Particle Accelerator Technologies: present status and future perspectives

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JENAS-2022

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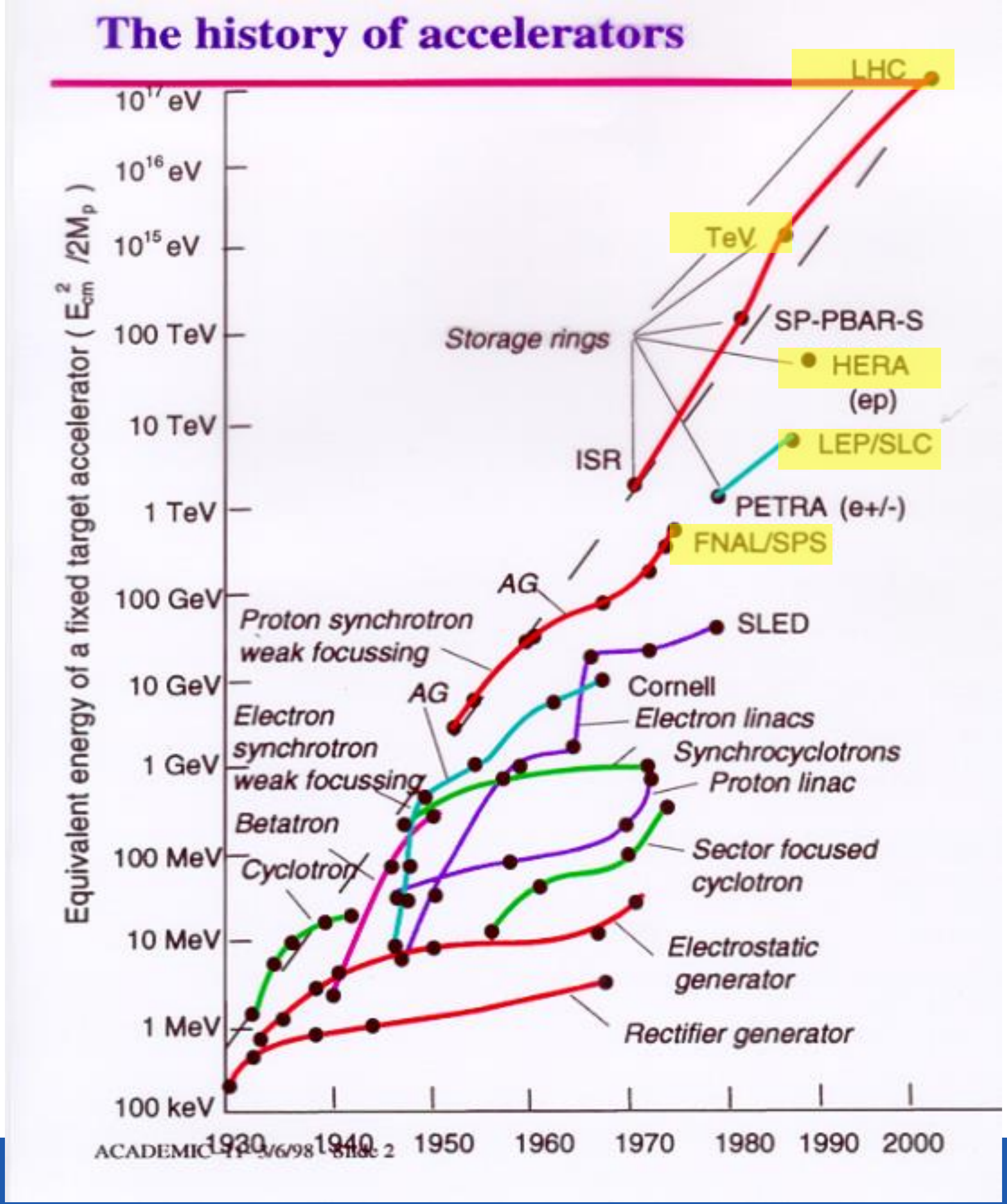
Brief look at history

- Fundamental discoveries made with "beams" from radioactive sources (Rutherford) trigger the demand for higher energies

- **New concepts** allow sustained exponential development for more than 80 years and progress achieved through repeated jumps from saturating to new technologies

- From early 80's, more **technology driven** progresses: superconductivity key technology of high-energy machines (RF and magnets)



Scientific priorities for the future: innovation

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs.

The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.

Development of **innovative accelerator technology** as driver for **science and industry**.

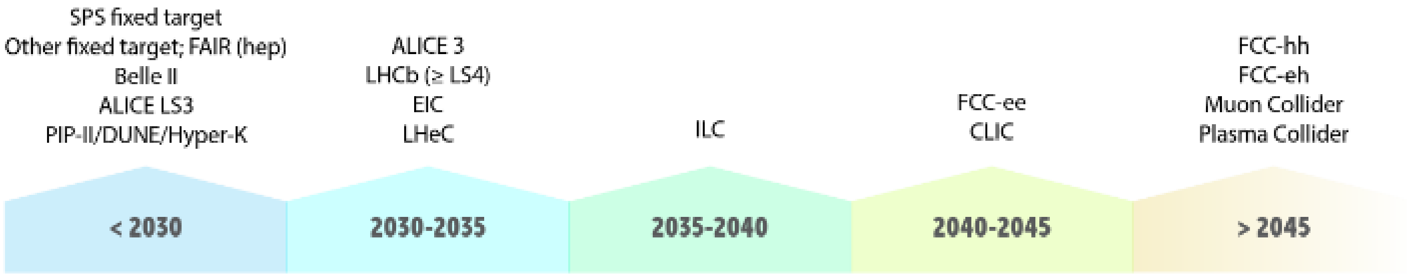
In particular:

1. high-field magnets and high temperature superconductors
2. Plasma wakefield and other high-gradient acceleration
3. Muon beams
4. Energy recovery linacs

1. Further development of high-field superconducting magnet technology.
2. Advanced technologies for superconducting and normal-conducting radio-frequency (RF) accelerating structures.
3. Development and exploitation of laser / plasma acceleration techniques.
4. Studies and development towards future bright muon beams and muon colliders.
5. Advancement and exploitation of energy-recovery linear accelerator technology.

The charge to each of the expert panels was to:

- establish the key R&D needs in each area, as dictated by scientific priorities;
- consult widely with the European and international communities, taking into account the capabilities and interests of stakeholders;
- take explicitly into account the plans and needs in related scientific fields;
- propose ambitious but realistic objectives, work plans, and deliverables;
- give options and scenarios for European investment and activity level.



Outline

All in 25 minutes !

Advanced Technologies:

- **Superconducting magnets**
- **Superconducting RF**
- **Cryogenics (see Steffen Grohmann's presentation)**

- **Materials and beam intercepting devices (BID)**
- **Vacuum system**

Advanced Concepts

- **Beam-driven Plasma Wakefield Acceleration (PWFA)**

Outline

Advanced Technologies:

- **Superconducting magnets**
- **Superconducting RF**
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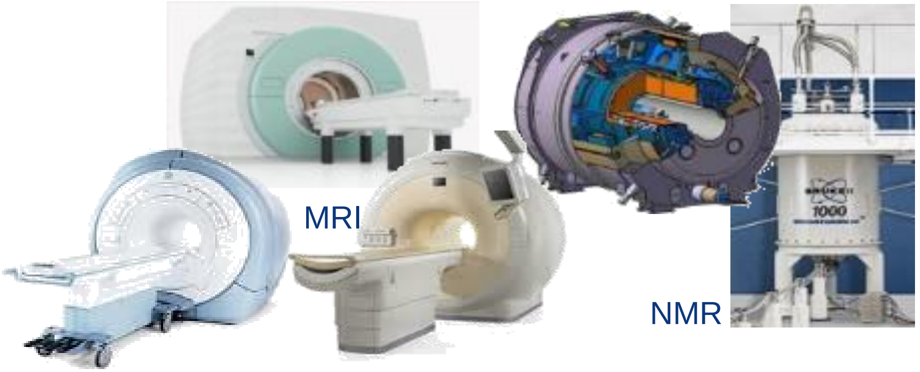
- **Collimators and materials**
- **Vacuum system**

