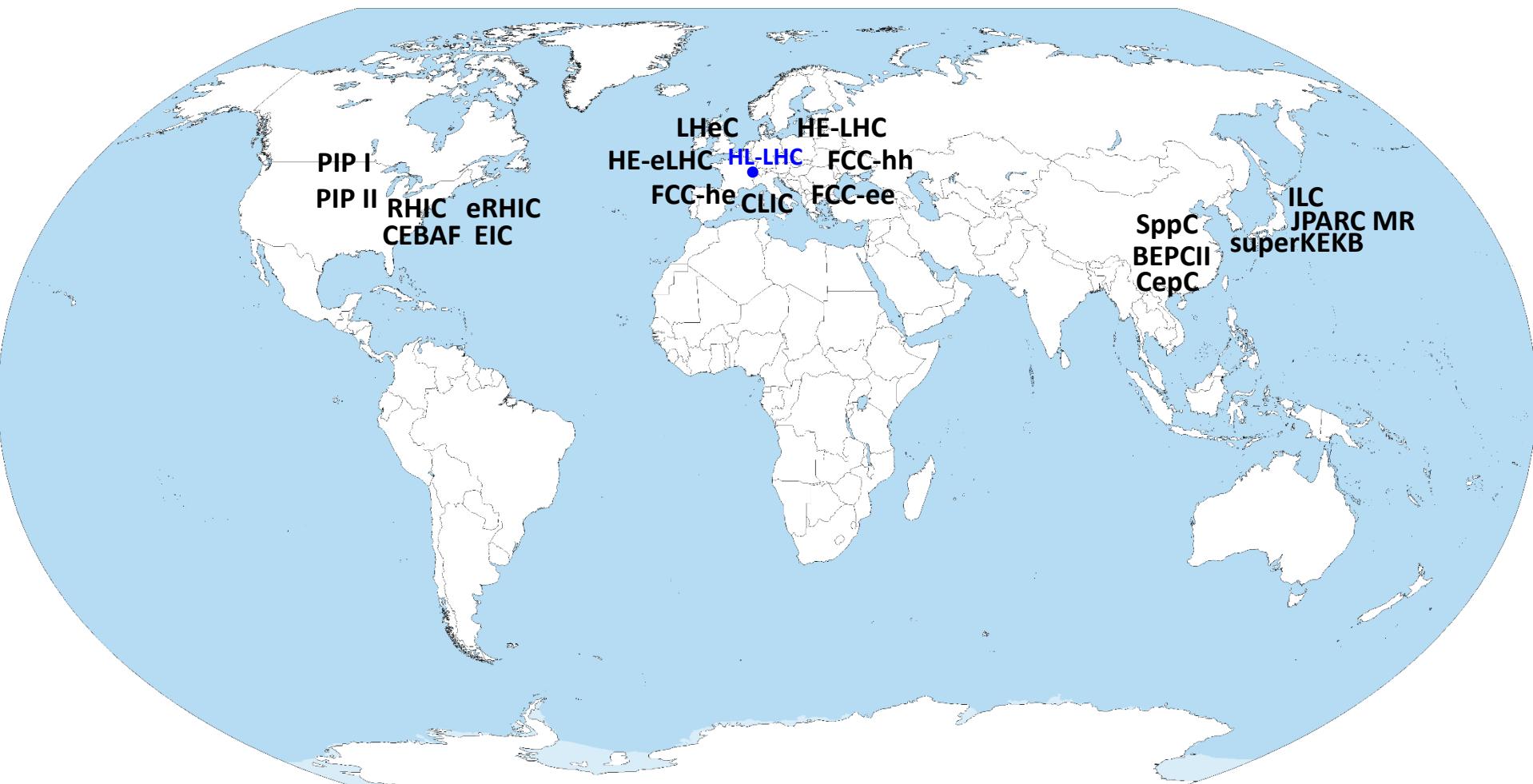


Future High Energy Accelerators

Barbara Dalena

CEA/DRF/Irfu/DACM, Université Paris-Saclay

Future HEP accelerators



$\gamma\gamma$ and $\mu^+\mu^-$ colliders

charm- τ factory
plasma acceleration \Rightarrow not included

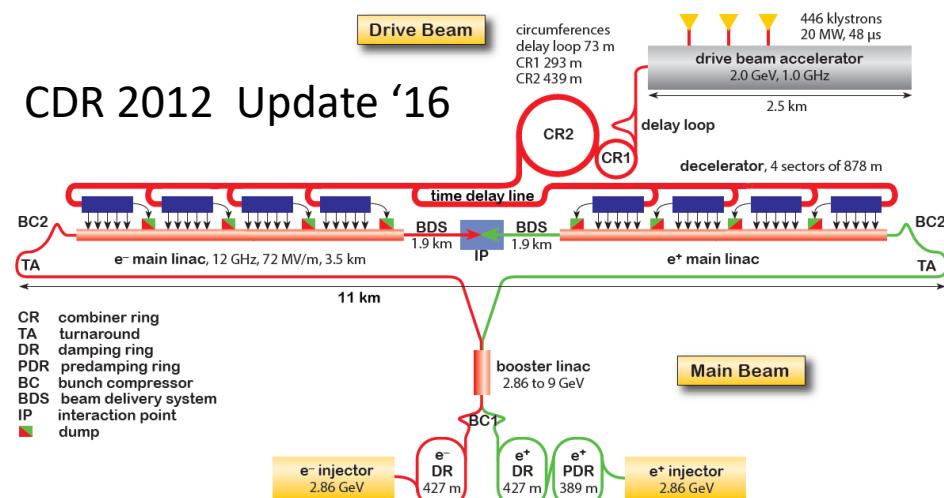
Linear Colliders: ILC/CLIC

TDR (2012) exists
Aim at cost reduction

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	$1.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@ 250GeV
SRF Cavity G.	31.5 MV/m (35 MV/m)
Q_0	$Q_0 = 1 \times 10^{10}$

