State of the Art and Challenges in Accelerator Technologies – Past and Present

Akira Yamamoto
(CERN and KEK)

A Plenary Talk at CERN Council Open Symposium on the Update of European Strategy for Particle Physics (ESPP)
13-16 May, 2019 – Granada, Spain
### Monday Plenary Session

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Presenter</th>
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<tbody>
<tr>
<td>30'</td>
<td>State of the Art and Challenges in Accelerator Technology — Past and Present</td>
<td>Akira Yamamoto (CERN/KEK)</td>
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<tr>
<td></td>
<td>- HEP today</td>
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<tr>
<td></td>
<td>- Technology — mainly rf and magnets</td>
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<td>- Lessons learnt</td>
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<tr>
<td>30'</td>
<td>Future — path to very high energies</td>
<td>Vladimir Shiltsev (Fermilab)</td>
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</table>
Outline

• **Introduction**
  – Advances in Accelerator Technology in Particle Physics

• **State of the Art in Accelerator Technologies, focusing on**
  – Nano-beam, Superconducting Magnet and RF, and Normal-conducting RF

• **Challenges for future**
  – Superconducting Technologies for future Lepton and Hadron Colliders

• **Summary**

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High-energy and High-Intensity frontier accelerators are relying on superconductivity as core technology to be focused in this talk.
## Accelerator Technologies advanced in Particle Physics

<table>
<thead>
<tr>
<th>Type</th>
<th>Accelerator</th>
<th>Op. Years</th>
<th>Beam Energy (TeV)</th>
<th>B [T]</th>
<th>E [MV/m]</th>
<th>Pioneering/Key Technology</th>
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<tbody>
<tr>
<td>CC</td>
<td>Tevatron</td>
<td>1983-2011</td>
<td>2 x 0.5</td>
<td>4 T</td>
<td></td>
<td>Superconducting Magnet (SCM)</td>
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<tr>
<td>CC</td>
<td>HERA</td>
<td>1990 -2007</td>
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<td>4.68 T</td>
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<td>SCM, e-p Collider,</td>
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<tr>
<td>hh</td>
<td>RHIC</td>
<td>2000 ~</td>
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<td>3.46 T</td>
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<td>SCM</td>
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<tr>
<td>hh</td>
<td>SPS LHC</td>
<td>1981-1991 2008 ~</td>
<td>2 x 0.42</td>
<td>(NC mag.)</td>
<td>7.8T --&gt;8.4 11~12</td>
<td>P-bar Stochastic cooling SCM (NbTi) at 1.8 K, SRF SCM (Nb₃Sn), SRF, e-cooling</td>
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<tr>
<td>hh</td>
<td>LHC HL-LHC</td>
<td>Under constr.</td>
<td>2 x ( 6.5 &gt;&gt; 7)</td>
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<tr>
<td>CC</td>
<td>TRISTAN</td>
<td>1986-1995</td>
<td>2 x 0.03</td>
<td>5</td>
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<td>SRF (Nb-bulk), SCM-IR-Quad (NbTi)</td>
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<tr>
<td>ee</td>
<td>LEP</td>
<td>1989-2000</td>
<td>2 x 0.55</td>
<td>5</td>
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<td>SRF (Nb-Coating) , SCM-IRQ</td>
</tr>
<tr>
<td>ee</td>
<td>KEKB Super-KEKB</td>
<td>1998~2010 2018 ~</td>
<td>0.002+0.008 0.003+0.007</td>
<td>5</td>
<td></td>
<td>Luminosity, SRF Crabbing, SCM-IRQ Luminosity, Nano-beam, SCM-IRQ</td>
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<tr>
<td>ee</td>
<td>SLC/PEP-II</td>
<td>1988/98~2009</td>
<td>2 x 0.5</td>
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<td>SRF (Nb-bulk)</td>
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<tr>
<td>ee</td>
<td>(Eu-XFEL)</td>
<td>(2018 ~)</td>
<td>(0.0175)</td>
<td></td>
<td>(23.6)</td>
<td>Normal conducting RF</td>
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• Introduction
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    >>>> To be discussed by V. Shiltsev and S. Steinar, and the information in Appendix

• Challenges for future, focusing on
  – Superconducting technologies for future Lepton and Hadron Colliders

• Summary
Low-emittance achieved in past 10 years to be discussed more by V. Shlitsev and S. Stapnes

- **Low emittance beam** sufficiently advanced for future colliders

More to be discussed by V. Shlitsev in next talk
Develop nano-beam technology for ILC/CLIC

- Goal: Realize small beam-size and stabilize beam position

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<tr>
<th>B Energy [GeV]</th>
<th>Vertical Size</th>
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<tr>
<td>ILC-250</td>
<td>125 7.7 nm</td>
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<tr>
<td>CLIC-380</td>
<td>190 2.9 nm</td>
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<tr>
<td>ATF2 (achieved)</td>
<td>1.3 41 nm (--&gt;8 nm eq. at ILC)</td>
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</table>

1.3 GeV S-band e- LINAC (~70m)

Damping Ring (140m)
Low emittance e-beam

Courtesy: N. Terunuma
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• Summary
Advances in SC Magnets for Accelerators

**Past:**
- ISR-IR
- Tevatron (Fermilab)
- TRISTAN-IR (KEK)
- HERA (DESY)
- Nuclotron (JINR)
- LEP-IR (CERN)
- KEKB-IR (KEK)

**Present:**
- RHIC (BNL)
- LHC (CERN)
- SRC (RIKEN) ....... *SC-Cyclotron*

**Under Construction**
- FAIR (GSI) .......... *Fast-cycle Shmchr.*
- HL-LHC (CERN)
- NICA (JINR)

**Future:**
- EIC (e-ion)
- FCC-hh / HE-LHC
- SppC

---

11 T Dipole

IR Quadrupole
**NbTi, Nb$_3$Sn Superconducting Magnets and MgB$_2$ SC Links for HL-LHC**

- **Nb$_3$Sn Quad. (MQXF)**
- **NbTi Mag. (D1, and …)**
- Large aperture

**Service gallery (UR)**

**Nb3Sn Dipoles w/ Collimator**
MgB$_2$ 18.5 kA Superconducting Link Demonstrated

- Innovative system supplying current to Interaction Region magnets.
- Several circuits in parallel with lengths in excess of 100 m.
- Multi-stage MgB$_2$ cable carrying up to ~129 kA @ 25 K, cooled by forced flow of GHe at 4.5-17 K.