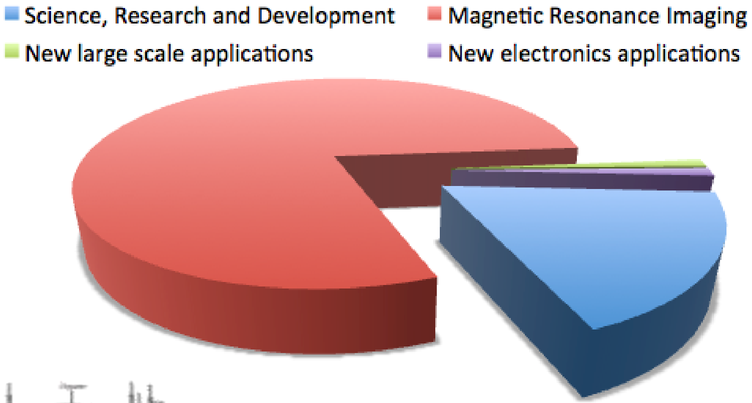
Advanced Concepts

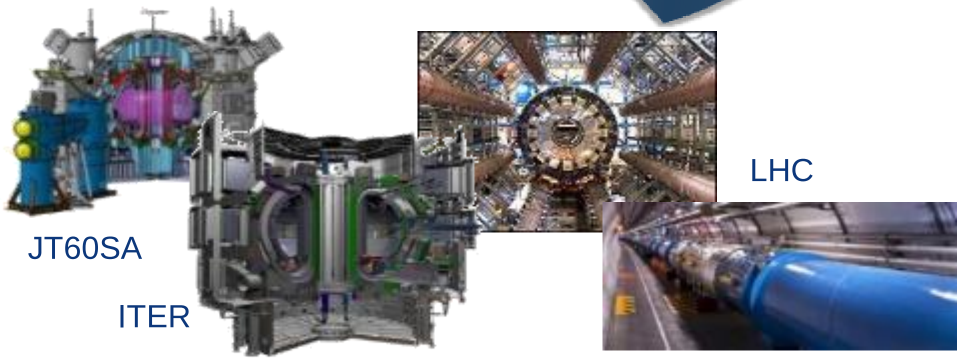
- **Beam-driven Plasma Wakefield Acceleration** (PWFA)

Superconducting magnet market

- At present, the vast majority of the use of superconductors is for magnet applications:
  - MRI: 5.5 BUSD/year[1]
  - NMR, science and research: approximately 1 BUSD/year[1]
- Large scale projects (HEP, Fusion) represent only a fraction of the total market:
  - Evaluated cost of LHC magnet system (material): 2 BUSD[2]
  - Quoted cost of ITER magnet system (material): 1.4 BUSD[3]

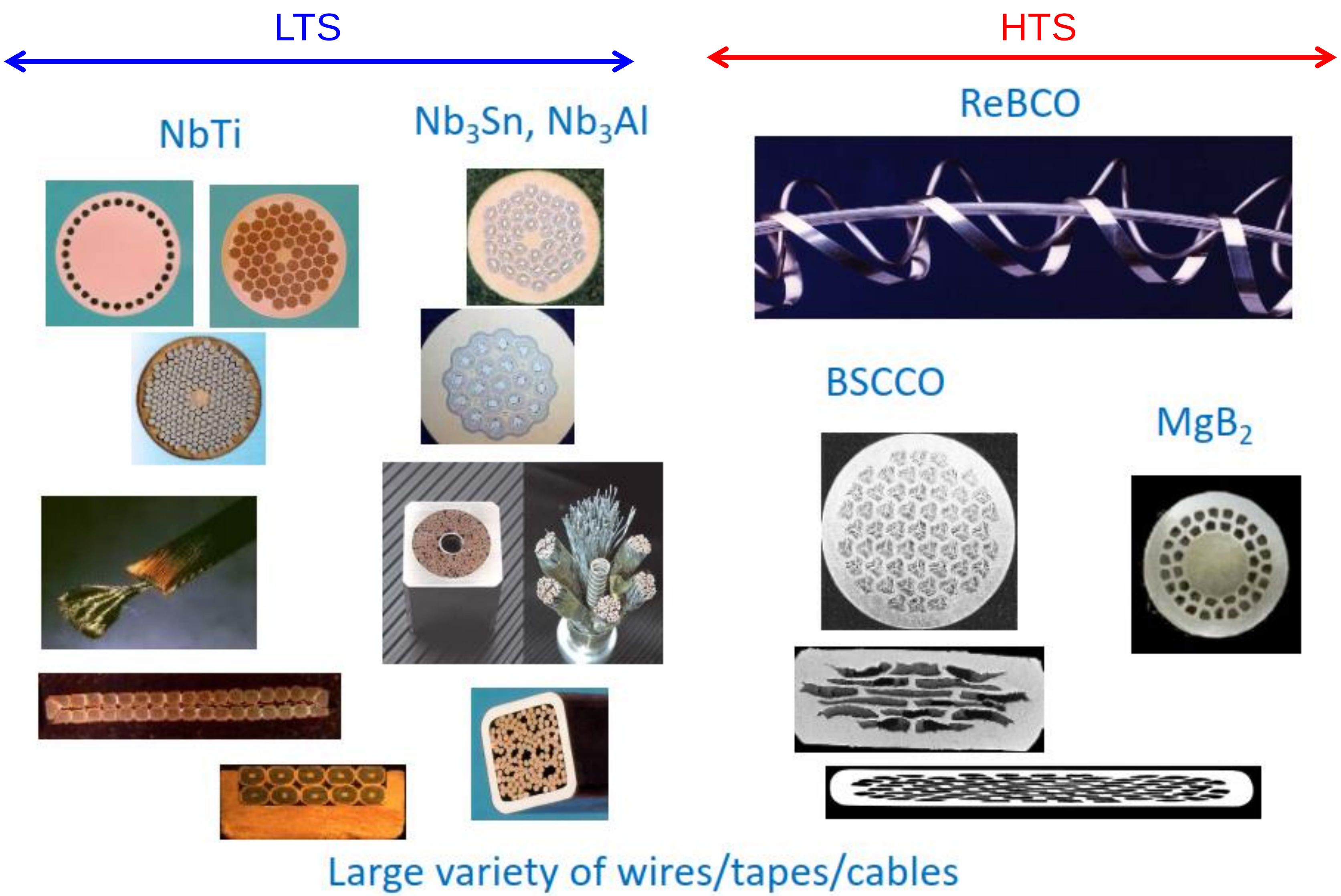






Sources: [1] from market report at Conectus.org, converted from repored 5.3 BEUR in 2013
[2] Report to the CERN Finance Committee, 2008, reported 1.7 BCHF(2008) escalated to 2013
[3] DOE Assessment of the ITER Project Cost Estimate, reported 1.09 BUSD(2002) escalated to 2013