ILC CLIC

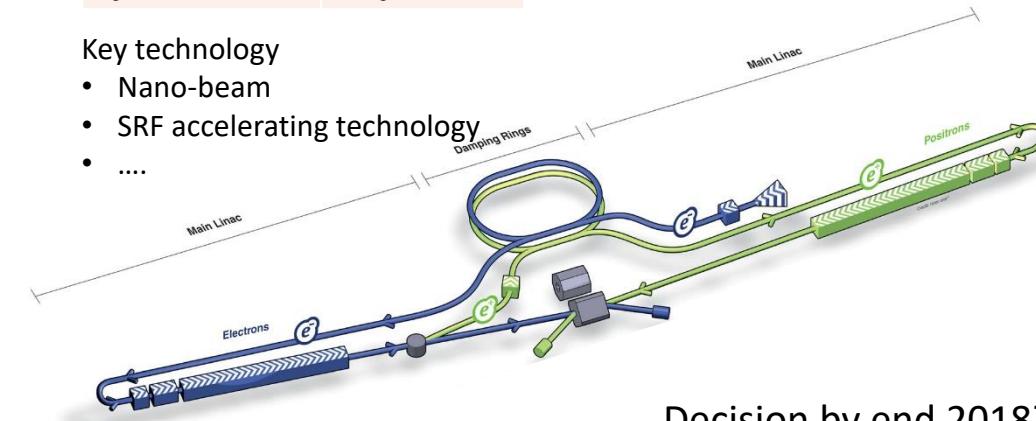
CDR 2012 Update '16



Parameter	unit	380 GeV	3 TeV
L	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$	1.5	5.9
G	MV/m	72	72/100
Length	km	11	50

Key technology

- Nano-beam
- SRF accelerating technology
-



Decision by end 2018?

Key technology

- Nano-beam
- X-band accelerating cavity
- High efficiency modulators and Klystron
- Permanent magnets
-

Decision by 2020?

Circular Colliders: FCC and CEPC/SppC

International **FCC** collaboration
(CERN as host lab) to study:

- **$p\bar{p}$ -collider (FCC-*hh*)**
→ main emphasis, defining infrastructure requirements

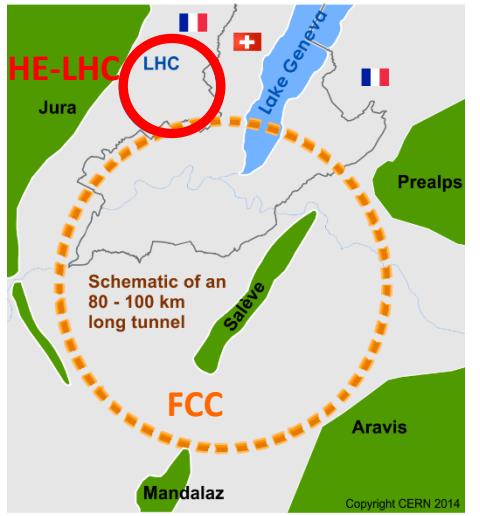
$\sim 16 \text{ T} \Rightarrow 100 \text{ TeV } p\bar{p} \text{ in } 100 \text{ km}$

- **$\sim 100 \text{ km}$ tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (FCC-*ee*),** as potential first step
- **HE-LHC** with *FCC-*hh** technology
- **$p-e$ (FCC-*he*) option,** IP integration, e^- from ERL

CDR for EU strategy end 2018

- earliest possible physics
- FCC-*hh*: 2043
 - FCC-*ee*: 2039
 - HE-LHC: 2040

11/22/2018



B. Dalena, journée de physique

Proposal for project in China

- from pre-CDR to CDR 2017-2018
- CEPC**
- Main emphasis on e^+e^- collider 90-240 GeV
 - focus on Higgs

Hadron collider (**SppC**)

- to later be installed in the same tunnel 75 to $O(150)$ TeV

- earliest possible physics
- CepC: 2028
 - SppC: 2045

Circular colliders: parameters and challenges

Leptons

Parameter [unit]	Z FCC-ee / CepC	WW FCC-ee/ CepC	H (ZH) FCC-ee/ CepC	ttbar FCC-ee
Beam energy [GeV]	45.6 / 45	80 / 80	120 / 120	182.5
Peak luminosity per IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	230 / 16.6-32.1	28 / 10.1	8.5 / 2.93	1.55
Beam current [mA]	1390 / 461	147 / 87.9	29 / 17.4	5.4
SR energy loss / turn [GeV]	0.036 / 0.036	0.34 / 0.34	1.72 / 1.73	9.21
Total RF voltage [GV]	0.1 / 0.1	0.44 / 0.47	2.0 / 2.17	10.9
H,V geometric emittance [nm/pm]	0.27,1.0 / 0.18,1.6-4	0.28,1.7 / 0.54, 1.6	0.63,1.3 / 1.21,3.1	1.46, 2.9

Hadrons

⇒ High efficient RF system, small emittance and small lifetime beam

Parameter [unit]	HL-LHC	HE – LHC (tentative)	FCC-hh baseline/ultimate	SppC 75 /150 TeV
Beam energy [GeV]	7	27	50 / 50	37.5/ 75
Peak luminosity per IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	5	25	5 < 30	10 /
Beam current [A]	1.1	1.1	0.5	0.7 /
SR power / length [W/m/ap.]	0.33	4.6	28.4	13 /
Events/bunch crossing	132	800	170/1000	490 /
Stored energy/ beam [GJ]	0.7	1.3	8.4	9.1 /
Arc dipole [T]	8	16	16	12 / 24

⇒ SR comparable to light sources, beam losses, high field magnets

Electron hadrons colliders

New Document (early 2019):