A demonstrator (2 x 60-m long, 18 kA cables) tested in Dec. 2018, exceeding requirements - $T_{CS}$ at 18 kA of 31.3 K

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12 March 2019
HL-LHC, **11T** Dipole Magnet

- The **1st Series**, 5.5 m long Dipole, powered as a single aperture in the initial test: Reached
- $B_c = 11.2$ T (at nominal current)
  - $I_{\text{nominal}}$, after 1 quench,
- $B_c = 12.1$ T (at ultimate current)
  - $I_{\text{ultimate}}$) after 6 quenches.

![Dipole Magnet Diagram](image)

![Quench Current Graph](image)

*Courtesy, A. Devred, F. Savary, G. Willering*
CERN and US-LARP/AUP Cooperation for Nb3Sn IR Quadrupoles

- **US-LARP Collaboration** taking a critical role for leading R&D:
  - Magnet science and technology
  - Nb3Sn accelerator magnet-technology beyond 10 T,
    - overcoming the very brittle feature (like ceramic),
    - with winding, reacting, and impregnating, and
  - Mechanical structuring w/ Bladder technology for
    - Rigid support of *magnetic pressure* proportional to $B^2$,

- **CERN** leading HL-LHC global collaboration and qualifying the Nb$_3$Sn accelerator magnet technology:
  - Being experienced with the project realization for future collider accelerators.
**Nb$_3$Sn Quadrupole (MQXF) at IR**

**US:** 4.5 m Prototype:
- Completed and tested

**CERN:** 1-m short Models:
- Successfully demonstrated the performance

**CERN:** 7 m Prototype under development

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**US:** 4.5 m Prototype

**CERN:** 1 m Model

**CERN:** 7 m long prototype under development
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• **Summary**
# Features of Normal- and Superconducting RF

<table>
<thead>
<tr>
<th>Normal conducting (CLIC)</th>
<th>Superconducting (ILC)</th>
</tr>
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</table>
| **Gradient:** 72 to 100 MV/m  
- Higher energy reach, shorter facility | **Gradient:** 31.5 to 35 (to 45) MV/m,  
- Higher power efficiency, more steady state beam power from rf input power |
| **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@:** order < $10^5$,  
- Resistive copper wall losses compensated by strong beam loading – 40% steady state rf-to-beam efficiency | **Q@:** order $10^{10}$,  
- High Q  
- Losses at cryogenic temperatures |
| **Pulse structure:** 180 ns / 50 Hz | **Pulse structure:** 600 µs / 5 Hz |
| **Fabrication:**  
- driven by micron-level mechanical tolerances  
- High-efficiency rf peak power production through long-pulse, low frequency klystrons and two-beam scheme | **Fabrication**  
- driven by material (purity) & clean-room type chemistry  
- High-efficiency rf also from long-pulse, low-frequency klystrons |

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Courtesy: W. Wuensch
Normal Conducting Linac Technology Landscape

Components:

- Laboratory with commercial
  - Accelerating structures
  - pulse compressors
  - alignment
  - Stabilization, etc.

- Full commercial supply
  - X-band klystrons
  - solid state modulator,

~ 100 (+/-20) MV/m

Systems Facilities:
(100 MeV-range)
- XBoxes at CERN
  - (NEXTEF KEK)
  - Frascati
  - NLCTA SLAC
  - Linearizers at Electra, PSI, Shanghai and Daresbury
  - Test stand at Tsinghua
  - Deflectors at SLAC, Shanghai, PSI and Trieste
  - NLCTA
  - SmartLight
  - FLASH

C-band (6 GHz), low-emittance GeV-range facilities
Operational:
- SACLA
- SwissFEL (8 GeV)

X-band (12 GHz)
GeV-range facilities
Planning:
- Eu-Praxia
- eSPS
- CompactLight

CLIC

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Courtesy: W. Wuensch
Advances in SRF Technology and Accelerators

Progress (1988~)
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation: \# cavities
- SNS: 1 GeV
- CEBAF 12 GeV: 80
- ISAC-II, ARIEL
- Super-KEKB
- Eu-XFEL: 800

Under Construction:
- LCLS-II: 300
- FRIB: 340
- PIP-II: 115
- ESS: 150
- Shine: 600

To be realized:
- HL-LHC-Crab: 20
- EIC
- ILC-250: 8,000
- FCC
- CEPC/SPPS

> 2,000 SRF cavities realized, in last 10 years!
Advances in L-band (~ 1GHz) SRF Cavity Field Gradient

Field Gradient

\[ E_{\text{acc}}^{\text{max}} = d \cdot \frac{\kappa \cdot H_{\text{crit,RF}}}{\beta_{\text{MAG}} \cdot (H_{pk} / E_{\text{acc}})} \]

Material

Surface

Thermal conductance

Surface, Shape

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European XFEL, SRF Linac Completed

**Progress:**
- **2013:** Construction started
- **2016:** E-XFEL Linac completion
- **2017:** E-XFEL beam start
- **2018:** 17.5 GeV achieved

1.3 GHz / 23.6 MV/m
800+4 SRF acc. Cavities
100+3 Cryo-Modules (CM)
: ~ 1/10 scale to ILC-ML

After Retreatment:
**E-usable:** 29.8 ± 5.1 [MV/m]

>10 % (47/420, RI) cavities exceeding 40 MV/m

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Fermilab, KEK achieving ILC Gradient Goal ≥ 31.5 MV/m with beam

Beam Acc. : 260 MeV by 8 Cavities, 
<\(G\rangle = 32.3 \text{ MV/m}

Beam Acc. : 230 MeV by 7 Cavities, 
<\(G\rangle = 32 \text{ MV/m}

Fermilab-FAST Progress, 2017

KEK-STF2 Progress, 2019

Courtesy: V. Shiltsev, S. Michizono
LCLS-II SRF Linac (SLAC/Fermilab/JLab Collaboration)

1 km SCRF-CW Linac

SRF e-Linac Parameters
- Beam: 4 (+4) GeV, up to 0.3 mA
- Frequency: 1.3 GHz, CW
- G: 18 ~21 MV/m
- Q: > 2.7 e10 (av.)
- # cavity = 280 (+160)
- # CM 35 (+20)
To be completed in 2020 (~2026)


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- > x 2 Q achieved,
- N-doping at 800°C, discovered by A. Grassellino et al., (Fermilab)

Anti-Q-slope

N-doped

Standard treatment

E_{acc} (MV/m)