SC materials: variety of wires, tapes, cable – LTS and HTS

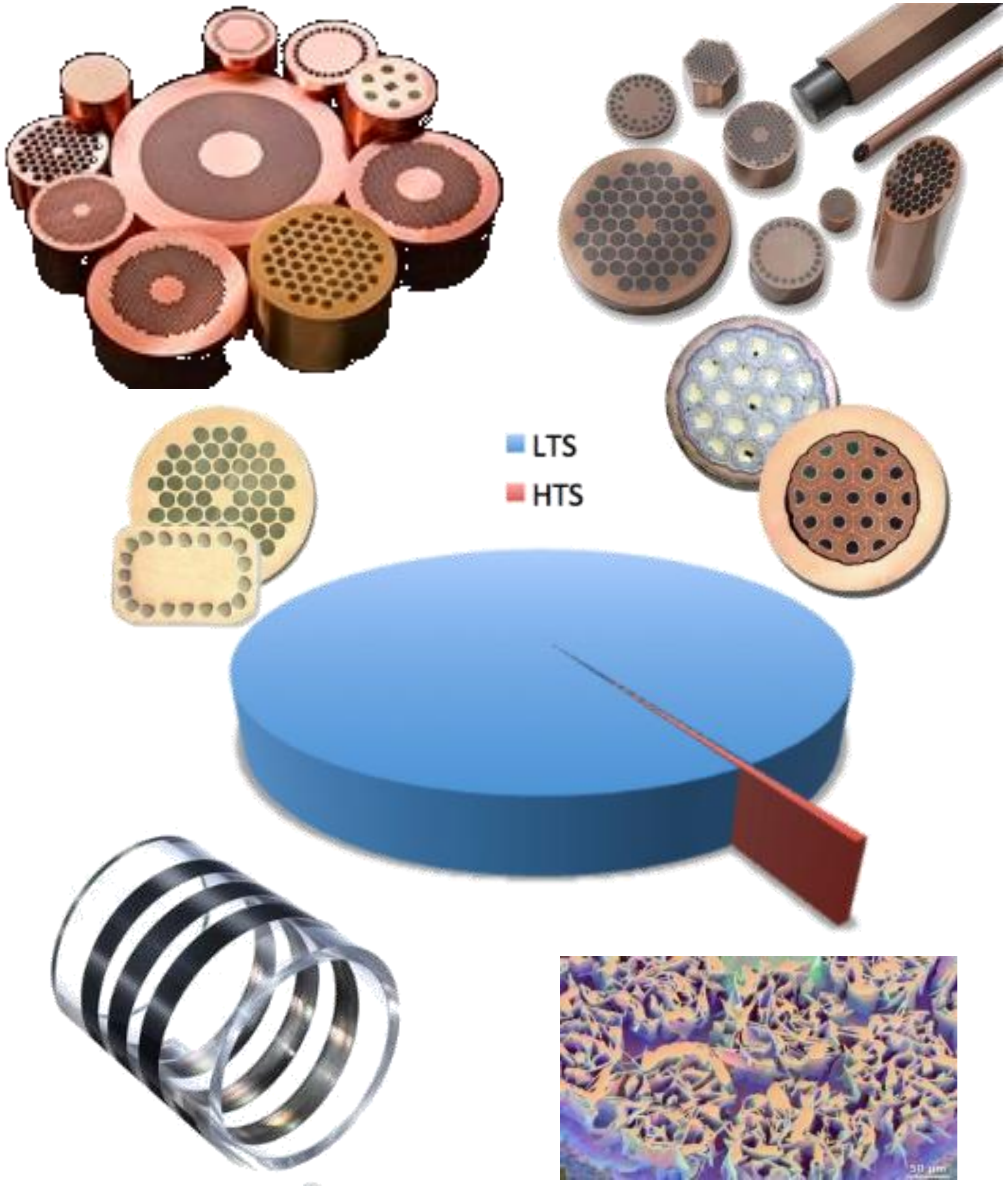


Superconducting materials

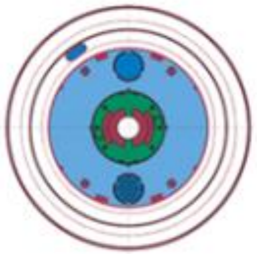
- **Nb-Ti: 1000 t/year**, mostly driven by MRI
- **Nb_3Sn: 10 t/year**, mostly driven by NMR and laboratory systems

- Big-science projects result in large demands, occasional and time-bound, which need to be accommodated
  - LHC required 1300 tons of Nb-Ti (**300 t/year peak production**)
  - ITER requires 300 tons of Nb-Ti and 600 tons of Nb_3Sn (**250 t/year peak production**)

- All of HTS (BSCCO, YBCO, REBCO,…) and MgB_2 (MTS) is below **1 ton/year**, mostly driven by Fusion and Power application R&D

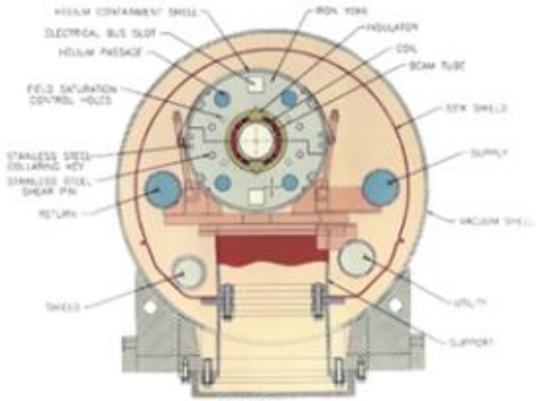


Superconducting accelerators (NbTi) : dipoles

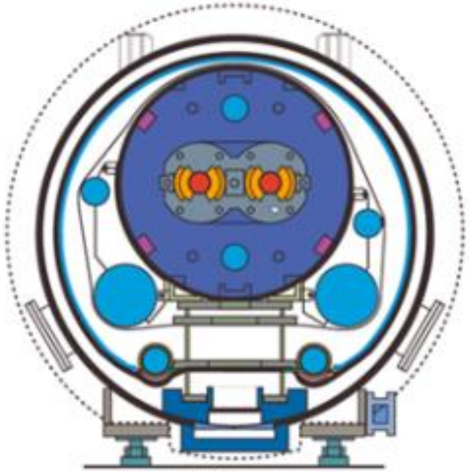


HERA
B = 4.7 T
BORE : 75 mm

TEVATRON
B = 4.5 T
Bore : 76 mm



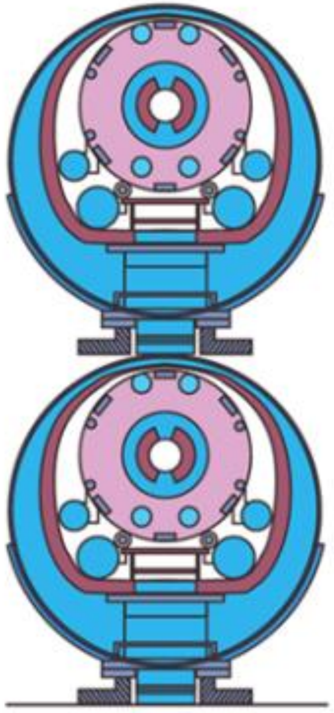
RHIC
B = 3.5 T
Bore : 80 mm



LHC
B = 8.3 T
Bore : 56 mm

Design and tested at 9T

In operation



SSC
B = 6.6 T
Bore : 50-50 mm

Nb-Ti magnets:
Mature technology

ISEULT
Whole body MRI magnet with high field
11.7 T

High Field Magnets
HFM ≥ 9 T

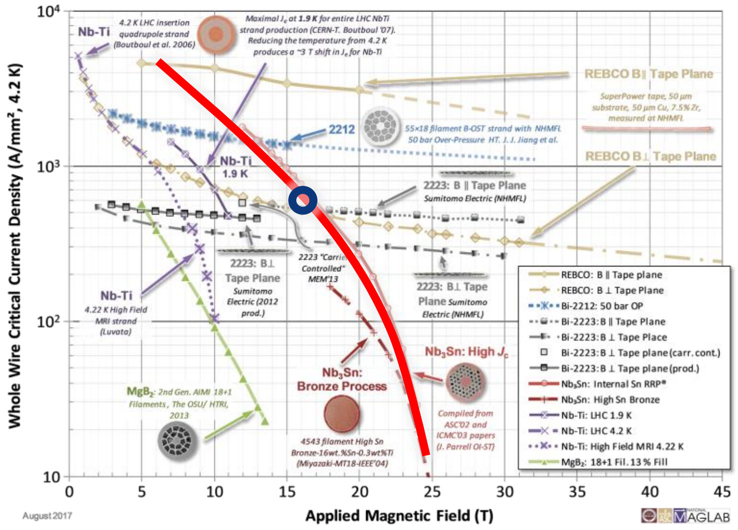
High Field SC Conductors

Nb3Sn

Nb3Sn is reaching the upper limit of performance:

goal Jc 600A at 16 T

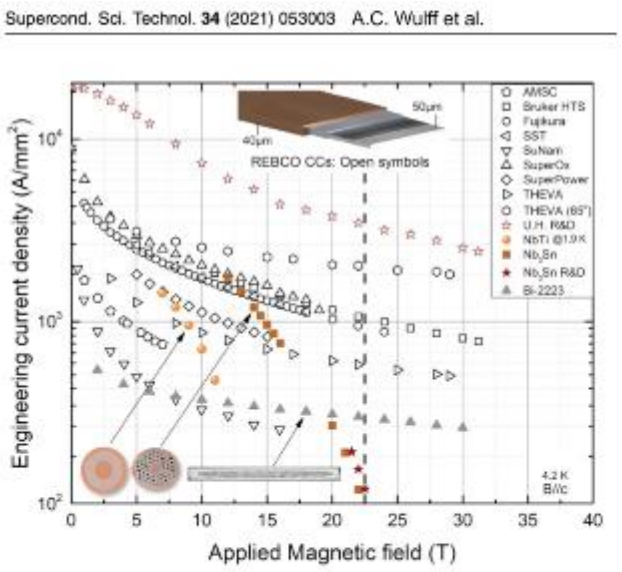
Advances in composition and architecture must be consolidated (laboratories : mechanical stress, magnetization,…), and made practical for large-scale production (industries: homogeneity, length unit, cost),



Jc ≈ 600 A at 16 T

HTS

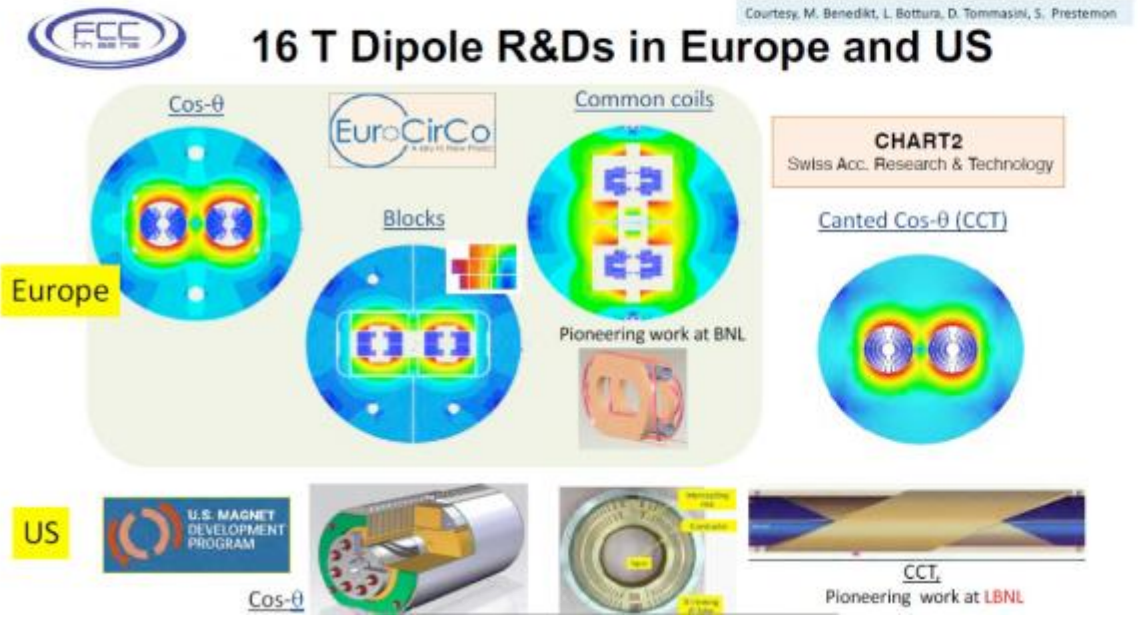
Remarkable electrical performance of HTS tapes, the challenge now is to combine critical current with mechanical properties and protection. High temperature operation (20 to 65 K) is an interesting option also carried for other fields (fusion, power and medical applications).



Industry drive for high field performance is independent of HEP (HTS cost will decrease due to substantial investments from power, medical and fusion applications).

High Field SC magnets

Length effects and electro-thermo-mechanics of Nb3Sn magnets are a critical problem (development of the 11 T dipole of HL-LHC). R&D is based on a combination of models and full-length prototypes before industrial mass production.

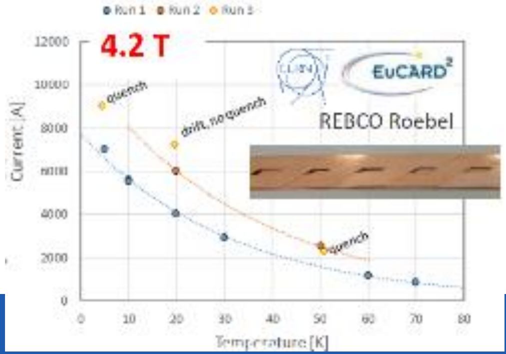


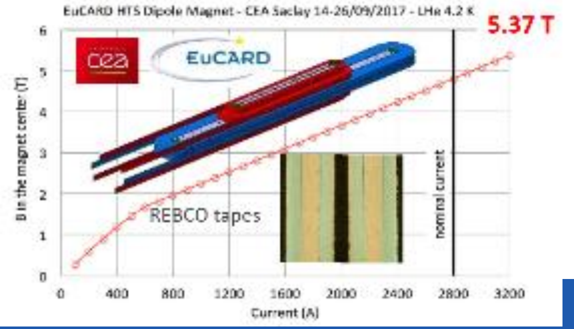
Global initiative to identify suitable design options for the various field levels targeted:

- 2-layers cos-theta suitable up to 12 T
- 4-layers cos-theta or blocks for the 14-16 T range
- Common coils to resolve the issue of the magnet heads
- CCT or other stress managed concept beyond 15-16 T

A decision on an optimal, reliable at the field of operation and industrial cost-effective production should be one of the main results of the R&D works in the next 5-7 years.

Investigation of the best HTS cable configuration (REBCO ?) for magnet applications, focused on magnet construction (head winding) and operation