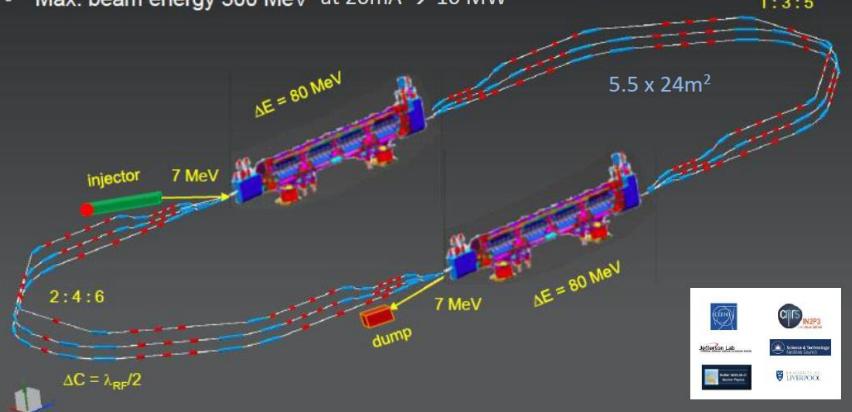
- higher luminosity goal for Higgs
- new ep/eA physics prospects
- updates on IR
- eh in FCC study
- eh in HE-LHC
- Low energy test facility PERLE
- Implementation of ERL at CERN

Submissions of eh Papers to EU Strategy:

- FCC eh as part of FCC hh
- LHeC with HL
- PERLE technology development at Orsay



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA \rightarrow 10 MW



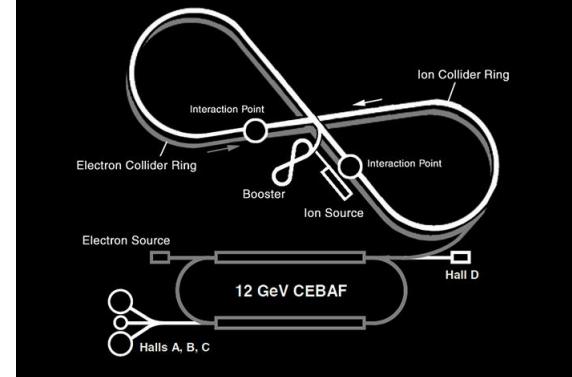
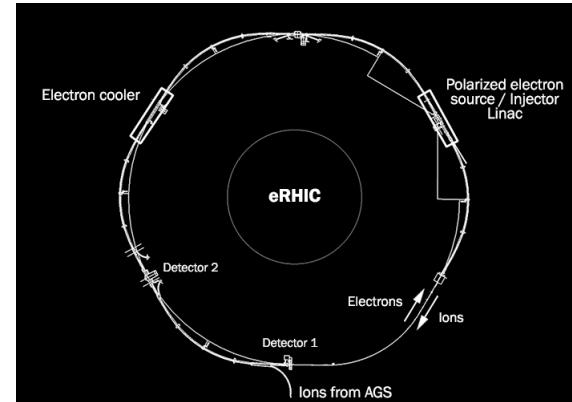
11/22/2018

Parameters [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E _p [TeV]	7	7	12.5	50
E _e [TeV]	60	60	60	60
\sqrt{s} [TeV]	1.3	1.3	1.7	3.5
Luminosity [$10^{33} \text{ cm}^{-2}\text{s}^{-1}$]	1	8	12	15

US options

- eRHIC (BNL)
- EIC (JLAB)

The U.S. Nuclear Science Advisory Committee recommends building an Electron-Ion Collider as the highest priority new facility for the field



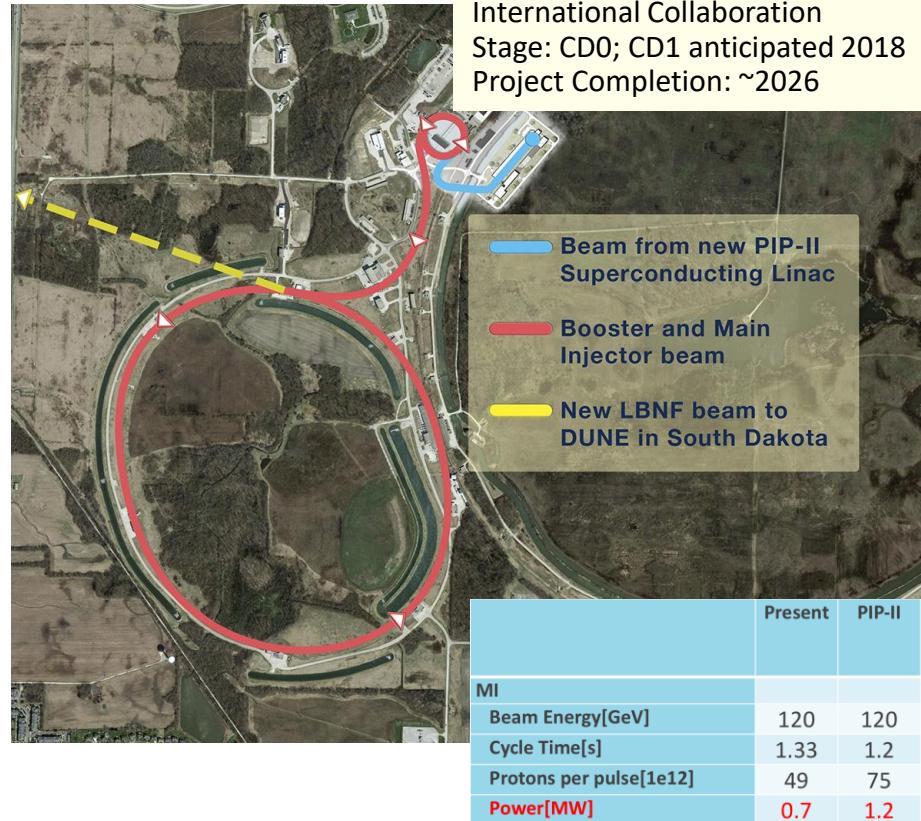
B. Dalena, journée de physique

High power protons drivers for neutrino beams

PIP II @



International Collaboration
Stage: CD0; CD1 anticipated 2018
Project Completion: ~2026