T= 2K

σ

10^{11}

10^{10}

10^{9}

0 5 10 15 20 25 30 35 40

10^{8}

Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
New Cryoplant

Existing Bypass Line

New Transport Line

Two New Undulators And X-Ray Transport

Exploit Existing Experimental Station

Courtesy, M. Ross
Nb SRF Crab Cavities for HL-LHC

CERN, US-AUP, STFC, TRIUMF Collaboration

Crabbing p beam demonstrated at SPS, 2018

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Courtesy,
R. Calaga, O.Capatina
A. Ratti, L. Ristori
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• Summary
## Technical Challenges in Energy-Frontier Colliders proposed

<table>
<thead>
<tr>
<th>Major Challenges in Technology</th>
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<tbody>
<tr>
<td>High-field SC magnet (SCM)</td>
</tr>
<tr>
<td>- Nb3Sn: Jc and Mechanical stress</td>
</tr>
<tr>
<td>Energy management</td>
</tr>
<tr>
<td>High-field SCM</td>
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<tr>
<td>- IBS: Jcc and mech. stress</td>
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<tr>
<td>Energy management</td>
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<tr>
<td>High-Q SRF cavity at &lt; GHz, Nb Thin-film Coating</td>
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<tr>
<td>Synchrotron Radiation constraint</td>
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<tr>
<td>Energy efficiency (RF efficiency)</td>
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<tr>
<td>High-Q SRF cavity at &lt; GHz, LG Nb-bulk/Thin-film</td>
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<tr>
<td>Synchrotron Radiation constraint</td>
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<tr>
<td>High-precision Low-field magnet</td>
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<tr>
<td>High-G and high-Q SRF cavity at GHz, Nb-bulk</td>
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<tr>
<td>Higher-G for future upgrade</td>
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<tr>
<td>Nano-beam stability, e+ source, beam dump</td>
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<tr>
<td>Large scale production of Acc. Structure</td>
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<tr>
<td>Two-beam acceleration in a prototype scale</td>
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<td>Precise alignment and stabilization. timing</td>
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# Technical Challenges in Energy-Frontier Colliders proposed

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<td>&lt; 30</td>
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<td>20 ± 40 (0.65)</td>
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<td>72 ± 10 (12)</td>
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## Major Technical Challenges:

### Hadron Colliders:
- High-field magnet
- Energy management

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

---

## Major Challenges in Technology

- High-field SC magnet (SCM)
  - Nb3Sn: Jc and Mechanical stress
  - Energy management
- High-field SCM
  - IBS: Jcc and mech. stress
  - Energy management
- High-Q SRF cavity at < GHz, Nb Thin-film Coating
  - Synchrotron Radiation constraint
  - Energy efficiency (RF efficiency)
- High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film
  - Synchrotron Radiation constraint
  - High-precision, Low-field magnet
- High-G and high-Q SRF cavity at GHz, Nb-bulk
  - Higher-G for future upgrade
  - Nano-beam stability, e+ source, beam dump
- Large scale production of Acc. Structure
  - Two-beam acceleration in a prototype scale
  - Precise alignment and stabilization, timing

---

A. Yamamoto, 190505b
State of the Art in
High-Q and High-G (1.3 GHz, 2K)

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

High-Q by N-Doping has been well established, and
High-G by N-infusion and Low-T baking still need to be well reproduced, worldwide.
State of the Art in High-Q and High-G (1.3 GHz, 2K)

The performance also confirmed by Cornell, JLab, and DESY, and expected to be confirmed by other laboratories

Repeated on second cavity TE1AES009 (fine grain, AES, WC)

https://arxiv.org/abs/1806.09824
Challenges in SRF Cavity Technology

- **Bulk-Nb**: High-G and High-Q optimization
  - Low-T treatment w/ or w/o N-infusion.
- **Bulk-Nb**: Large-Grain directly sliced from ingot
  - For possible less contamination and cost-reduction
- **Thin-film Coating**
  - Nb thin film coating on Cu-base cavity structure
  - Nb3Sn/MgB2 film coating on Bulk-Nb or Cu structure
    - Much higher G, w/ high-Bc (Bsh)
    - Important for lower frequency and/or low-beta application.
      - A New approach by using **High Impulse Power Magnetron Sputtering (HiPIMS)**, instead of **DC Magnetron Sputtering (DCMS)**, resulting flatter Q-slop, resulting better thermal efficiency.
DC Magnetron Sputtered Nb/Cu Films

• Q = 1x10^{10} @ 15 MV/m is a value that would make film cavities a competitive option in several future projects.
• Current R&D is focused on improving the “slope”, applying films to new geometries, new materials

HiPIMS coatings – QPR Sample

• HiPIMS Nb/Cu films appear to be comparable to bulk Nb on quadrupole resonator sample at 400MHz, 800MHz and 1.2GHz.
• Q-slope phenomenon seems to disappear and support the effort to evolve this technology into real cavities, and High-Q resulting Power Saving,
• Projected performance > 2x better than LHC specifications

A. Yamamoto, 190505b
Outline

• Introduction
  – Advances in Accelerator Technology in Particle Physics

• State of the Art in Accelerator Technology, focusing on
  – Nano-beam, Applied Superconductivity, and RF

• Challenges for future, focusing on
  – **Superconducting technology** for future Lepton and **Hadron Colliders**

• Summary
Advances in Nb₃Sn Magnet Development

2003: LBNL HD1
(16 T at 4.2 K)

2015: CERN RMC
(16.2 T at 1.9 K)

2018: FRESCA2
(100 mm aperture, 14.6/14.95 T bore/peak at 12.1 kA, 1.9 K)

A. Yamamoto, 190505b

Courtesy: G. De Rijk, A. Devred
16 T Dipole Options and R&D Cooperation

Cos-\(\theta\)

Common coils

Blocks

Canted Cos-\(\theta\) (CCT)

Pioneering work at BNL

CHART2
Swiss Acc. Research and Technology
See; Appendix

CCT,
Pioneering work at LBNL

Courtesy, M. Benedikt, L. Bottura, D. Tommasini, S. Prestemon
**Artificial Pinning Center (APC) approach has been successful, for**

- $J_c (16T, 4.2K)$ to have reached $\sim 1500 \text{ A/mm}^2$ in pure research,
- **Industrialization and cost-reduction is yet to come!!**

$$B = \frac{2\mu_0}{\pi} J w \sin(\phi)$$

**Main development goals:**
- $J_c (16T, 4.2K) > 1500 \text{ A/mm}^2$
  - 50% higher than HL-LHC

**Global cooperation:**
- CERN/KEK/Tohoku/JASTEC/Furukawa
- CERN/Bochvar High-tec. Res. Inst
- CERN/KAT
- CERN/Brucker
- T.U. Vienna, Geneve U., U. Twente,
- Florida S.U. - Appl. Superc. Center
- US-DOE-MDP, Fermilab

**Progress in APC approach:**
X. Xu et al (Fermilab)

https://arxiv.org/abs/1903.08121
Mechanical Constrain to consider Operating Margin

- Reversible $I_c$ reduction already at 150 MPa (~15% at 11.6 T);
- Irreversible $I_c$ degradation onset, around at 160-170 MPa.