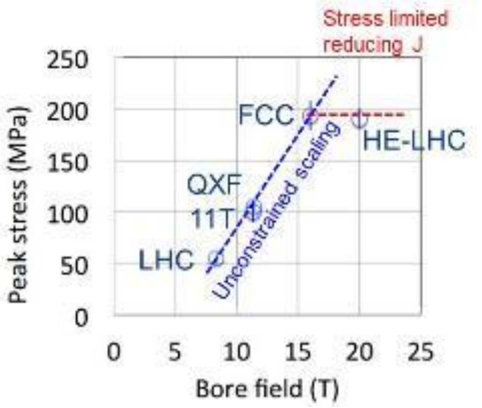


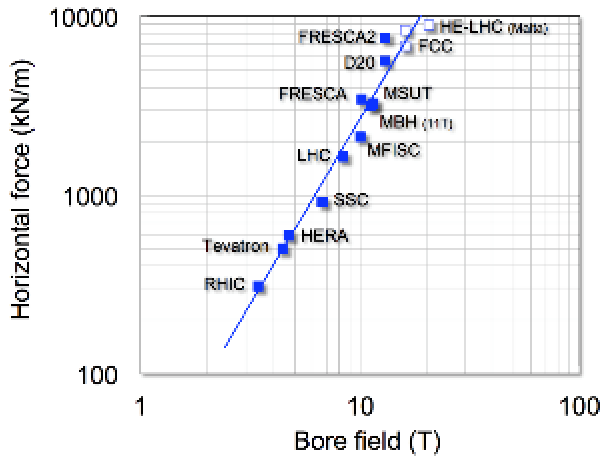


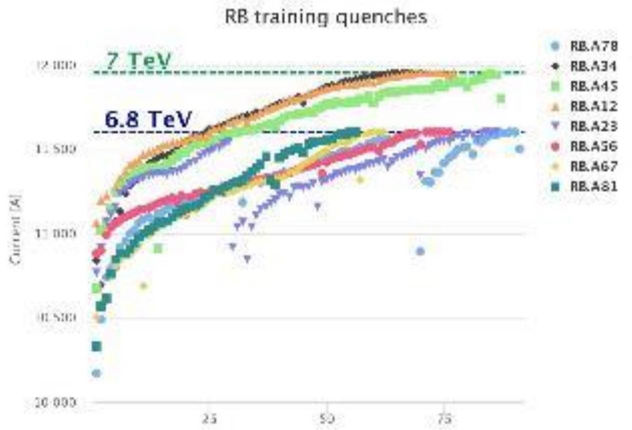
High Field Magnet challenges

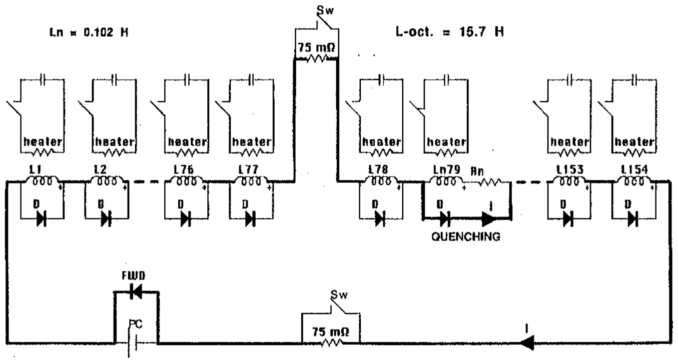
- To increase the critical current Jc
- To sustain larger forces
- To protect those magnets (large numbers in series)
- To train those magnets faster
- To keep the memory after installation and thermal cycles

- Global optimization: magnet and powering
  current leads, superconducting links, energy extraction, power converters

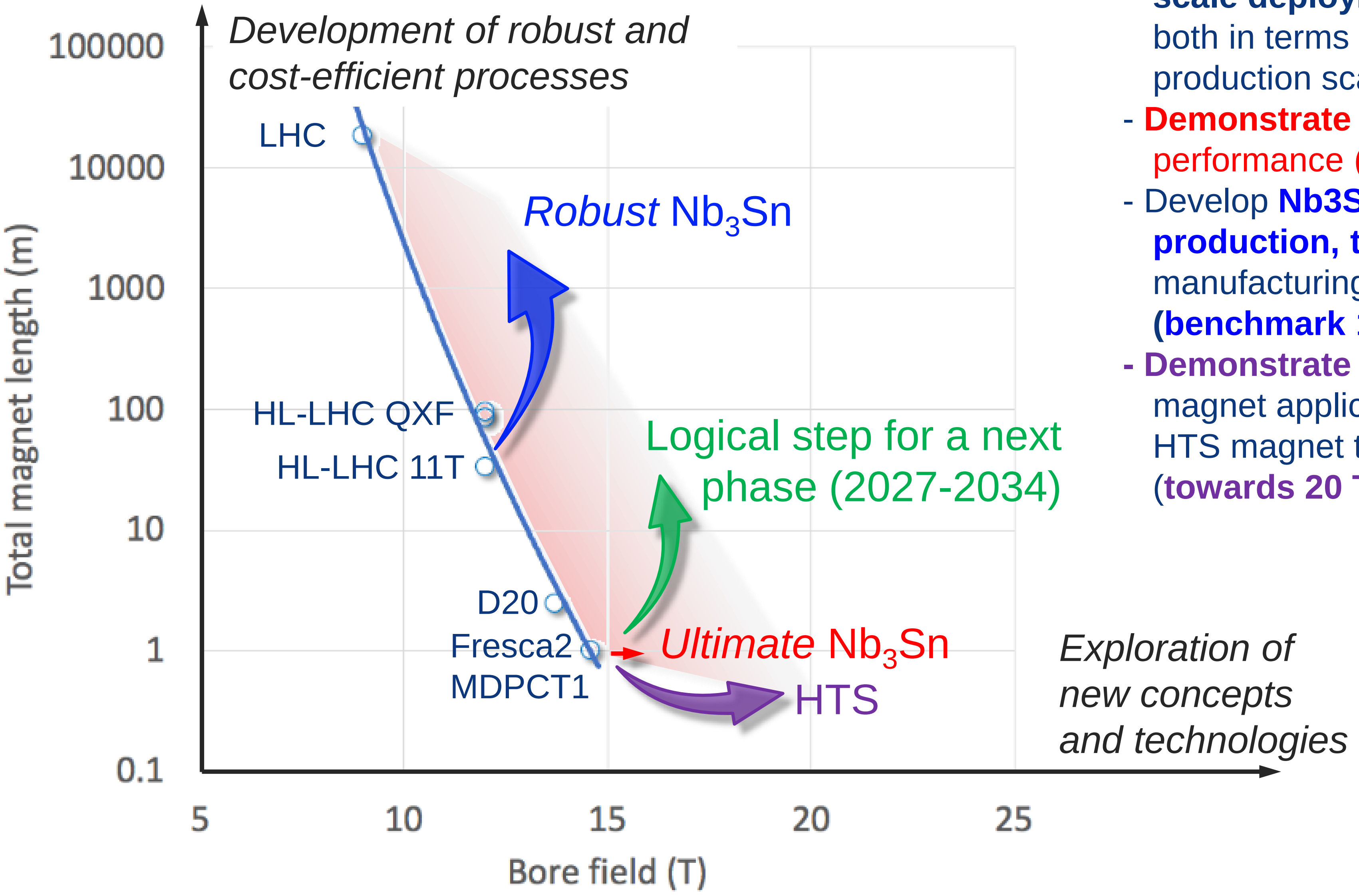








HFM strategy



- **Demonstrate Nb3Sn magnet technology for large scale deployment**, pushing it to its practical limits, both in terms of maximum performance as well as production scale
- **Demonstrate Nb3Sn** full potential in terms of ultimate performance (towards 16 T)
- Develop **Nb3Sn** magnet technology **for collider-scale production, through robust design**, industrial manufacturing processes and cost reduction (**benchmark 12 T**)
- **Demonstrate suitability of HTS** for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb3Sn (**towards 20 T**)

Other key parameters:
- Cost of Magnets & R&D
- Timeline of a realistic development
- Potential for wider societal applications
- Training and education

Revamping of (existing) beam line magnets

1. Reuse the same iron yoke
   Substitute only the copper coil with MgB_2 or HTS conductors

2. Develop a new magnet
   Possibility to exploit more coil dominated configurations

Energy SAving Beam LIne Magnets
ESABLIM project

Reduce from 10 to 50 times the power loss in resistive magnets working at 20-35 K with solid conduction cooling

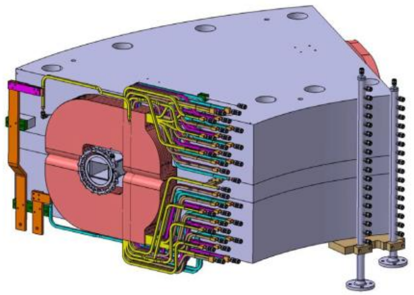
Cryogenics

Reduce the power consumption working at 20 K (MgB_2 or HTS) or 30-35 K (only HTS conductors) using only cryocoolers and conduction cooled technology

Courtesy Mariotto Samuele and Lucio Rossi

PAUL SCHERRER INSTITUT

Dipolar «Window-Frame» Bending Magnets for the 590 MeV high intensity proton beam line



