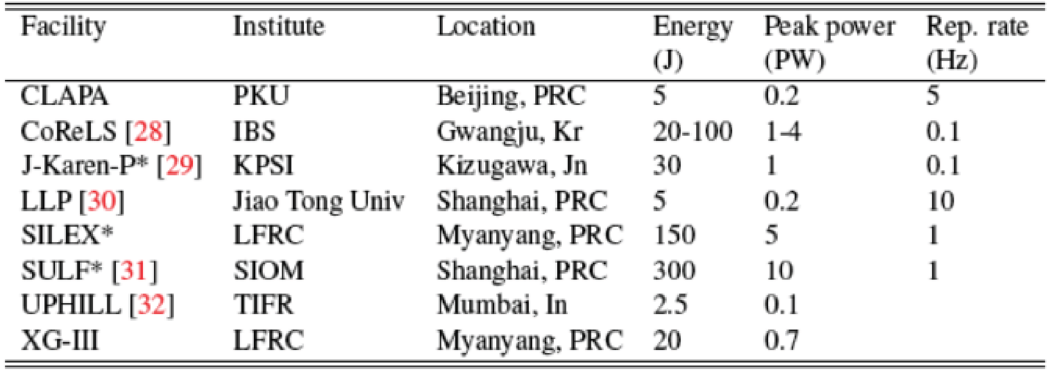
Table 2.2: Laser facilities (≳100 TW) performing LWFA R&D in Europe.



Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
ELBE [16]	HZDR	Dresden, Ge	30	1	1
GEMINI [17]	STFC, RAL	Didcot, UK	15	0.5	0.05
LLC [18]	Lund Univ	Lund, Se	3	0.1	1
Salle Jaune [19]	LOA	Palaiseau, Fr	2	0.07	1
UHI100 [20]	CEA Saclay	Saclay, Fr	2	0.08	1
CALA* [21]	MPQ	Munchen, Ge	90	3	1
CILEX* [22]	CNRS-CEA	St Aubin, Fr	10-150	1-10	0.01
ELIbeamlines* [23]	ELI	Prague, TR	30	1	10
ILIL* [24]	CNR-INO	Pisa, It	3	0.1	1
SCAPA* [25]	U Strathclyde	Glasgow, UK	8	0.3	5
ANGUS	DESY	Hamburg, Ge	5	0.2	5

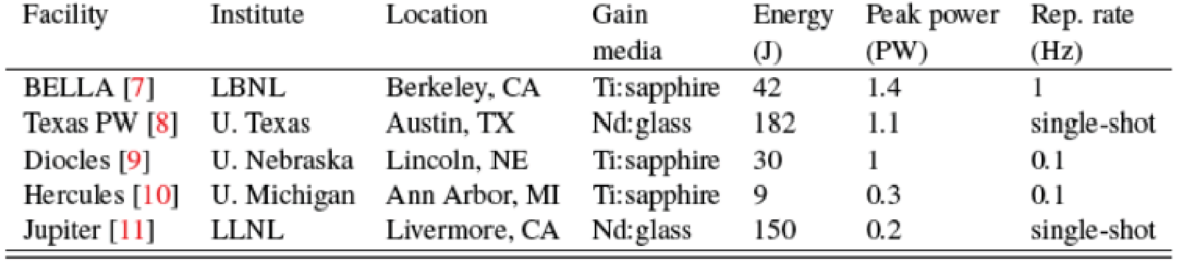
KALDERA at DESY will focus on high average power

Table 2.3: Laser facilities (≳ 100 TW) performing LWFA R&D in Asia



Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
CLAPA	PKU	Beijing, PRC	5	0.2	5
CoReLS [28]	IBS	Gwangju, Kr	20-100	1-4	0.1
J-Karen-P* [29]	KPSI	Kizugawa, Jn	30	1	0.1
LLP [30]	Jiao Tong Univ	Shanghai, PRC	5	0.2	10
SILEX*	LFRC	Myanyang, PRC	150	5	1
SULF* [31]	SIOM	Shanghai, PRC	300	10	1
UPHILL [32]	TIFR	Mumbai, In	2.5	0.1	
XG-III	LFRC	Myanyang, PRC	20	0.7	

Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.