Magnetic pressure ($p$):
- Mechanical stress ($\sigma$)

$$ F \mu B^2 $$

$$ w \mu \frac{B}{J} $$
MDP taking Steps to realize 16 T

MDP Goals:
1. Explore $\text{Mb}_3\text{Sn}$ magnet limit
2. Demonstrate HTS magnet (5 T – self field)
3. Investigate fundamentals for performance and cost reduction
4. Pursue $\text{Nb}_3\text{Sn}$ and HTS conductor R&D

For strands:

- L1-L2: 28 strands, 1 mm RRP 150/169
- L3-L4: 40 strands, 0.7 mm RRP 108/127

• **Step 1:** We are here in 2019
  – Realize 14 T w/ mechanical design for 16 T

• **Step 2:**
  – Realize 15 T w/ pre-stress optimization

• **Step 3:**
  – Challenge to realize 16 T,
    – with SC conductor satisfying 1,500 A/mm² and sufficiently controlled mechanical design

See Appendix

Courtesy: S. Prestemon
MDP: SC Magnet R&D at Fermilab: 15 T Dipole

- The 15 T dipole demonstrator magnet assembly is finished
- The dipole is in being prepared for the first test expected to start in a week

Courtesy: S. Belomstnykh
HTS Superconductor, focusing on Bi2212 (in MDP)

Application expected for CCT coil
High-Field Superconductor and Magnets, focusing on IBS

Iron Based Superconductor (IBS) in China.


Iron-Based Layered Superconductor: LaOFeP

To be applied for Common Coil in SPPC

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

To be applied for Common Coil in SPPC

Modified version by Q. Xu in Oct. 2017
High-Field Superconductor and Magnets

Conductor property summarized by P. Lee

A. Yamamoto, 190505b

Eucard2: HTS-insert to be tested in 2019
3~5 + 13.5 T : > 16 T
Three HTS inserts (CERN and Collaborations)

EuCARD1: insert (CEA-CNRS-CERN), racetrack, ReBCO 4 tape stack cable, stand alone tested Sept 2017: Reached 5.37 T @ 4.2K (I=3200A)

EuCARD2: Feather-M2 (CERN), flared ends coil ReBCO, Roebel cable, stand alone tested Apr 2017: Reached 3.37 T @ 4.2K (I=6500A)

EuCARD2: cosθ insert (CEA), cosθ coil, ReBCO, Roebel cable, being fabricated, stand alone test in autumn 2019

Eucard2+ HTS-insert to be tested in 2019

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Courtesy: G. De Rijk
Some Cost References for High-field Conductors

- An approach for cost consideration:
  - Superconductor cost to be 30% of the total cost for the LHC NbTi dipole magnet assembled.
  - It gives a general guideline for acceptable superconductor cost.
  - The currently available HTS cost is still too far, except for Iron-based-SC (IBS) potential.

- Goal for Nb₃Sn for FCC or HE-LHC:
  - 3.5 €/kA.m at 16 T and 1.9 K
  - Corresponding to 500...600 €/kg, a factor 2.5 ~ 3 lower than the present cost 1300 ~ 1500 EUR/kg for HL-LHC (RRP)

* Note: 16-T magnet requires x 2 conductor to that of 14 T.
Further challenges in Accelerator Technologies

• Vacuum,
• Targetting,
• Beam collimator,
• Beam dump,
• Radiation hardness,
• Others

Some Information in Appendix
Outline

• Introduction
  • Advances in Accelerator Technology in Particle Physics

• State of the Art in Accelerator Technologies, focusing on
  • Nano-beam, Superconducting Magnet and RF, and Normal-conducting RF

• Challenges for future, focusing on
  • Key technologies and energy management for future Lepton and Hadron Colliders

• Comments on
  • Complementarity for Energy-Frontier vs. Intensity-Frontier, and Energy Management

• Summary
Questions given by EPPSU2020 Acc. Session Conveners:
Lenny Rivkin (PSI) and Caterina Biscari (ALBA)

Open Symposium

Big Questions

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?
Intensity frontier vs. Energy frontier

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<td>Collider</td>
<td>SCM, SRF</td>
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Common Issues:
- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management

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

Discussed by V. Shiltsev in Parallel Session

Courtesy: N. Saito, S. Belomestnykh, R. Garoby

A. Yamamoto, 190505b
Energy Management
Major issue in Energy- and Intensity-frontier Accelerators

• Energy Saving
  • Superconducting technology (partly covered in this talk)
    • Magnet
    • RF cavity -> further contribution by High-G and High-Q

• System Efficiency Improvement
  • Power system efficiency (to be covered by E. Jensen in Acc. Session)
    • RF modulator, Klystron,
    • Two beam acceleration
  • Cryogenics system efficiency
    • Further optimization depending on the operational temperature (eg; Ne-He refrigerator for SR heat removal)
  • Efficient beam dynamics (to be covered by V. Shiltsev)
    • Low-emittance/nano-beam,
  • Novel, further efficient accelerator scheme (to be covered by V. Shiltsev)

• Dynamic Energy Balance
  • Important issue: not power (W) efficiency, but energy (W-hour) efficiency
  • Accelerator operation in best harmonized condition in season/day/time.
  • Energy re-use/recycling more communicated with surrounding community/industry

More in Appendix
Outline

• **Introduction**
  • Advances in Accelerator Technology in Particle Physics

• **State of the Art in Accelerator Technology, focusing on**
  • Nano-beam, Applied Superconductivity, and RF

• **Challenges for future, focusing on**
  • Superconducting technology for future Lepton and/or Hadron Colliders

• **Comments on**
  • Complementarity of Energy-Frontier and Intensity-Frontier, and Energy Management