MAGNET PARAMETERS

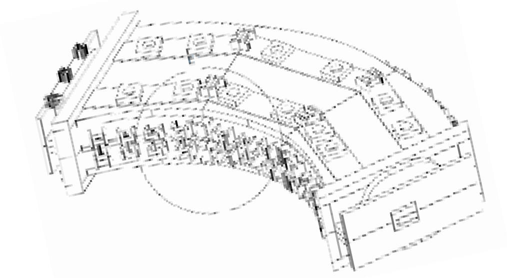
	AHC	AHO
Air Gap	100 mm	100 mm
Max. Current	970 A	1000 A
Max. Voltage	63.5 V	95 V
Max. Electrical Power	61.6 kW	95 kW
R @ 20°C	73 mΩ	83 mΩ
Cond. Dimensions	12×11 mm	18.5×18.5 mm
Cooling Channel Diam.	7 mm	11.5 mm
Water Flow	35 l/min	60 l/min
Pressure drop	6 bar	8 bar
T Rise	23°C	23°C
Turns	76	144

Estimated New Power consumption: 12 kW each (2 x 6kW cryocooler for each magnet)
Further advantage: smalller coils, radiation shielded by iron yoke, reduced maintenance

Courtesy Mike Seidel, PSI

CNAO
Centro Nazionale di Adroterapia Oncologica

Dipolar «Window-Frame» Bending Magnets



MAGNET PARAMETERS

Nominal Current	2280 A
Min Current	380 A
Nominal Field	1.74 T
Magnetic Lenght	5740 mm
Entrance Angle	30°C
Exit Angle	21°C
Field Homogenity	2 units
Maximum Power	700 kW

Estimated New Power consumption: 70-120 kW (saving factor: 5-10)
Further advantage: no bulky pumping and hot water cooling tower

Courtesy Marco Pullia, CNAO)

CERN

NA62-CERN-PH SPS north area

MNP33-2016:
7560 MWh

SM2-2016:
6953 MWh

Courtesy Philip Schwarz, CERN

Outline

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- **Superconducting RF**
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- Vacuum system

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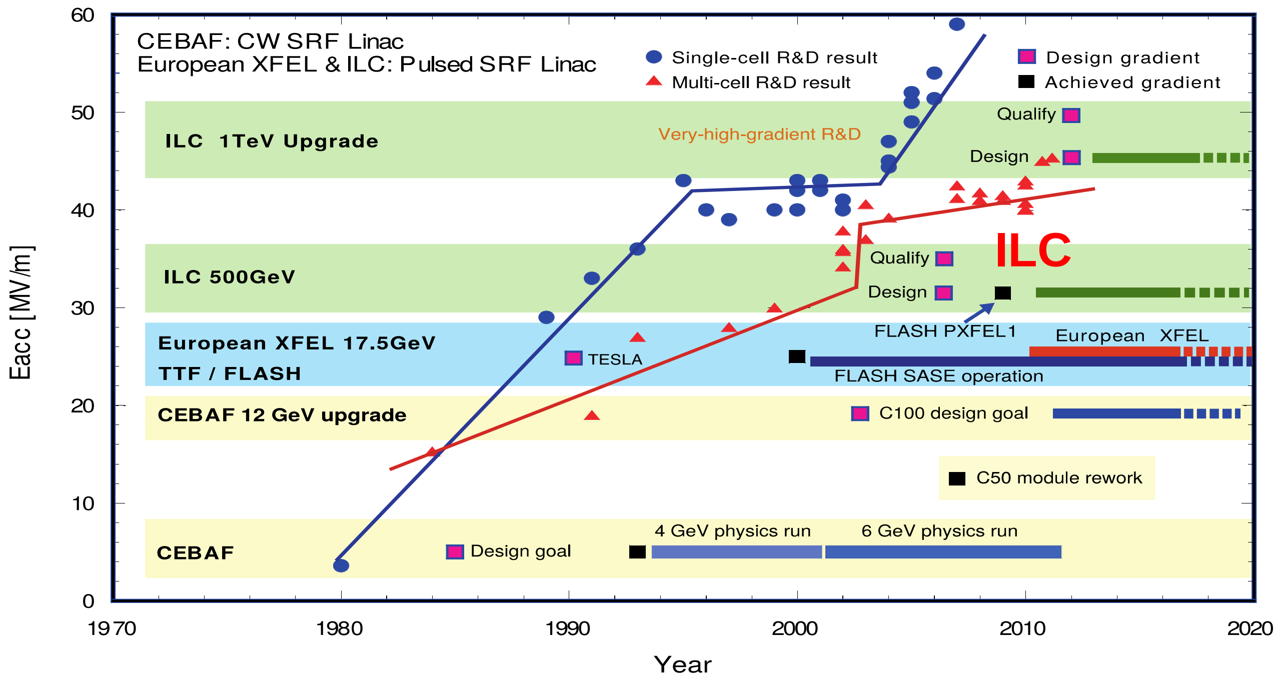
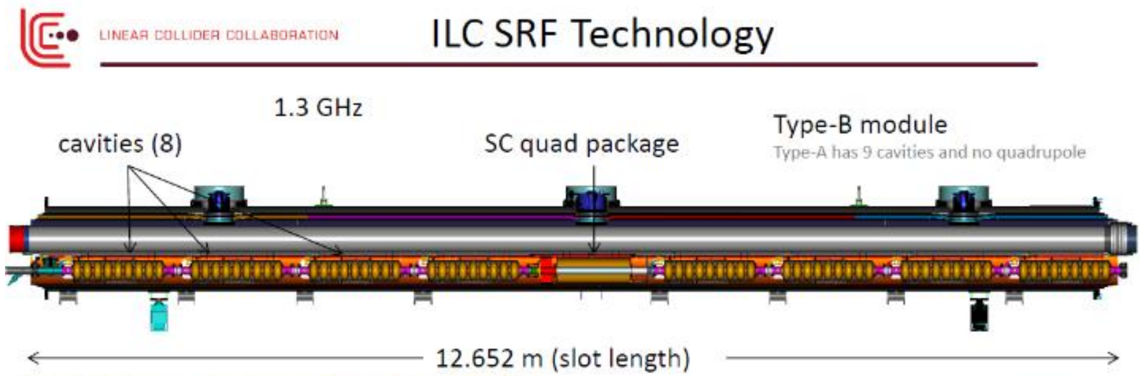
SRF: The Quest for High Gradient



ILC SRF Technology



Advantages: superconducting (cavity absorbs little power), long pulse train, large aperture, low impedance, high beam currents, conservative linac design

Disadvantages: limited gradient, demanding (though widespread) technology, not cheap

Cavities: 35 MV/m ;$Q_0 \geq 10^{10}$
Solid niobium ; standing wave; 9 cells operated at 2K (LHe)

European XFEL, SRF Linac Completed

Courtesy, H. Weise

Progress:

2013: Construction started

...