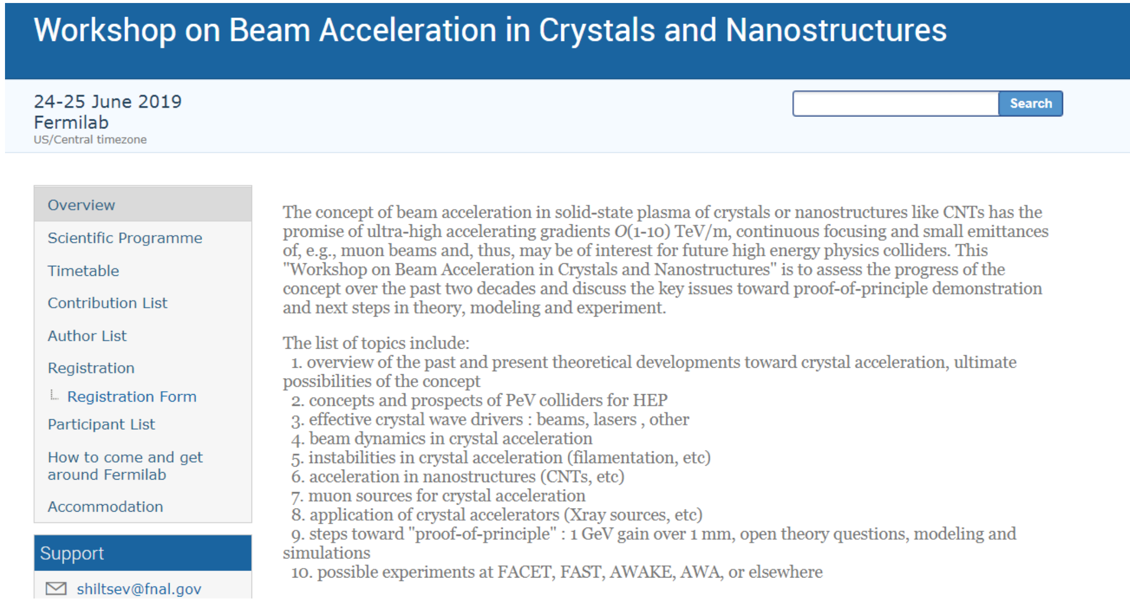
Facility	Institute	Location	Gain media	Energy (J)	Peak power (PW)	Rep. rate (Hz)
BELLA [7]	LBNL	Berkeley, CA	Ti:sapphire	42	1.4	1
Texas PW [8]	U. Texas	Austin, TX	Nd:glass	182	1.1	single-shot
Diocles [9]	U. Nebraska	Lincoln, NE	Ti:sapphire	30	1	0.1
Hercules [10]	U. Michigan	Ann Arbor, MI	Ti:sapphire	9	0.3	0.1
Jupiter [11]	LLNL	Livermore, CA	Nd:glass	150	0.2	single-shot

for FEL lasing?

Can we inject into a storage ring?

The future is in accelerating muons in plasma!

Vladimir Shiltsev



Workshop on Beam Acceleration in Crystals and Nanostructures

24-25 June 2019
Fermilab
US/Central timezone

The concept of beam acceleration in solid-state plasma of crystals or nanostructures like CNTs has the promise of ultra-high accelerating gradients O(1-10) TeV/m, continuous focusing and small emittances of, e.g., muon beams and, thus, may be of interest for future high energy physics colliders. This "Workshop on Beam Acceleration in Crystals and Nanostructures" is to assess the progress of the concept over the past two decades and discuss the key issues toward proof-of-principle demonstration and next steps in theory, modeling and experiment.

The list of topics include:

1. overview of the past and present theoretical developments toward crystal acceleration, ultimate possibilities of the concept
2. concepts and prospects of PeV colliders for HEP
3. effective crystal wave drivers : beams, lasers , other
4. beam dynamics in crystal acceleration
5. instabilities in crystal acceleration (filamentation, etc)
6. acceleration in nanostructures (CNTs, etc)
7. muon sources for crystal acceleration
8. application of crystal accelerators (Xray sources, etc)
9. steps toward "proof-of-principle" : 1 GeV gain over 1 mm, open theory questions, modeling and simulations
10. possible experiments at FACET, FAST, AWAKE, AWA, or elsewhere

Q3: How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?