• **Summary**
Summary: State of the Art – RF and SC Magnet

**NRF, SRF:**
- **NRF** ( ~ 12 GHz, 20 cm unit):
  - E (CLIC R&D: 12 GHz): 70 ~ 100 MV/m
- **SRF** (1.3 GHz, 9-cell cavity)
  - \( <E> \) (Eu-XFEL): 30 MV/m, (~ 800 cavities)
  - **SRF** (Crab cavity)
    - Experienced at KEK-B, and demonstrated at CERN-SPS

**SC Magnet:**
- **NbTi**: LHC (Main Dipole)
  - \( B_{\text{bore}} = \sim 8 \ T \) at 1.9 K
  - Re-training aft. thermal cycling (TC) still a critical issue
- **Nb3Sn**: HL-LHC (11 T Dipole)
  - \( B_{\text{bore}} = \sim 11 \ T \) at 1.9 K
  - Good memory  after TC, but more statistic needed
  - Loadline-ratio, however, should stay lower (< 80%)
Summary:
Challenges - SRF and SC Magnet

• **Superconducting RF:**
  • **Nb-bulk** (for > 1 GHz)
    • High-Q (> 3E10) and High-G (> 45 MV/m), w/Low-T treatment w/ or w/o N-infusion.
    • Large-Grain SRF cavity for cleaner condition with cost-reduction,
  • **Thin-Film** (for wider applications)
    • Potential thin-film on Nb to improve effective Bsh, resulting higher gradient, and further Potential for new SC material such as NB3Sn/MgB2 to much/drastically improve Bc.

• **Superconducting Magnet:**
  • **Nb3Sn** technology, to reach 16 T, requires much longer steps for much improvement of SC current density, mechanical property, control for field quality and limited training quenches, and industrialization effort.
  • “**Nb3Sn + HTS-insert**” technology will be required, beyond 16 T, and cost effective HTS will be essentially required for practical accelerator applications.
Personal Prospect

• Accelerator Technologies are ready to go forward for lepton colliders (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory to start the construction in 5 ~ 7 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.

• $\text{Nb}_3\text{Sn}$ high-field superconducting magnet, as a core technology for energy-frontier hadron colliders, still requires step-by-step development efforts to reach 14, 15, and 16 T.

• A field range of 14 -16 T, with accelerator quality, would requires much longer time:
  – 12~14 T, 5~10 years for short model work, and next 5~10 years for prototype/pre-series work in cooperation with industry, resulting 10 – 20 yrs to reach the production stage
  – 14~16 T: 10-15 years for short model work, and next 10 ~ 15 years for prototype/pre-series work in cooperation with industry, resulting 20 – 30 yrs to reach the production stage. It would be consistent with the FCC- integral time scale.

• $\text{NbTi}$ Superconducting magnet technology at 8~9 T is well proven with LHC, and $\text{Nb}_3\text{Sn}$ magnet at 10 – 11 T is being demonstrated with HL-LHC. A hadron collider with either technology should be practical to start the construction in 5 ~ 7 years.

• Continuing R&D effort for the high-field magnet, present to future, should be critically important, to realize highest energy frontier hadron accelerators in future.

• High-energy and Intensity-frontier needs to work together on energy management including energy-efficiency improvement, energy-saving, energy-recycling, in wider networks with surrounding communities.
### Personal View for possible, Relative Timelines

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A. Yamamoto, 190505b
Acknowledgments

• This talk has been prepared in communication with
  – HiLumi-LHC, and US-LARP/AUP collaboration
  – Euro-CirCol (FCC study body),
  – EUCARD-2 succeeded by ARIES,
  – US-DOE Magnet Development Program (MDP),
  – US-General Accelerator SRF R&D program (GARD-SRF),
  – Tesla Technology Collaboration (TTC), European XFEL, and LCLS-II,
  – Linear Collider Collaboration (LCC) for ILC and CLIC,
  – FCC Study at CERN,
  – CEPC-SPPC study at IHEP, and
  – SC magnet and SRF accelerator laboratories:
    • Fermilab, BNL, JLab, Cornell, SLAC, CERN, CEA-Saclay, LAL-Orsay, DESY, STFC, KEK, ...

• Special thanks to: F. Bordry, L. Rossi, S. Steinar, J. M. Jimenez, L. Bottura, A. Devred,
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  for their kindest cooperation to provide various information and discussion.
Appendix
**Goal 1:** Establish the FF method with same optics and comparable beamline tolerances

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

**Goal 2:** Develop nm position stabilization at FF:

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

---

**History of ATF2 small beam**

- 1 Skew Sextupole Installed
- 4 Skew Sextupoles
- 4 FF Sextupoles
- Orbit Stabilization
- 5 FF sextupole Modification
- FONT FB ON

A. Yamamoto, 190505b
Progress in Normal Conducting RF Acc. Structure

• Achieved 100 MV/m gradient in main-beam RF cavities

Curtesy: S. Stapnes, P. Barlow, W. Wuensch
NRF Technology for CLIC-380 and beyond

- Linear $e^+e^-$ collider, staged $\sqrt{s} = 0.38$ TeV

- 70 MV/m accelerating gradient needed for compact (~11 km) machine based on:
  - normal-conducting accelerating structures
  - two-beam acceleration scheme

**Issue remaining:**
- Power efficiency at higher energies
- Large scale production experience for Acc. Structures
- System-level alignment and stabilization
Better Cavity Shapes to Beat the Limit:
Lower $H_{pk}$ even if you have to raise $E_{pk}$

\[ E_{acc} = \frac{H_{RF}^{CR}}{H_{pk} / E_{acc}} \]

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<tbody>
<tr>
<td>D-iris [mm]</td>
<td>70</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$E_{p}$/Eacc</td>
<td>1.98</td>
<td>2.36</td>
<td>2.28</td>
<td>1.98</td>
</tr>
<tr>
<td>$H_{p}$/Eacc [Oe/MV/m]</td>
<td>41.5</td>
<td>36.1</td>
<td>35.4</td>
<td>37.1</td>
</tr>
<tr>
<td>$G*R/Q$ [$\Omega^2$]</td>
<td>30840</td>
<td>37970</td>
<td>41208</td>
<td>36995</td>
</tr>
<tr>
<td>$E_{acc}$-max [MV/m]</td>
<td>42.0</td>
<td>48.5</td>
<td>49.4</td>
<td>47.2</td>
</tr>
</tbody>
</table>
New potential breakthrough: very high Q at very high gradients with low temperature (120°C) nitrogen treatment.