2016: E- XFEL Linac completion

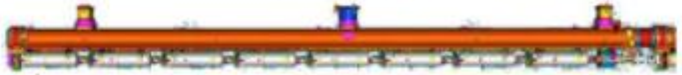
2017: E-XFEL beam start

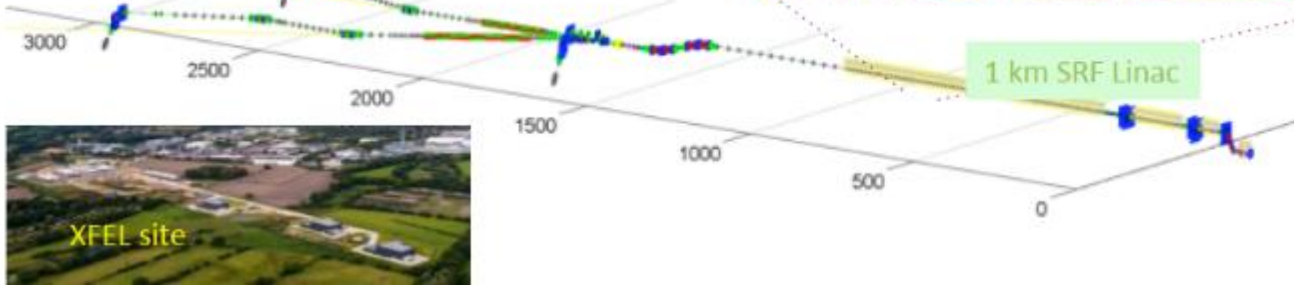
Note : ~ 1/10 scale to ILC-ML

1.3 GHz / 23.6 MV/m

800+4 SRF acc. Cavities

100+3 Cryo-Modules (CM)





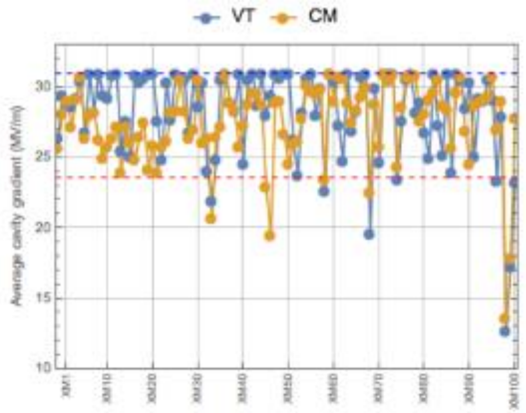
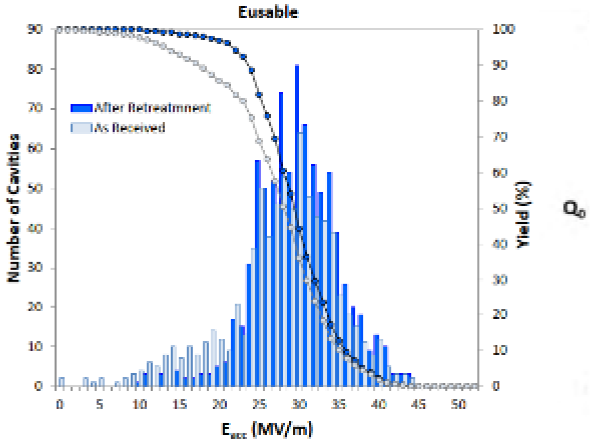


Figure 11: Average operational gradient for all EXFEL cryomodules (CM, orange data points). The blue data points are the average expected performance from the vertical tests (VT, blue data points, assumed capped at 31 MV/m). The red and blue dashed lines represent the nominal EXFEL gradient (23.6 MV/m) and the administrative limit in the cryomodule test (31 MV/m) respectively.



After Retreatment:

E-usable: 29.8 ± 5.1 [MV/m]

(RI): E usable 31.2 ± 5.2 [MV/m]), w/ 2nd EP

(EZ): E usable 28.6 ± 4.8 [MV/m]) , w/ BCP (instead of 2nd EP)

Recent Trends

- Nitrogen doping of Nb cavities at $800\ ^{\circ}\mathrm{C}$ (e.g. Grasselino, FNAL)
- Effective magnetic flux expulsion by fast/high thermal gradient
- Cooldown to achieve record low residual resistances
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency, e.g. Posen, Cornell)
- Use of large grain Nb (e.g. JLAB)

} Bulk Nb

- Coating of Cu cavities with Nb by HiPIMS (High Power Impulse Magnetron Sputtering, e.g. Calatroni, CERN)

} Thin film coating on copper

- Cool Copper Cavities (C3) (Liquid nitrogen)

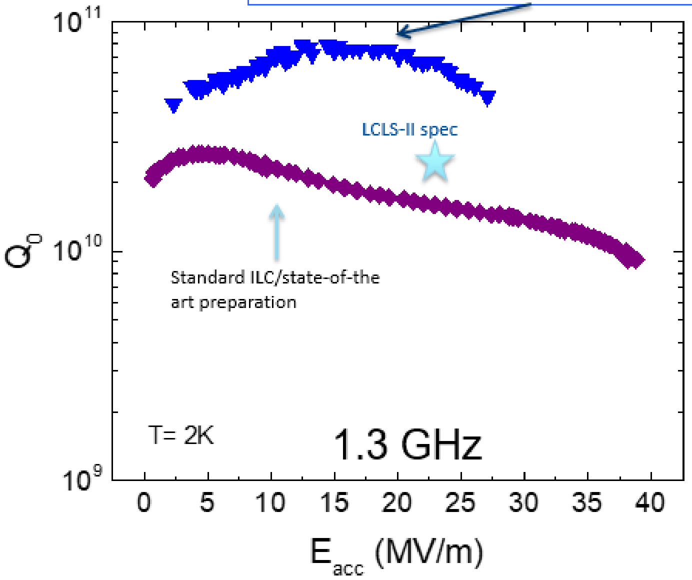
- High-efficiency klystron
- Solid state amplifiers

- Design optimization, fabrication and operation of high power couplers of CW operation (e.g. Montesinos, CERN)

Nitrogen doping: a breakthrough in Q (BCS resistance)

Grassellino, Romanenko, Rowe

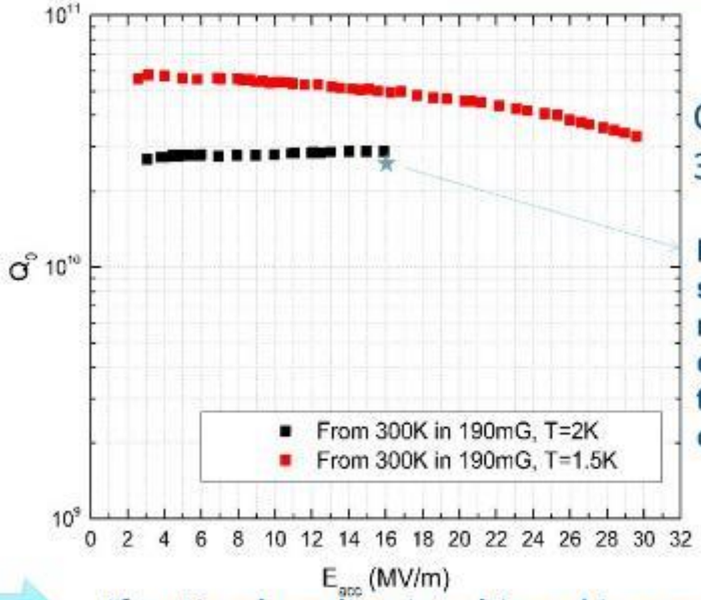
Record quality factors after nitrogen doping – up to 4 times higher Q!



- Injection of s…
  partial press…
  800C degass…
  EP-> drastic …
- Demonstrate…
  and 9-cell 1.…

A further breakthrough at FNAL: optimal cooling conditions can preserve high Q despite large ambient fields