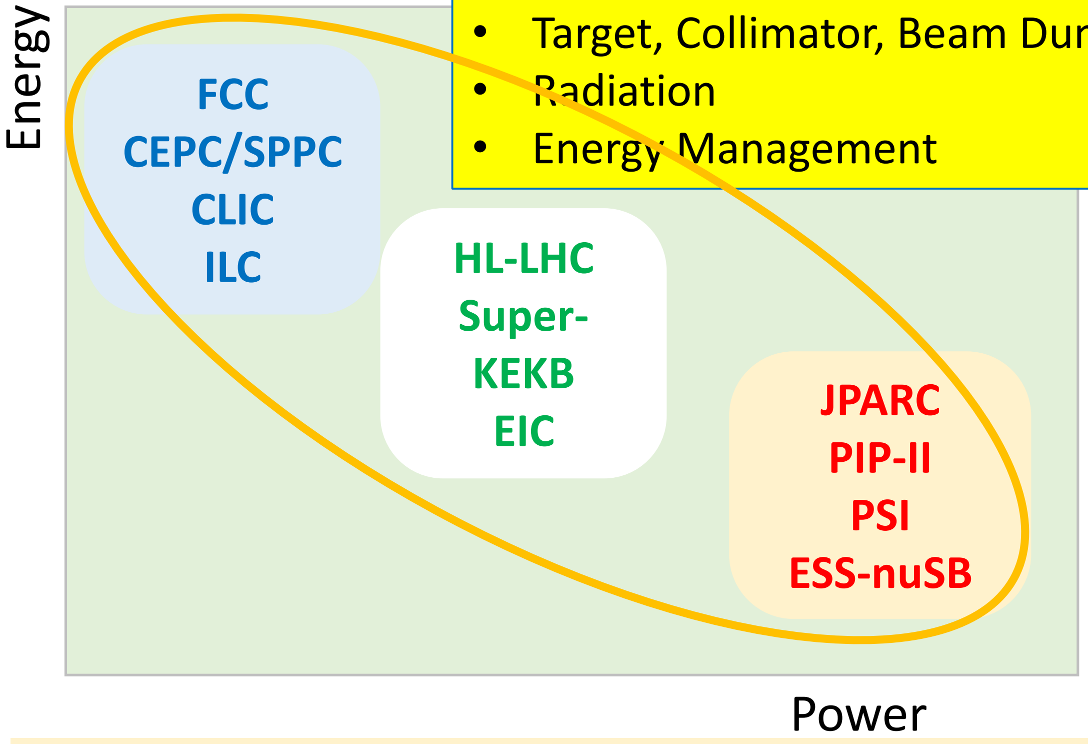
Intensity frontier vs. Energy Frontier

Intensity – Acc.	Energy [GeV]	Power [MW]	Acc. Tech. Feature	SC Tech.
SPS*	**450**		Synchrotron	
Fnal M. Injector	**120**	**0.7**	Synchrotron	
J-PARC*	**3** **30**	**1** **0,49 ~ 1.3**	Linac/Synchr Ext. Beam	**SCM**
PIP-II	**60 -120**	**1.2**	Linac (SRF) Synchrotron	**SRF**
PSI-HIPA*	**0.59**	**1.4**	Cycrotron	
FAIR (SIS100)	**29**	**0.2**	Synchrotron	**SCM**
(ESS) ESSnuSB *	**2** **2**	**2 ~ 5 (+5)** **2 x 5**	Linac	**SRF**
CEBAF	**12**	**1**	LINAC+Ring	**SRF**
Super-KEKB		**---**	Collider	
HL-LHC	**2 x 7,000**	**---**	Collider	**SCM. SRF**
EIC*		**---**	Collider	**SCM, SRF**

A. Yamamoto, 190512b

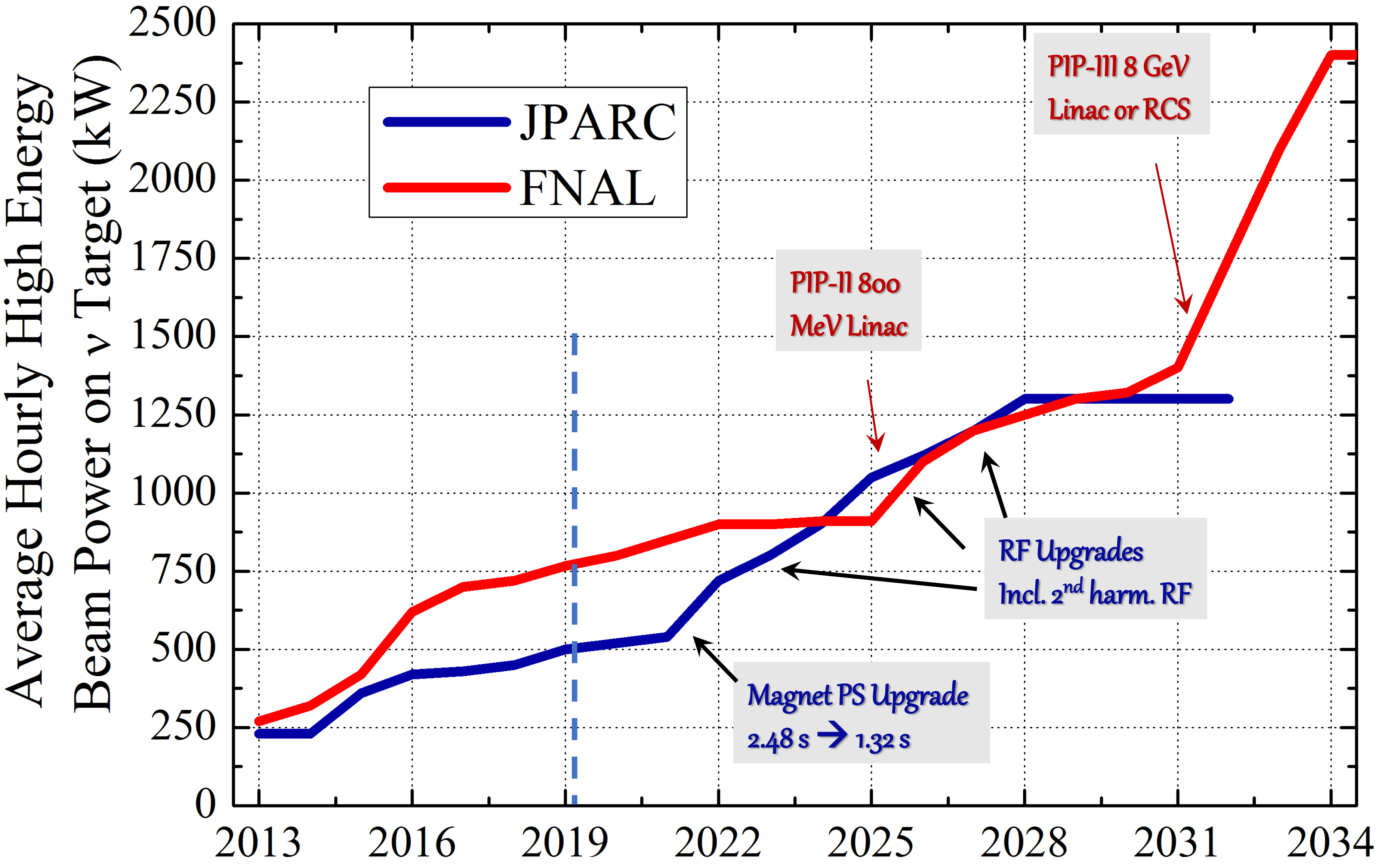
Common Issues:

- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management



- Science is complementary, and
- Technology is based on common technology,
- Let us work together and maximize synergy !!