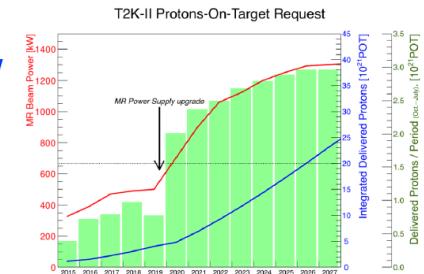


Beam Power	470 (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/pulse	2.4×10^{14}	2.0×10^{14} [3.3×10^{14}] $+25\%$	2.6×10^{14} $+18\%$	3.2×10^{14}
Operation cycle	2.48 s	1.3 s [2.1 s]	1shot	1.16 s

Method

- Increase repetition rate for 750kW
- Increase beam intensity for >1.3MW

> 2022



- Study groups explore the possibility to use ESS and CERN-SPS as proton drivers for neutrino beams

Key R&D and challenges

Many common and some project-specific developments required

<ul style="list-style-type: none">• High gradient and high efficient RF systems• High intensity beams (collective effects, beam losses, etc..)• Beam Quality (Generation and preservation of low emittance beams)• High field magnets• ...	<p>FCC-ee, CepC, ILC, CLIC...</p> <p>FCC-hh, HE-LHC, SppC, PIP II, JPARC MR...</p> <p>ILC, CLIC, LHeC, eRHIC, EIC, FCC-ee, FCC-he, HE-eLHC...</p> <p>FCC-hh, HE-LHC, HL-LHC, SppC...</p>
----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

Not exhaustive list. In the following some selected examples, only.

The R&D are addressed in world wide collaborations, country (EU, US...) or national level

Nano beams: ATF Collaboration

beam parameters at IPs
 7.7 nm ILC 250 GeV
 2.9 nm CLIC 380 GeV



ILC, CLIC

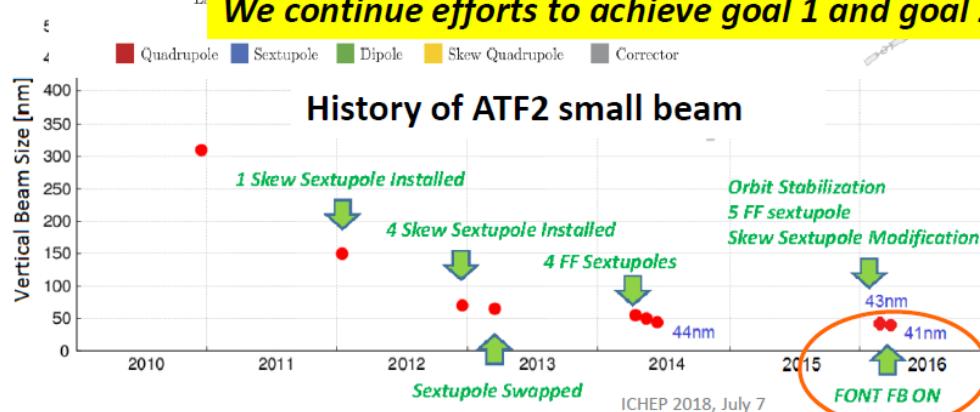
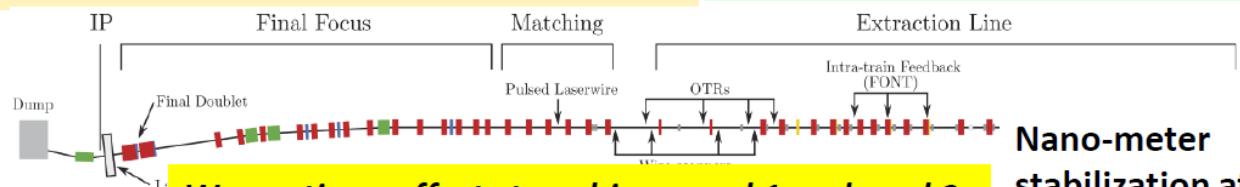


Goal 1: Establish the ILC final focus method with same optics and comparable beamline tolerances

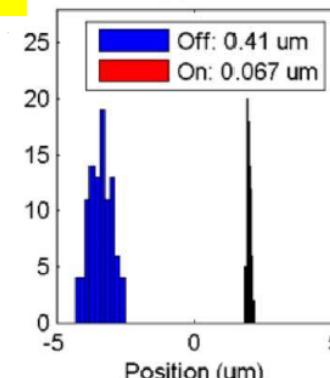
- ATF2 Goal : 37 nm → 6nm @ILC500GeV
 7.7nm@ILC250GeV
- Achieved **41 nm (2016)**

Goal 2: Develop a few nm position stabilization for the ILC collision

- **FB latency 133 nsec achieved**
 (target: < 300 nsec)
- **positon jitter at IP: 410 → 67 nm (2015)** (limited by the BPM resolution)