Achievements at Fermilab:
- G-max = 45.6 MV/m → 194 mT
- Q (at 35 MV/m) : ~ 2.3e10

Improvements:
- G : ~ 15 %
- Q : x 2 → Cryogenics saving

The recipe discovered and demonstrated at Fermilab (by A. Grassellino et al.).
- Global collaboration extends the R&D and demonstrate the statistics.
Possible Consideration and Models

- 120C bake is known to manipulate mean free path at very near surface (~nm) on clean bulk Nb.

- The Nitrogen (N) infusion is a variation of the 120 C bake where N dopes the near surface w/o working lossy nitrides.

- A dirty (doped) layer at the surface seems beneficial in order to increase the quench field above Bc1.

Surface current is suppressed:
- means an enhancement of the field limit, because of the theoretical field limit to be determined by the current density.


(Figure above)
HiPIMS principle / setup

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration (us)</td>
<td>1-200</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>20-500</td>
</tr>
<tr>
<td>Power (W)</td>
<td>100 peak, 2 avg</td>
</tr>
<tr>
<td>Gas</td>
<td>Ar, Kr</td>
</tr>
<tr>
<td>Pressure (mbar)</td>
<td>8.10^-5-5.10^-2</td>
</tr>
</tbody>
</table>

Same setup as DCMS
- Only the power supply changes
- High level of ionization of the sputtered species (up to 70%)
- High instantaneous power (100’s kW) for same average power as in DCMS.
- Possibility to densify the layer using a negative voltage (biasing) on the substrate.
- Lower coating rate than in DCMS (ions re-attracted at the cathode surface)

DC Magnetron Sputtering vs. HiPIMS

**HiPIMS** allows densifying Nb thin film on any substrate shape and complexity.

Coating with ionized Nb⁺ can be easily directed on the substrate with an electric field (bias).

Paves the way toward Q-slope mitigation.

700 MHz β=0.65 Single Cell Cavity profile, coating at 150 °C

Courtesy: S. Cteroni
State of the art biased HiPIMS coatings: QPR sample

Extrapolation of surface resistance of biased HiPIMS Nb/Cu film as measured at 400 MHz with quadrupole resonator, to the LHC cavity geometry

Q-slope phenomenon strongly suppressed and support the effort to evolve this technology into real cavities.

Projected performance > 2x better than LHC specifications

Second conclusion

- Film crystalline structure has an impact on the “slope”

- Directions for future research lines (FCC 400 MHz):
  - Improve film crystal structure at any angle of incidence
  - Densify films
  - Pursue efforts to mitigate hydrogen effects (high-temperature coatings, N₂ treatments [?])
Progress in Nb$_3$Sn-Coating Research
reported at TTC meeting, Vancouver, Feb. 2019

**New Progress in Nb$_3$Sn: Fermilab 1.3 GHz Cavity**

- Meets LCLS-II spec at 2 K
- World record CW gradient for Nb$_3$Sn accelerator cavities!

- $Q_0 > 10^{10}$ at 20 MV/m at 4.4 K

**Comparison to Other Cavities**

- World record CW gradient for Nb$_3$Sn accelerator cavities! Higher by 4 MV/m (~25% increase)

---

**B$_{sh}$ = practical limit for SRF**

- $B_{sh-Nb} : 210$ mT
- $B_{sh-Nb3Sn} : 430$ mT
- $B_{sh-MgB2} : 310$ mT

Courtesy: S. Posen
Training Quench in NbTi Magnets (LHC)

Nb–Ti Work Horse: the LHC

- LHC remains the largest superconducting magnet system ever assembled and is now operating reliably at 6.5 TeV, corresponding to a dipole magnet current of 10,980 A and a bore/peak field of 7.73/7.95 T.

- Although all magnets were cold tested prior to tunnel installation, a training campaign is required after each warm-up/cool-down.

- Bringing the machine up to 7 TeV (11,850 A and a bore/peak field of 8.33/8.57 T) is expected to require several hundred quenches.

(Courtesy of MP3, chaired by A. Verweij, CERN)
• Mission with regard to applied superconductivity:
  – Develop a sustainable and Swiss-based expertise in applied superconductivity and superconducting magnets for HEP, in view of a possible FCC-hh or HE-LHC. This shall be anchored in the existing institutes and universities, and further developed thanks to additional recruitment and hands-on training of applied scientists and technicians in the practical objectives described below (R&D, prototyping and testing).

• High-field magnets:
  – prove (or disprove) CCT technology for Nb₃Sn 16-T dipoles,
  – develop an up to 2-m-long high-field demonstrator – possibly of different coil geometry.
  – contribute to the development of Nb₃Sn conductors that match the performance targets […] and of the cable optimization and test.

• HTS magnets:
  – develop technologies for HTS based accelerator magnets,
  – design, build, and test an HTS variant of the SLS 2.0 superbend magnet.
  – design, build, and test several periods of an HTS undulator magnet.

• Infrastructure:
  – To establish the infrastructure needed to build and test all aspects of FCC-hh, HE-LHC magnets and other SC accelerator magnets.
after 10 years of development the US and EU development gave us the Nb$_3$Sn conductor for HILUMI.


**Nb₃Sn conductor program**

- **Nb₃Sn** is one of the *major cost & performance* factors for FCC-hh
- **Highest attention** is given

\[ B = \frac{2\mu_0}{\pi} J_w \sin(\phi) \]

---

**Main development goals:**
- \( J_c \) (16T, 4.2K) > 1500 A/mm²
  - 50% higher than HL-LHC

**Global cooperation:**
- CERN/KEK/Tohoku/JASTEC/Furukawa
- CERN/Bochvar High-tec. Res. Inst
- CERN/KAT
- CERN/Bruker
- T.U. Vienna, Geneve U., U. Twente,
- Florida S.U. - Appl. Superc. Center
- New US-DOE-MDP

---

**Requirement (FCC)**

- **Non-Cu**
  - \( J_c : 1,137 \text{ A/mm}^2 \) @ 16T
- **Non-Cu**
  - \( J_c : \sim 1,450 \text{ A/mm}^2 \) @ 16T

**Figures to be updated**

https://arxiv.org/abs/1903.08121

**Ternary add. Approach:**
K. Saito et al. (JASTEC/KEK)

**Artificial Pinning Center (APC) approach:**
X. Xu et al (Fermilab)
The US Magnet Development Program was founded by DOE-OHEP to advance superconducting magnet technology for future colliders.

Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D.

A clear set of goals have been developed and serve to guide the program.

Technology roadmaps have been developed for each area: LTS and HTS magnets, Technology, and Conductor R&D.
Magnets start with the superconductor: we are about to put Nb$_3$Sn into a collider for the first time, and are investigating the potential of HTS.
A Cos(t) 4-layer design led by FNAL is being pursued with the ultimate goal of achieving ~15T

- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
  - Intrinsic difficulty with 4 layers
  - Collared-structure approach includes new features that provide some prestress increase during cool down

- Status:
  - Coils fabricated
  - Structure designed, fabricated
  - Mechanical model assembly completed
  - Assembly readiness review completed
  - Assembly underway now

Thanks to CERN!

- Thin StSt coil tube space
- Vertically split iron laminations
- Aluminum I-clamps
- 12-mm thick StSt coil
- Thick end plates and StSt foot

60-mm aperture, 4-layer graded coil

Courtesy: S. Prestemon
On the HTS magnet front, Bi2212 has matured to become a magnet-ready conductor

- Bi2212 has made dramatic strides in Jc over last 3 years => ready for magnets
  - Wire has been cabled and tested in racetrack configuration (RC5)
  - First Bi2212 CCT dipoles have been wound and await reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

- Nano-spray combustion powder technology
- 55x18 wire design
- At 15 T, Jc ~1365 A/mm², twice the target desired by the FCC Nb3Sn strands
- At 27 T, Jc ~1000 A/mm², adequate for 1.3 GHz NMR.
FRESCA2 + HTS-Insert

Fresca2 a 13T Nb3Sn dipole

- $B_{\text{center}} = 13.0 \, \text{T}$
- $I_{\text{F3T}} = 10.7 \, \text{kA}$
- $B_{\text{peak}} = 13.2 \, \text{T}$
- $E_{\text{mag}} = 3.6 \, \text{MJ/m}$
- $L = 47 \, \text{mH/m}$
- Aperture = 100 mm
- L coils = 1.5 m
- L straight = 700 mm
- L yoke = 1.6 m
- $\Phi$ magnet = 1.03 m

13T nominal field dipole for the CERN cable test station, reached 14.6T (record field)

HTS insert test in Fresca2

To approach 20T the 3 HTS inserts will be tested in Fresca2 in a 13T background field.

1. EuCARD2 Feather2, second magnet with high perf. tape, (end summer 2019)
2. EuCARD1 flat racetrack (end 2019)
3. EuCARD2 cost: (spring 2020)

- Questions to be answered: maximum insert field in a background field, tolerance of the tapes for high fields, transition behavior at high field (quench), mechanical issues.
Three HTS inserts (CERN and collaborations)

EuCARD1: insert (CEA-CNRS-CERN), flat racetrack, ReBCO 4 tape stack cable, stand alone tested Sept 2017: Reached 5.37 T @ 4.2K (I=3200A)

EuCARD2: Feather-M2 (CERN), flared ends coil ReBCO, Roebel cable, First magnet (low perf tape), stand alone tested Apr 2017: Reached 3.37 T @ 4.2K (I=6500A)

EuCARD2: cosθ insert (CEA), cosθ coil, ReBCO Roebel cable, being fabricated, stand alone test in autumn 2019

Courtesy: G. de Rick
Technical Challenge: Vacuum

Trend in vacuum technology for particle accelerators

- Extinction of gas sources
- Eradication of eclouds
- Remote handling of vacuum components
- Smaller aperture and thinner walls
- Detailed simulation

Extinction of gas sources

- Innovative surface modifications and coatings
- Innovative mechanical design and materials
- Taylor-made Monte Carlo methods

Non Evaporable Getter (NEG) thin film coatings transform beampipes into pumps.
- After activation at 180°C, they provide very low beam induced desorption and low secondary electron yield.
- E.g more than 1500 vacuum chambers coated at CERN.

Eradication of eclouds: carbon coatings

Reduction of synchrotron-radiation desorption yield after NEG activation

MAX IV vacuum chamber: before and after NEG coating

Courtesy: Paolo Chiggiato

Advanced Technology for particle accelerators

Courtesy: F. Bordry
Challenges in Target, Collimator, and Beam Dump

• To be filled:
Technical Challenges: Radiation Hardness

Material Challenges in Future Accelerators

- **Future machines** are set to reach unprecedented **Energy** and **Energy Density**.
- No existing material can meet extreme requirements for Beam Interacting Devices (Collimators, Absorbers, Windows ... ) as to **robustness** and **performance**.
- New materials are being developed to face such extreme challenges, namely **Metal-and Ceramic-Matrix Composites** with **Diamond** or **Graphite** reinforcements.
- **Molybdenum Carbide - Graphite** composite (MoGr) is the most promising candidate material with outstanding thermo-physical properties.

<table>
<thead>
<tr>
<th>MoGr Key Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</td>
</tr>
<tr>
<td>Melting Point Tm [°C]</td>
</tr>
<tr>
<td>CTE [10⁻⁶ K⁻¹]</td>
</tr>
<tr>
<td>Thermal Conductivity [W/mK]</td>
</tr>
<tr>
<td>Electrical Conductivity [MS/m]</td>
</tr>
</tbody>
</table>

- Understanding of **unexplored conditions** call for state-of-the-art numerical simulations complemented by advanced tests in dedicated facilities.

**e.g. HiRadMat Experiments**

- Test of complete devices and materials under extreme beam impact conditions with comprehensive acquisition systems.
- Benchmark of experimental measurements with results of state-of-the-art numerical codes.

[Images of material properties and experiment setup]

_A. Yamamoto, 190505b_
- High Intensity Accelerator requires investigation of radiation damage of target and beam window
- RaDIATE: an internat’l collab. of scientists and engineers from acc. and reactor facilities to solve the problems
- J-PARC has joined the team since 2014. MOU is in preparation.