Fermilab and J-PARC: Proton Beam Power on ν Target



PIP-III 8 GeV Linac or RCS

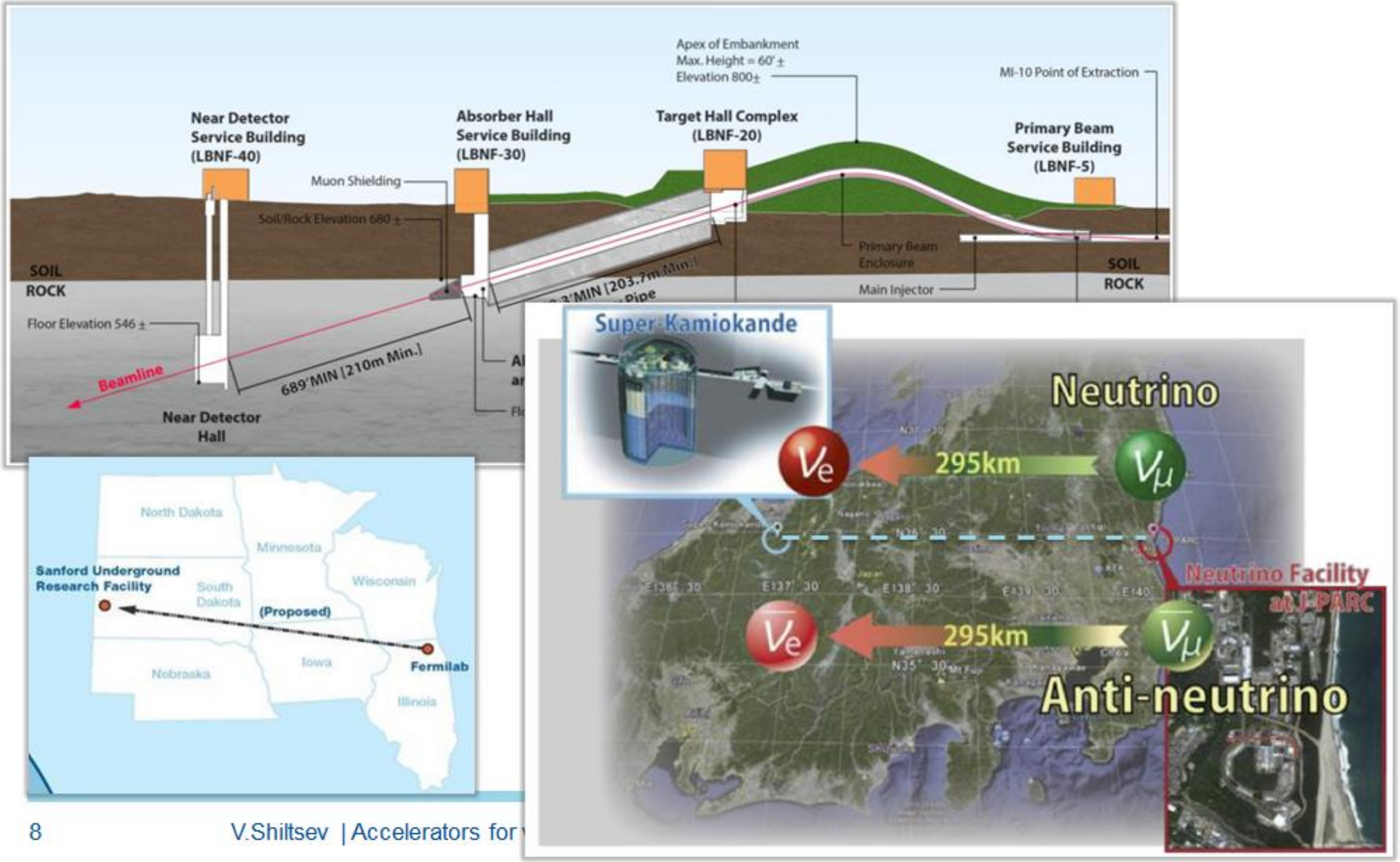
PIP-II 800 MeV Linac

RF Upgrades Incl. 2nd harm. RF

Magnet PS Upgrade 2.48 s → 1.32 s

40 kt LAr DUNE @ 2.4 MW & 1000 kt water Hyper-K @ 1.3 MW

** complimentary in terms of CPV sensitivity because of different ν’s spectrum, different baseline (1300 km vs 295 km) and detector technology*



Ways to Increase Beam Power on Target

Particles per pulse

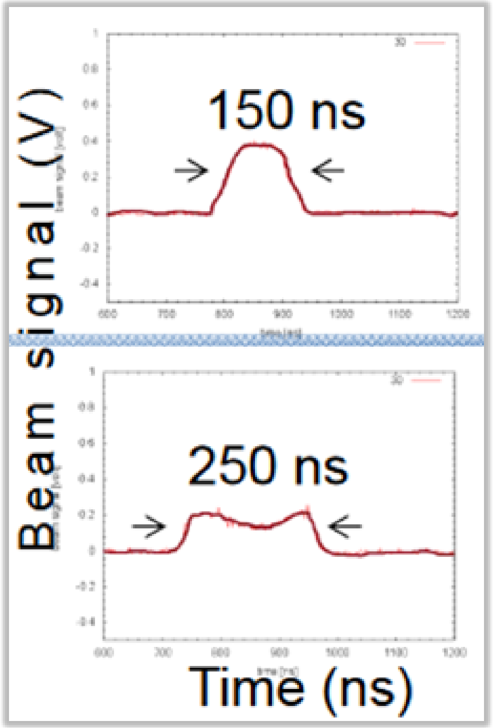
Particle energy [eV]

$$P_{beam} = \frac{N_{pulse} E}{T_{cycle}}$$

Accelerator cycle period

- **Brute force** :
  - increase the energy *E* – *magnets, RF*
  - decrease the cycle time *T* – *magnets, RF*
  - key challenge : cost (e.g., J-PARC TPC ~$1.7B) and power
- **Increase PPP** (protons per pulse) N_p :
  - key challenges : many beam dynamics issues & cost
- In both cases – **need reliable horns and targets :**
  - key challenge : *lifetime* gets worse with power