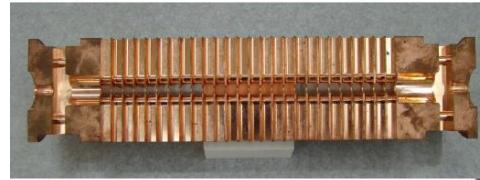
Nano-meter stabilization at IP



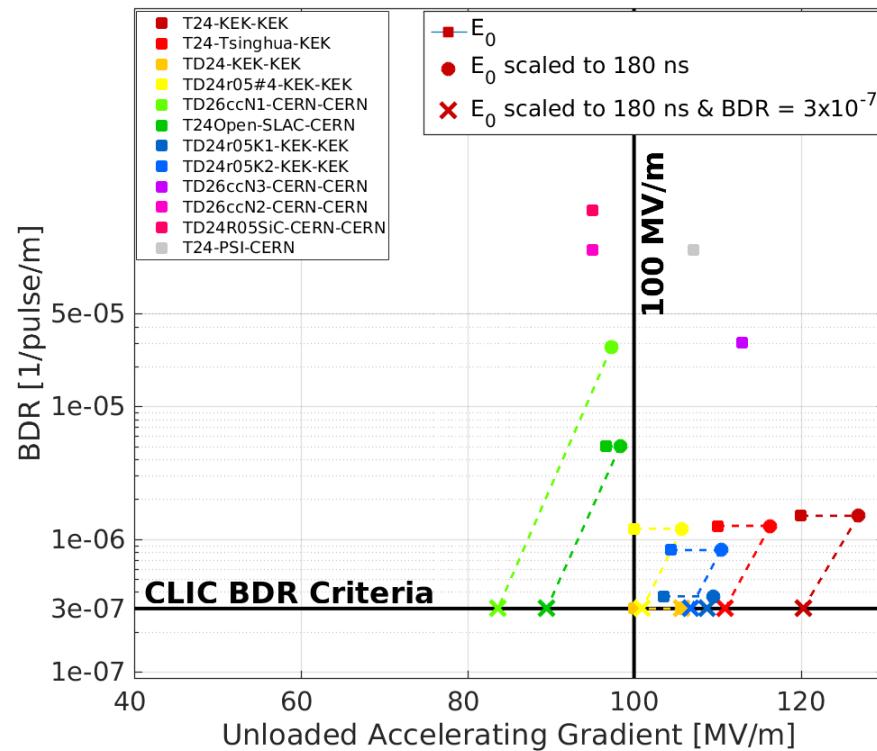
High gradient RF: NC

X-boxes (klystron based test stand) to test cavities

Target BreakDown Rate (BDR) 3×10^{-7} pulse $^{-1}$ m $^{-1}$



CLIC

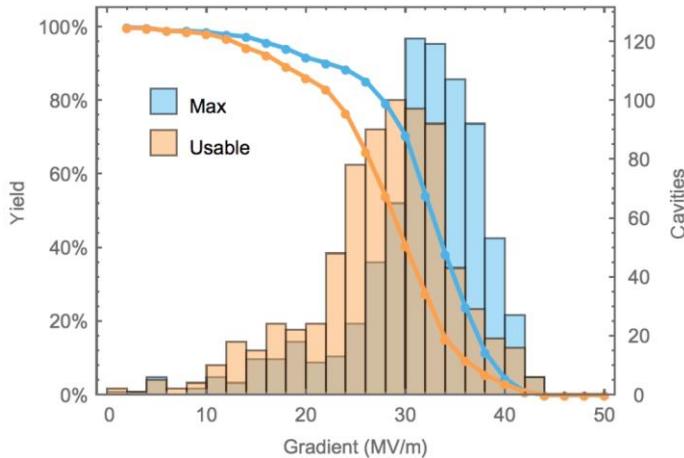


Further optimization ongoing of structure production for industrialization

High gradient RF: SRF



ILC



PRAB 20, 042004 (2017)

Performance in vertical test of
~800 cavities for the European XFEL:

Average maximum 31.4 MV/m

Average usable 27.7 MV/m

XFEL Goal 24 MV/m

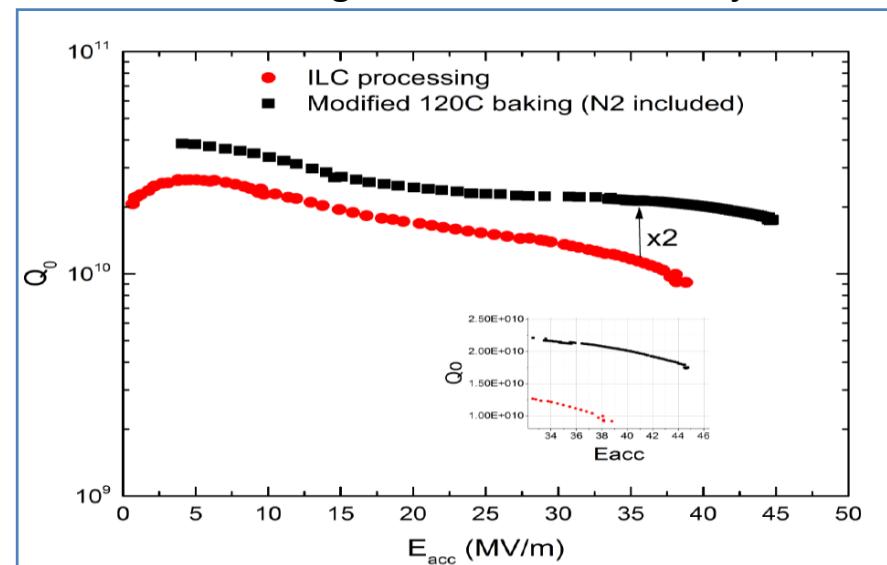
ILC goal 31.5 MV/m

⇒ US-Japan Collaboration on SRF technology

- Coupler design
- Cavity material
- High gradient and high efficient cavities

N2-doping: few minutes 800°C N2 injected

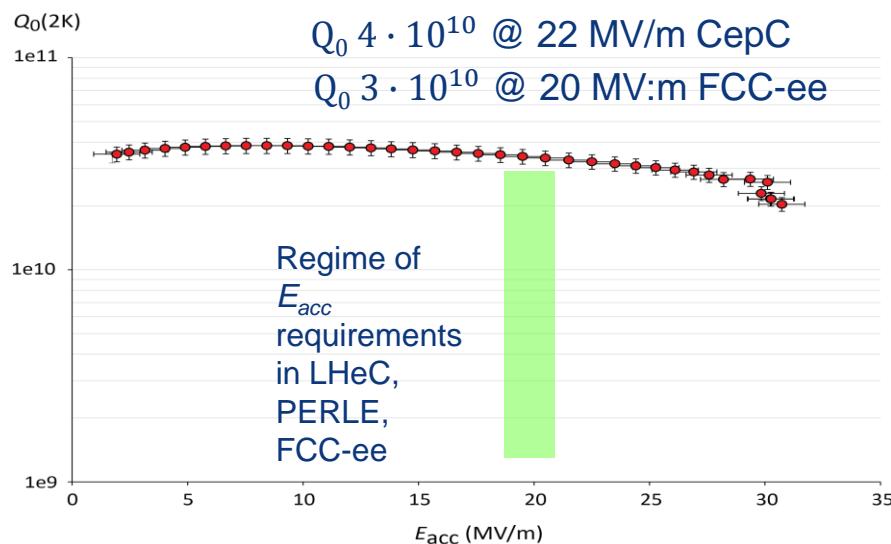
N-infusion: longer time at 120°C N2 injected



High efficient RF system

Recovery energy loss by SR in high current beam

⇒ develop techniques to improve Q_0 of SRF cavity (max gradient modest)



2-cells 650MHz CepC
Vertical test $Q_0=4 \cdot 10^{10}$
@19.2 MV/m



FCC-ee(eh), CepC, ERL based machines, CLIC

5-cell 800 MHz, JLAB prototype for both FCC-ee (t-tbar) and FCC-eh ERL



Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL



CERN half-cells formed using Electro-Hydro-Forming (EHF) at Bmax.

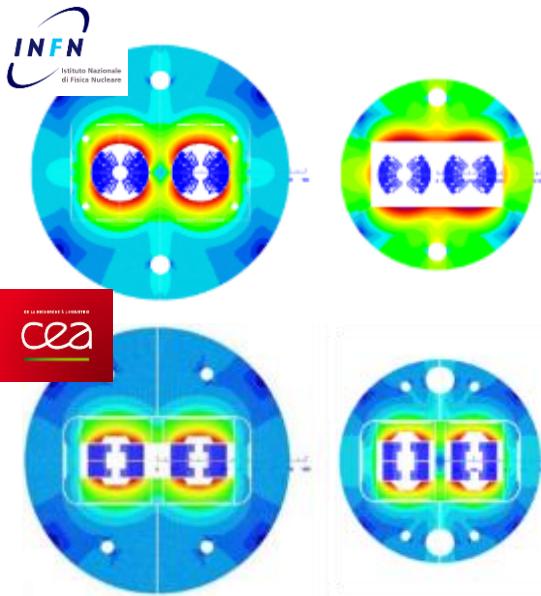


High efficiency RF generation (Klystrons)

- Inside CepC study
- In EuCARD² now ARIES

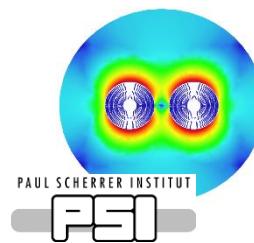
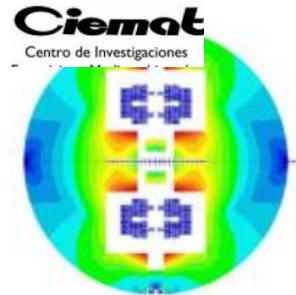
High Field Magnets: dipoles

FCC-hh, HE-LHC



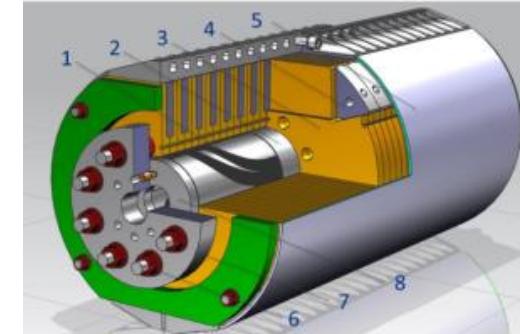
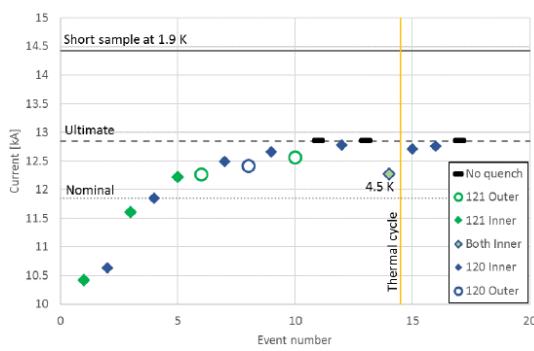
Need 16 T to reach 50(14) TeV /beam
 ⇒ Move from NbTi (LHC technology)
 to Nb_3Sn

14.3 m long dipoles



HL-LHC

11T First Nb_3Sn magnet, FRESCA2 dipole



Fermilab
 50 Years of Discovery

U.S. MAGNET DEVELOPMENT PROGRAM

15 T dipole demonstrator
 60-mm aperture
 4-layer graded coil

Russian 16 T magnet program launched by BINP recently

Beam losses: beam screen

FCC-hh

~30 W/m synchrotron radiation (LHC: 1 W/m)

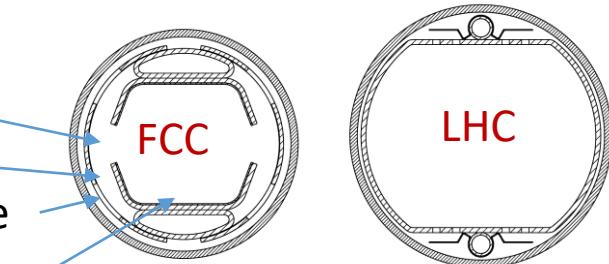
Small to make magnet cheap (aperture 50 mm)