Neutrino Beam Window
Ti Alloy ~1x10^{21} pot
~ 1 Displacement Per Atom
(Existing data up to ~0.3DPA)

NuMI graphite broken target
Post-Irradiation Examination (PIE)
at PNNL: Swelling effect observed

New Irradiation Run at BNL (2017 February ~)
Intensity Frontier Accelerators

Hi-Intensity P-driver

- 1 MW class
- Multi-MW potential

- J-PARC, KEK&JAEA: 3-GeV RCS, 1 MW
- 38-GeV MR, 750 kW
- Spallation Neutron Source, ORNL: 1-GeV AR, 1.4 MW

- HIPA, PSI: 590 MeV/u cyclotron, 1.4 MW

- Main Injector, FNAL: 120-GeV Synchrotron, 700 kW

- SPS, CERN: 460-GeV Synchrotron

A Quest for High Intensity

- High Intensity
- High Statistics
- More Precision
- More Rare Searches
- More Materials
- Discovery!

Jie Wei / Y. Yamazaki

Courtesy: N. Saito
US Electron-Ion Collider

National Academy of Sciences : 2018 Assessment of US EIC
The committee finds the scientific case compelling, fundamental and timely.

“EIC can address three profound questions..
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense system of gluons?”

US DOE Budget Justification

Volume 4, Page 272:
“(EIC). Critical Decision-0, Approve Mission Need, is planned for FY 2019.”

Requirements from the EIC Whitepaper
- Highly polarized (~70%) electron and nucleon beams [as well as light ions]
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 - ~100 GeV, upgradeable to ~140 GeV
- High collision luminosity ~10^{33-34} cm^{-2} s^{-1}
- Possibilities of having more than one interaction region

Two realization concepts being developed. Realization could be as early as 2026-2030.
EIC Accelerator Sci Tech & Synergies with European projects

Accelerator R&D ongoing with strong cooperation between several DOE labs under DOE NP guidance

Collaboration from international partners is welcome!

Common areas of sci-technological advances:
- Unprecedented collider that needs to maintain high luminosity and high polarization
- Combine challenges of Super-B factories & hadron colliders
- Crab cavities, hadron beam cooling, high field magnets for the interaction points

Common areas of synergy with European projects:
- HL-LHC and EIC crab cavities
- PERLE ERL and ERL for hadron cooling
- High voltage DC cooling for EIC and for HESR/FAIR GSI
- Nb3Sn and thin film cavities for cost-effective SRF
- Highly HOM-damped SRF cavities
- IR SC magnets for HE-LHC, FCC, EIC
- General accelerator beam dynamics and simulations

EIC accelerator technology development is synergistic with the projects (HL-LHC, HE-LHC, FCC, etc.) discussed within the European Strategy update process.
Encourage creating a global world-wide collaboration on EIC accelerator and machine-detector interface R&D
ESSnuSB: An Intensity-frontier ACC. for PP in future

**ESS proton linac**

- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, $10^{15}$ protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- $>2.7 \times 10^{23}$ p.o.t/year.

**How to add a neutrino facility?**

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - $H^+$ source (instead of protons),
  - space charge problems to be solved.
- $\sim$300 MeV neutrinos.
- Target station (studied in EUROv).
- Underground detector (studied in LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.
Energy Efficiency and Management in Accelerators

- The good news: power consumption grows slower than collision energy
- The bad news: future projects need hundreds of MW

**Beam power, particle energy, intensity**

- **Average beam power**
  \[ P_{\text{beam}} = \frac{\delta I E}{e} = f_{\text{rep}} N_{\text{pulse}} E \]
  - Beam current
  - \( E \) = 2 GeV
  - \( I \) = 62.5 mA
  - \( \delta \) = 4 %
  - \( P_{\text{beam}} = 5 \text{ MW average} \)

*Ph. Lebrun*
Energy Efficiency and Management in Accelerators

Collider efficiencies

Grid-to-beam efficiency [%]  
Accelerator systems efficiency [%]

Infrastructure systems: cryogenics
COP of cryogenic helium refrigerators (installed)

C.O.P. [W/W @ 4.5K]

LHC  HL-LHC  CLIC 500  ILC 500  CLIC 3000

TORE SUPRA  RHIC  TRISTAN  CEBAF  HERA  LEP  LHC

Ph. Lebrun  4th W Energy for Sustainable Science
Energy Efficiency and Management in Accelerators

### Cryogenic Refrigeration for FCC-hh

**The real cost of intrinsic losses**

- **RH**: resistive heating
- **BGS**: beam-gas scattering
- **BS**: beam screen
- **CM**: cold mass heat-inleaks
- **CL**: current leads
- **BS cir.**: Beam screen circulator (RT)
- **TS**: thermal shield
- **IC**: image current
- **SR**: synchrotron radiation

Carnot efficiency:
- Ne-He plants: 40 %
- Helium plants: 28.8 %

Isentropic efficiency:
- Cold compressors: 75 % per stage
- Warm circulator: 83 %

### Summary

**Reasons for low efficiency**

- For all types of accelerators, the average beam power is proportional to the product of particle energy and luminosity or delivered particle flux.
- The energy-luminosity performance, and possibly the physics reach of a collider can be represented by a single “coefficient of performance”.
- The ratio of “coefficient of performance” to beam power quantifies the relation between collider performance and beam parameters: it is lower for single-pass machines than for circular colliders.
- “Intrinsic” losses due to basic physics processes add up to the beam power and often exceed it (synchrotron radiation).
- Accelerator systems and infrastructure represent the bulk of electrical power consumption.
- Comparing total power consumption and average beam power yields very low values for overall “grid-to-beam” efficiency.
- Linear colliders show higher overall “grid-to-beam” efficiencies than circular colliders. This partly compensates for their much lower COP/beam power ratio.
Energy Management
to be discussed by E. Jensen (Acc. Session)

A reference: Outlook – Strategies pointed out by Ph. Lubrun (EUCARD2 study)

- Maximize energy-luminosity performance per unit of beam power
  - Minimize circumference for a given energy (high-field magnets)
  - Operate at beam-beam limit
  - Low-emittance, high-brilliance beams
  - Low-beta insertions, small crossing angle (“crabbing”)
  - Short bunches (beamstrahlung)

- Contain “intrinsic” losses
  - Synchrotron radiation
  - Beam image currents
  - Electron-cloud

- Optimize accelerator systems
  - RF power generation and acceleration (deceleration)
  - Low-dissipation magnets (low current density, pulsed, superconducting, permanent)

- Optimize infrastructure systems
  - Efficient cryogenics (heat loads, refrigeration cycles & machinery, distribution)
  - Limit electrical distribution losses (cables, transformers)
  - Absorb heat loads preferably in water rather than air
  - Recover and valorise waste heat

Ph. Lebrun
Workshop on Magnet Design Nov 2014

Courtesy: Ph. Lebrun, V. Shiltsev