Ways to Increase "Protons per Pulse"



- **Increase the injection energy**:
  - Gain about $N_p \sim \beta\gamma^2$, need (often - costly) linacs
- **Flatten the beams** (using 2nd harm, RF) :
  - Makes peak SC force smaller, $N_p \sim$ x2
- **"Painting" beams** at injection:
  - To linearize SC force across beams $N_p \sim$x1.5
- **Better collimation system beams:**
  - From $\eta \sim 80\%$ to ~95% $N_p \sim$x1.5
- **Make focusing lattice perfectly periodic**:
  - Eg P=24 in Fermilab Booster, P=3 in JPARC MR → $N_p \sim$ x1.5
- **Introduce *Non-linear Integrable Optics*** :
  - Reduces the losses, $N_p \sim$ x 1.5-2
- **Space-Charge Compensation** by electron lenses :
  - Electrons focus protons $N_p \sim$x1.5 - 2

Protvino-to-ORKA: *L*=2590km, E_ν ~5 GeV

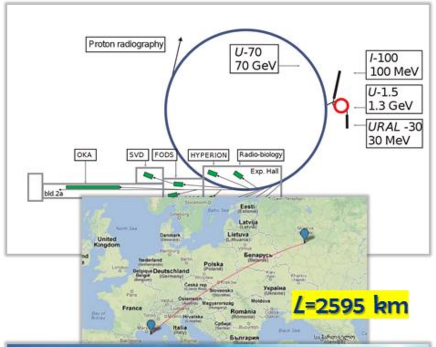
Input #124

U-70 *p+* synchrotron:

70 GeV protron beam

1.5 10^{13} *p+* per pulse, T_{cycle}=10s

5μs (fast extraction), P_{avg} =15kW



Needed upgrades:

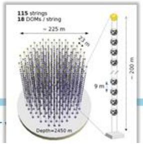
Decay pipe ~180 m long

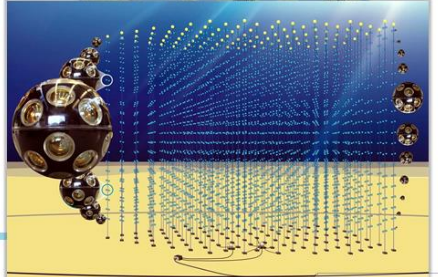
Power to 90 kW by 2026:

- 5 10^{13} *p+* per pulse, T_{cycle}=7 s
- 5 yrs of ORCA data taking

Then to 450 kW by 2035

- (no details yet)
- Super-ORCA





ESS Neutrino Super Beams

ESSνSB **Input #98**

European Spallation Source:

~600 m SC linac, 1.83 B Euros

2 GeV x 62.5 mA x (η=4%) = **5 MW**

2.8 ms pulses

32 MW site power after all the measures

ESSνSB

CDR 2021, TDR 2024

Construction start 2026-2029

Linac upgrade 14 Hz → 28 Hz (η→ 8%)

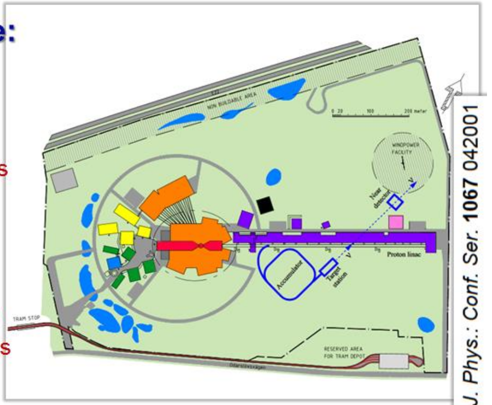
Accumulator *C*~400 m to compress to μs

H- instead of p+, space charge effects

Target station

Cost estimate 1.3 B Euro

Linac upgrade	230 MEUR
Accumulator ring	150 MEUR
Target Station	170 MEUR
Near and Far Detector	750 MEUR



~0.3 GeV neutrino beam is directed towards the north in the direction of the Garpenberg mine, 540 km away, which could host the far 1 megaton water Cerenkov detector

Marcos Dracos 2018 *J. Phys.: Conf. Ser.* **1067** 042001

ENUBET : SPS-based Short base-line ν's

Input #57

- to measure the cross sections as *f*(energy) with much better precision

SPS at CERN (max CNGS):

E=400 GeV protron beam

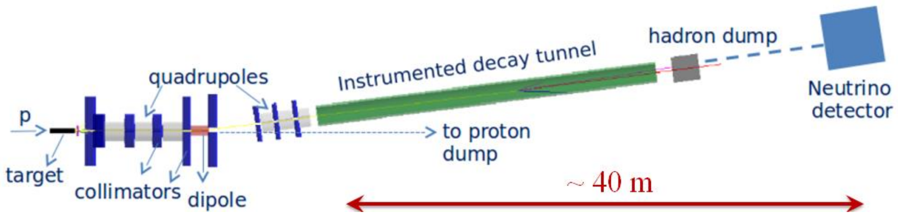
2.25 10^{13} *p+* per pulse,

T_{cycle}=5.8s, 10 μs (fast extr.)