Extract photons for good vacuum

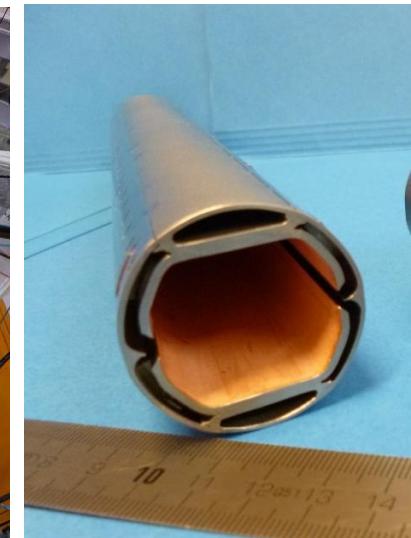
Strong to withstand quench

Hide pumping holes from beam for low impedance

Laser treatment / carbon coating against e-cloud



- Measurements (pressure evolution) confirm MC vacuum simulations
- Confident to use simulations for all vacuum design

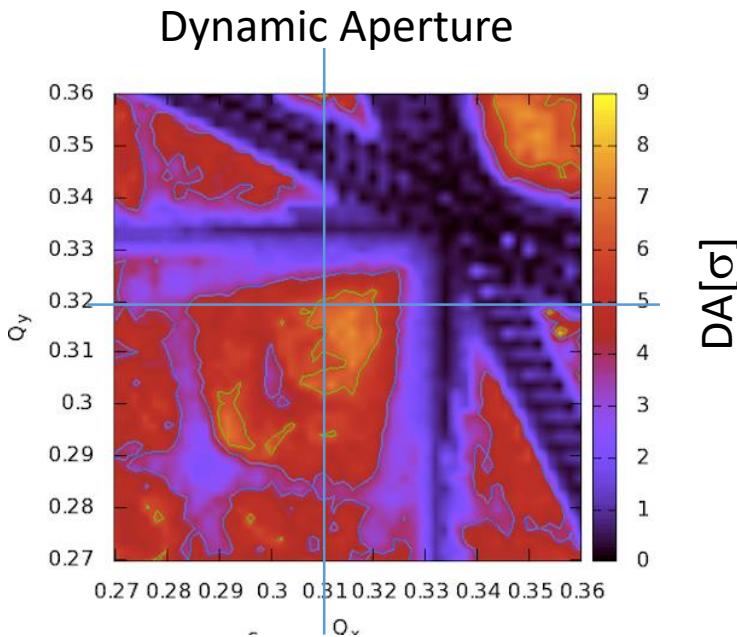


Beam Losses

FCC-hh

~8 GJ kinetic energy per beam in FCC-hh

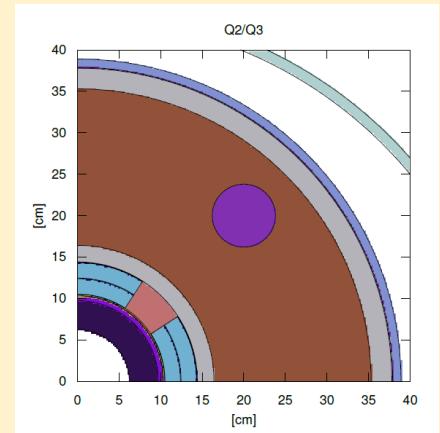
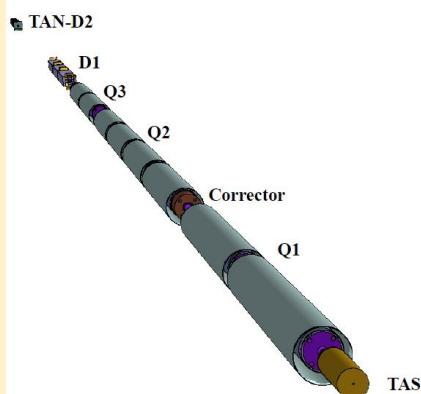
- O(20) times LHC
- Boeing 747 at cruising speed
- 400 kg of chocolate
 - Run 25,000 km to spent calories



LHC experience to benchmark simulation tools

Mitigation of losses and heat load **must be** taken into account in the optics design and integration

Designed shielding to cope with the 500 kW collision debris per experiment



Triplet design allows for thick shielding

Collimation system design

- Designed system that can cope with the losses
- Detailed studies and optimization of performance
- Also reduction of impedance

Beam dump design

Machine protection

Advanced accelerators concepts

ALEGRO (Advanced LinEar collider study GROup, for a multi-TeV Advanced Linear Collider)

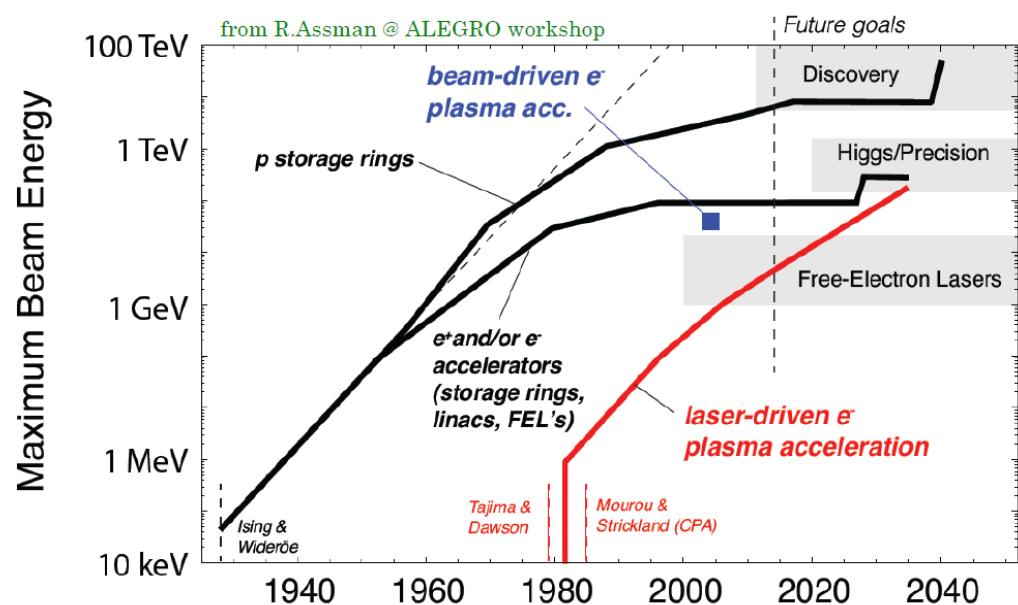
The aim of the first ALEGRO workshop was to prepare and deliver, by the end of 2018, a document detailing the international roadmap and strategy of Advanced Novel Accelerators (ANAs) with clear input for the European Particle Physics Strategy Update.