→ avg. *P*_beam = 510kW

8.5 GeV central energy of secondaries (pions, kaons)

0.5-3.5 GeV neutrino's



νSTORM

Input #154 2017 *JINST* **12** P07018 2017 *JINST* **12** P07020

SPS at CERN :

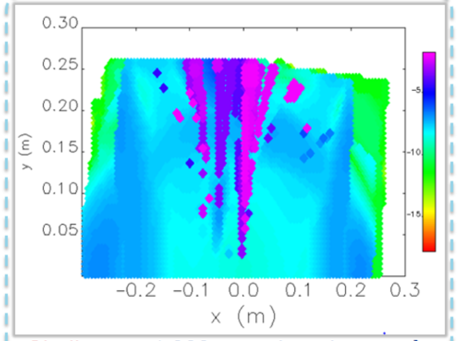
E=100 GeV *P*_beam =156kW

4 10^{13} *p+* per pulse

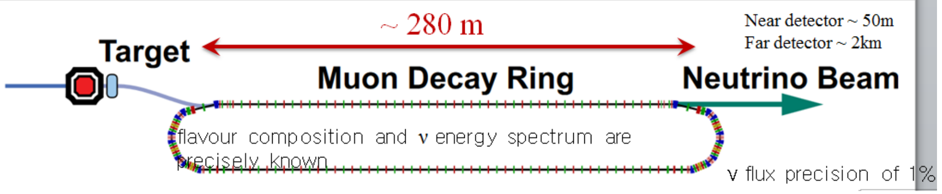
T_{cycle}=3.6 s, 2 x 10 μs (fast extr.)

$\mu\pm$ beams 1 GeV/c - 6 GeV/c momentum spread of 16%

Cost est. 160 MCHF @ CERN



Challenge: a) 300 μmrad emittance → 0.5 dia magnets; b) survival ~60% after 100 turns for $\delta P/P$ ~10%



flavour composition and ν energy spectrum are precisely known

ν flux precision of 1%

Q4: Energy management in the age of high-power accelerators?

Energy Efficiency

European Strategy
Update

- Energy efficiency is not an option, it is a must!
- Proposed HEP projects are using $\mathcal{O}(\mathrm{TWh/y})$, where energy efficiency and energy management must be addressed.
- Investing in dedicated R&D to improve energy efficiency pays off since savings can be significant.
- This R&D leads to technologies which serve the society at large.
- District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery are areas where energy efficiency can be significantly be improved.

Sevearl TWh/year

위치 : 부산광역시 장안읍 (울산 울주군 : 신고리 3호기)

발전소명		노형	설비용량 (Mwe)	상업운전일	발전량 (Mwh/2018년)	이용률 (%/2018년)	가동률 (%/2018년)
고리	#2	경수로	650	`83.7.25	2,861,348	47.9	49.7
	#3		950	`85.9.30	5,801,930	63.4	64.0
	#4		950	`86.4.29	6,541,235	71.5	71.7
신고리	#1	경수로	1,000	`11.2.28	7,377,798	80.7	81.1
	#2		1,000	`12.7.20	7,229,539	79.0	80.0
	#3	신형경수로	1,400	`16.12.20	6,340,766	48.7	49.8

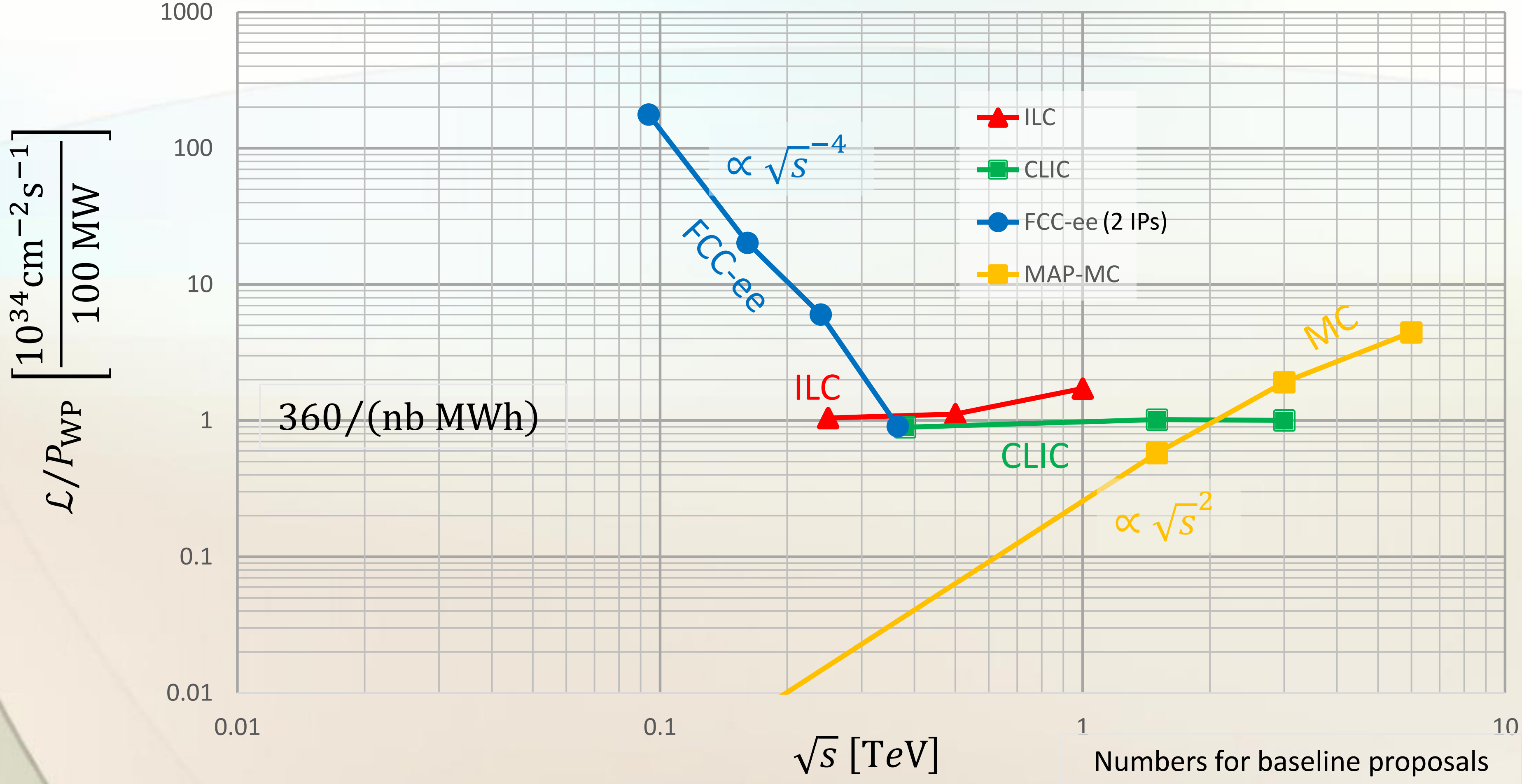
위치 : 경북 경주시 양남면

발전소명		노형	설비용량 (Mwe)	상업운전일	발전량 (Mwh/2018년)	이용률 (%/2018년)	가동률 (%/2018년)
월성	#1	중수로	679	`83.4.22	0	0.0	0.0
	#2		700	`97.7.1	4,635,316	83.3	82.1
	#3		700	`98.7.1	4,280,157	73.6	73.4
	#4		700	`99.10.1	4,682,551	83.1	83.9
신월성	#1	경수로	1,000	`12.7.31	7,379,097	80.4	81.0
	#2	경수로	1,000	`15.7.24	7,091,934	77.2	77.4

Figure of merit for proposed lepton colliders

Disclaimers:

1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations



Numbers for baseline proposals

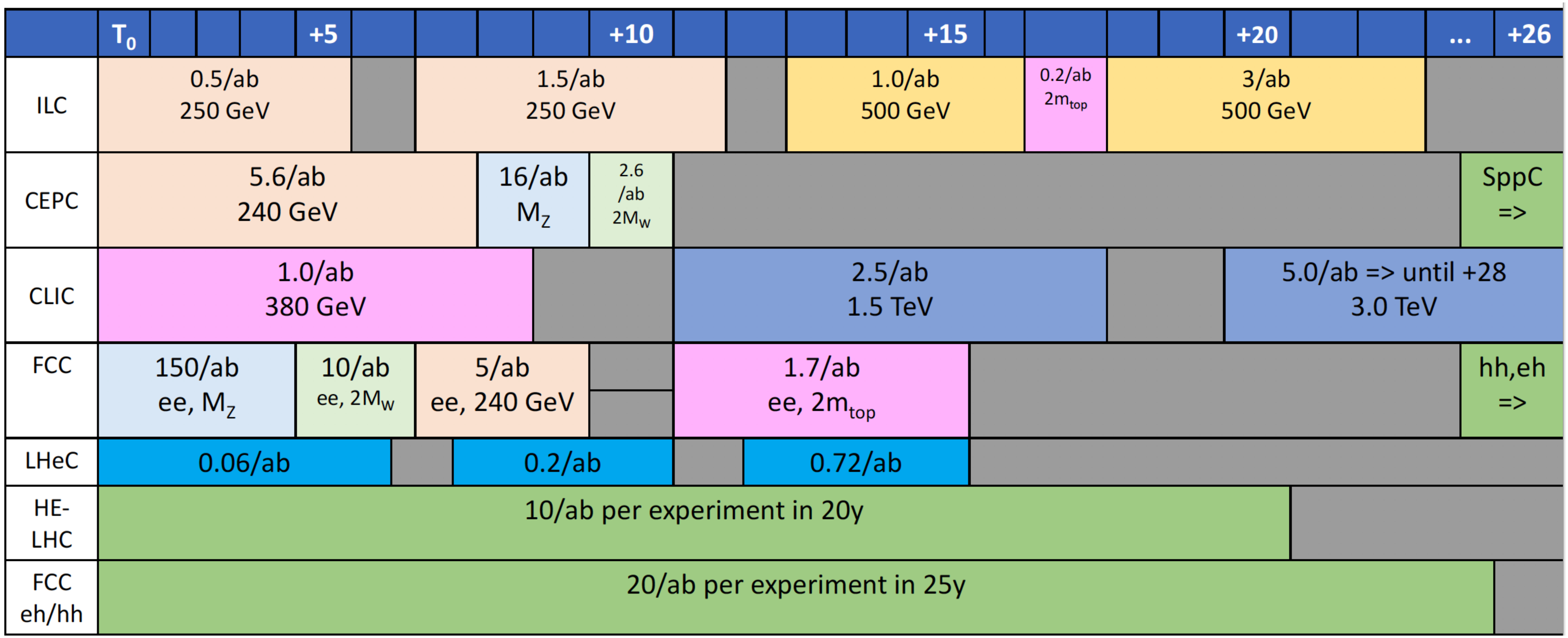
Summary

Expect Shortage of Expert Accelerator Workforce

- ***"Oide Principle"*** :
  1 Accelerator Expert
  can spend intelligently
  (only) ~1 M$ a year
- + it takes significant time to get the team together (XFEL, ESS)
- Scale of the team: 10B$/10 years=1 B$/yr → need 1000 experts ← world's total now ~4500