Specific topics to be addressed

- Positron acceleration
- Technological issue
(efficiency, cooling,
polarization,...)

The R&D focus on beam quality,
beam stability, staging and
continuous operation

Support from Particle Physics
community is required, to make
sure that specific research topics
for collider are addressed



Acknowledgements – many many thanks

- D. Schulte <https://indico.cern.ch/event/686555/contributions/2962553/attachments/1682220/2703710/>
<https://indico.cern.ch/event/686555/contributions/2962555/attachments/1681197/2702849/>
<https://indico.cern.ch/event/686555/contributions/2962542/attachments/1681194/2702876/>
<https://indico.cern.ch/event/466934/contributions/2474221/attachments/1489758/2320028/>
- R. Aleskan http://irfu.cea.fr/Phocea/Vie_des_labos/Seminaires/index.php?id=4270
- S. Michizono <https://indico.cern.ch/event/686555/contributions/2962510/attachments/1682330/2703201/>
- E. Levichev <https://indico.cern.ch/event/686555/contributions/2962546/attachments/1682189/2702955/>
- J. Gao <https://indico.cern.ch/event/686555/contributions/2962503/attachments/1680976/2700616/>
- Y. Chi <https://indico.cern.ch/event/686555/contributions/2962538/attachments/1682997/2704639/>
- S. Cosineau <https://indico.phys.vt.edu/event/34/contributions/609/>
- R. Assmann <https://indico.cern.ch/event/677640/contributions/2866274/attachments/1622621/2582653/>
- E. Cenni
- A. Chancé

Documents

- <https://arxiv.org/abs/1711.00568> ILC
- <https://arxiv.org/abs/1608.07537> CLIC
- <https://arxiv.org/ftp/arxiv/papers/1810/1810.13022.pdf> future colliders at CERN
- <https://arxiv.org/abs/1809.00285> CepC CDR
- FCC CDR:
 - concise summary volumes 1(PH), 2 (hh), 4(ee), 6(HE) → December 2018
 - Long technical volumes 3, 5, 7 → Spring 2019
- Friend J. Phys. A Conf. Ser. 888_012042, 2017 JPARC MR
- http://pxie.fnal.gov/PIP-II_CDR/PIP-II_CDR_v.0.0.pdf PIP II
- <https://www.worldscientific.com/toc/rast/09> Application of Advanced Accelerator Concepts for Colliders

High Field Magnets: Conductors

HL-LHC,HE-LHC,FCC-hh,SppC

New activity with many collaborators started in 2017 with ambitious targets

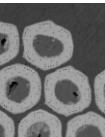
FCC Conductor Development Workshop at CERN, 5-6 March 2018



Workshop series

Workshop series announcement

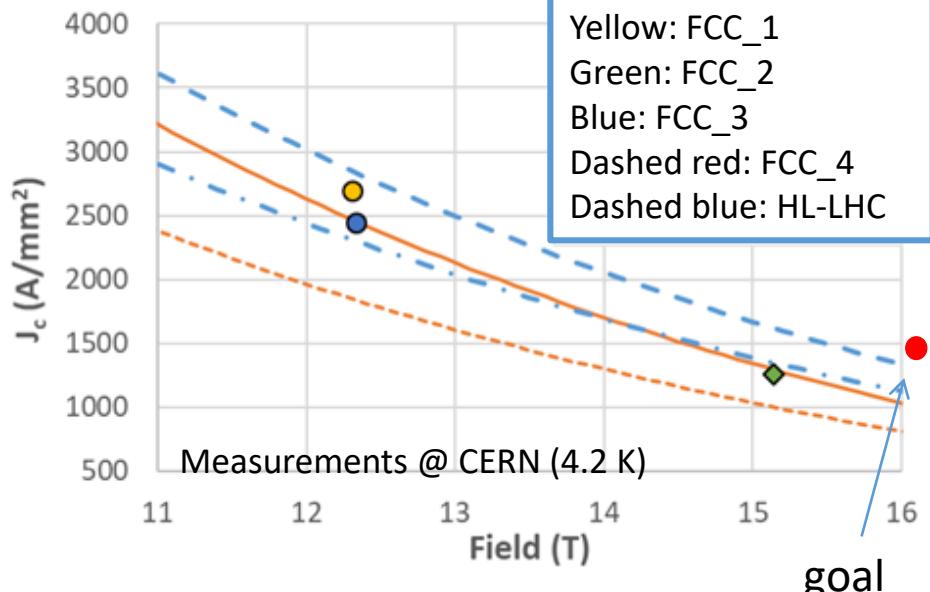
Nb₃Sn technology for accelerator magnets



To push the Nb₃Sn technology safely towards the 16 T frontier, the community is invited to settle on a set of common characterization practices based on a shared vision of the underlying phenomenon and their consequences, the results of which will be applied to magnet design and fabrication phases.



Wire diameter	mm	~ 1
Non-Cu J_c (16 T, 4.2 K)*	A/mm ²	≥ 1500
Unit length	km	≥ 5
Cost	€/kA m**	≤ 5



First wires almost reached HL-LHC requirements