K.Oide (KEK)

Proposed Schedules and Evolution



	T$_0$	+5	+10	+15	+20	… +26
ILC	0.5/ab 250 GeV	1.5/ab 250 GeV	1.0/ab 500 GeV	0.2/ab 2m$_{top}$	3/ab 500 GeV	
CEPC	5.6/ab 240 GeV	16/ab M$_Z$	2.6 /ab 2M$_W$			SppC =>
CLIC	1.0/ab 380 GeV		2.5/ab 1.5 TeV		5.0/ab => until +28 3.0 TeV	
FCC	150/ab ee, M$_Z$	10/ab ee, 2M$_W$	5/ab ee, 240 GeV	1.7/ab ee, 2m$_{top}$		hh,eh =>
LHeC	0.06/ab	0.2/ab	0.72/ab			
HE-LHC	10/ab per experiment in 20y					
FCC eh/hh	20/ab per experiment in 25y					

Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

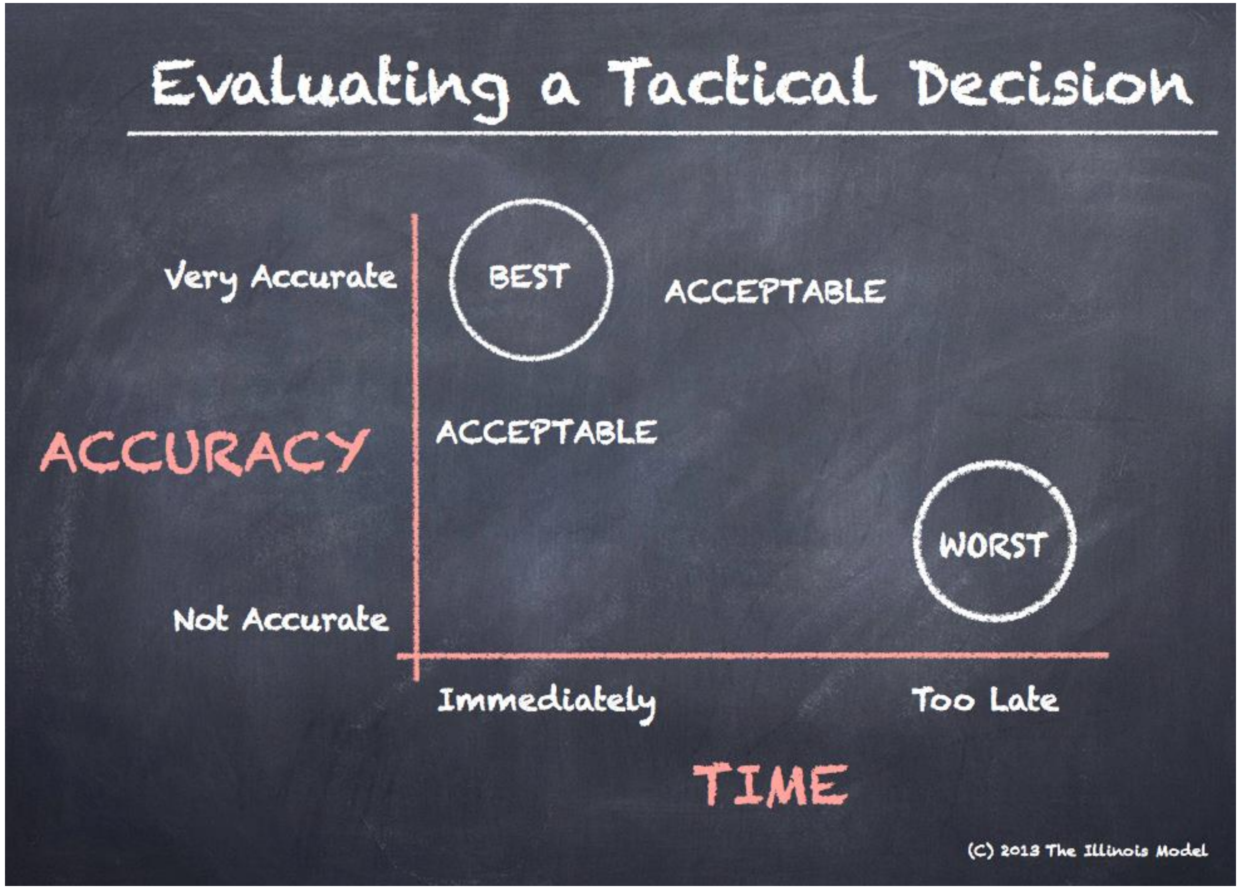
Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

Comparisons

1 G = 1 Billion = 1,000,000,000
“ILCU” as the United States dollar as in January 2012
CHF ~ US$

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF



Thank you for your attention !