Grassellino, Romanenko, Rowe



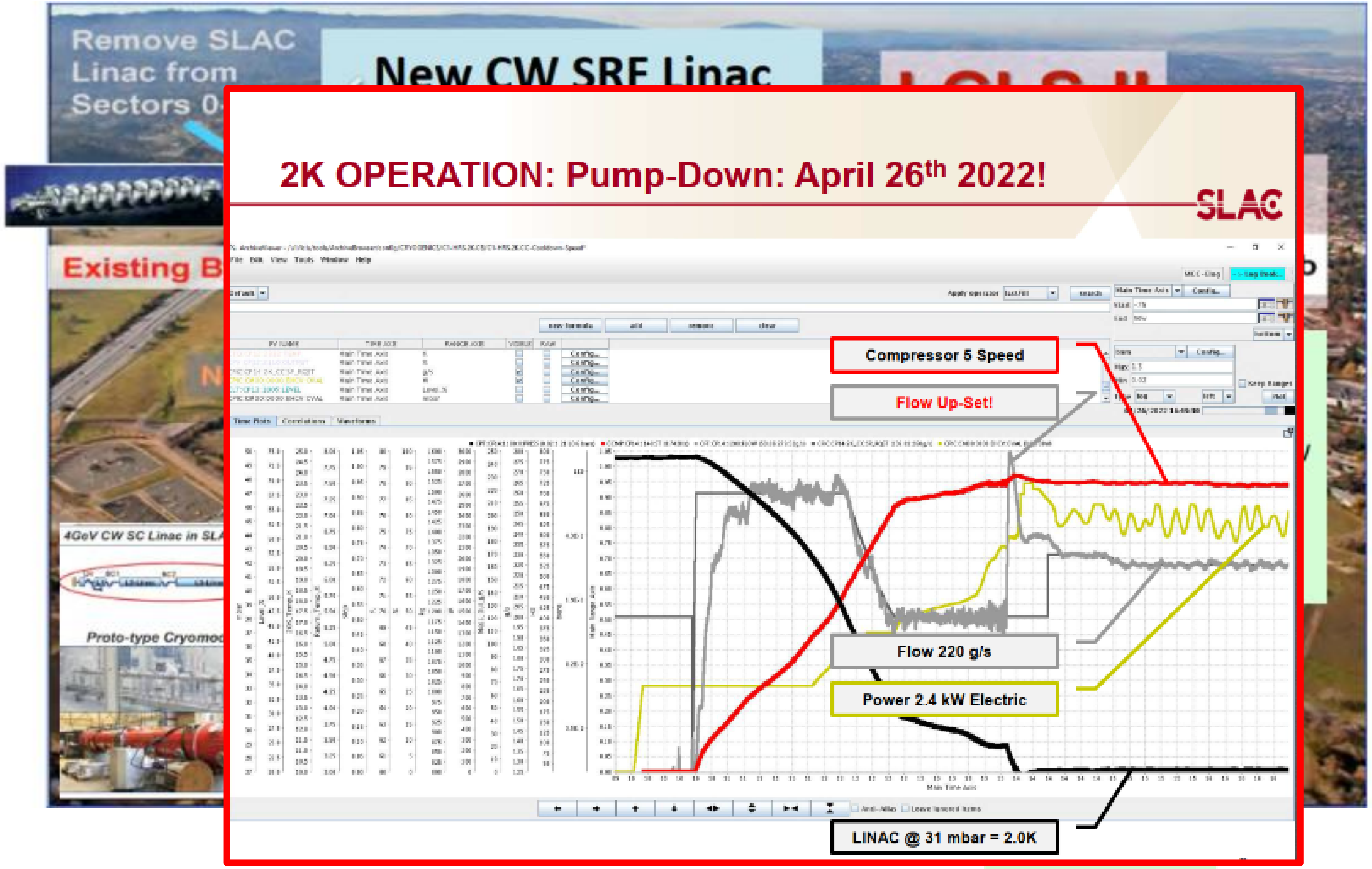
Cavity quenching at 30 MV/m

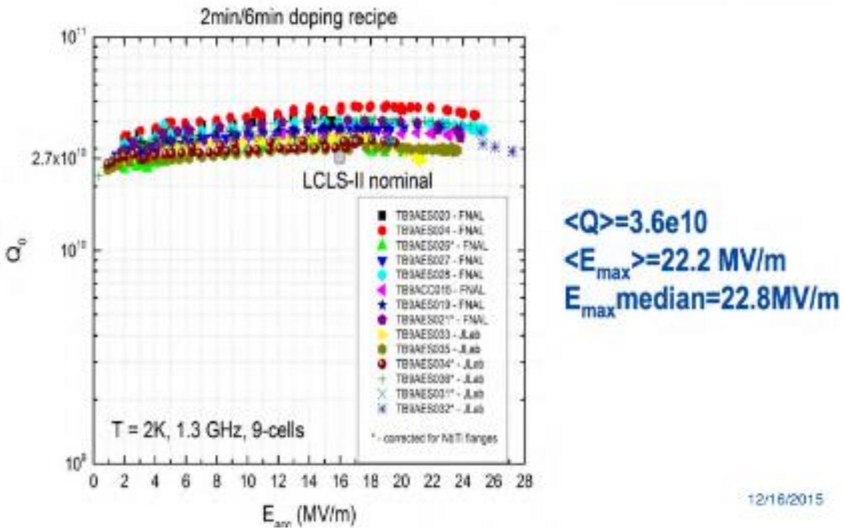
N doped cavity meets LCLS specs in ~200 mGauss magnetic field (when cooled down with large thermogradients across the cavity)

If optimal cooling is achieved in cryomodule, additional magnetic shielding may not be not needed!

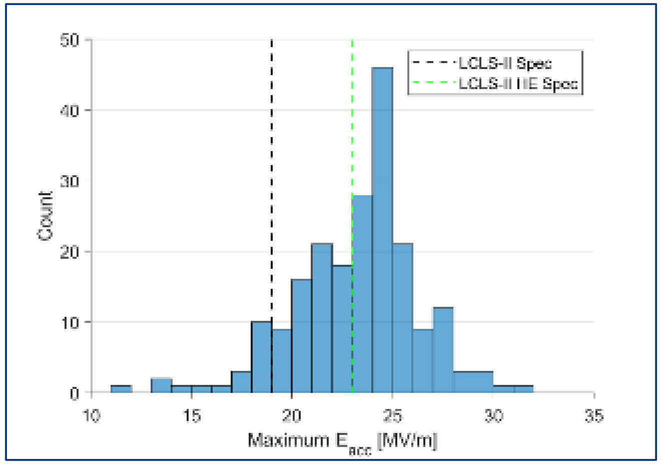
LCLS-II at SLAC

Use 1st km of SLAC Linac for CW SCRF Linac





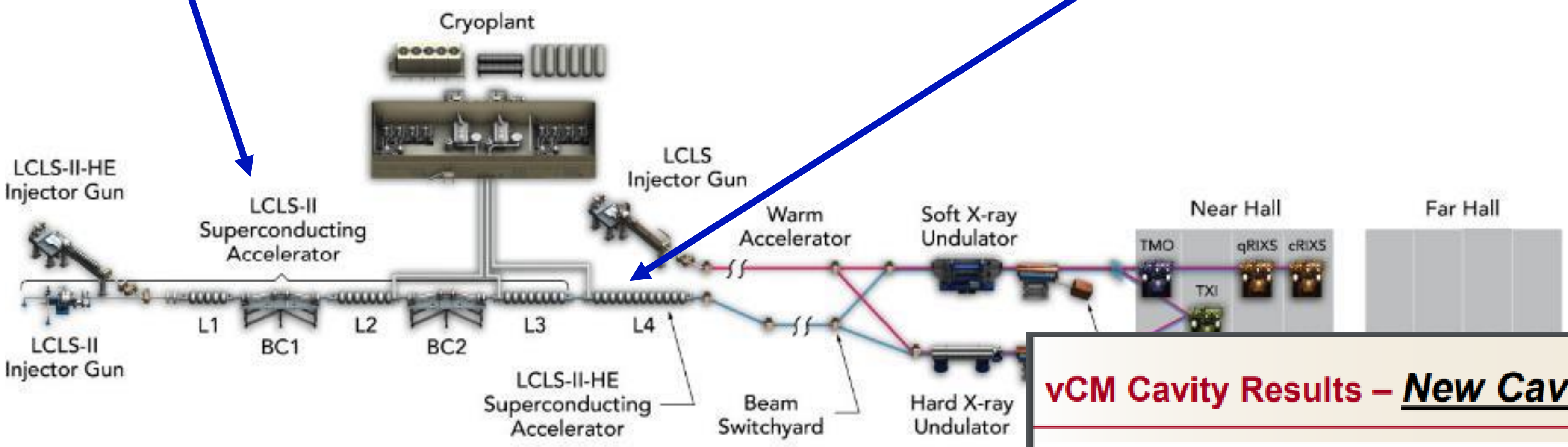
$<Q>=3.6e10$
$<E_{max}>=22.2$ MV/m
E_{max} median=22.8MV/m

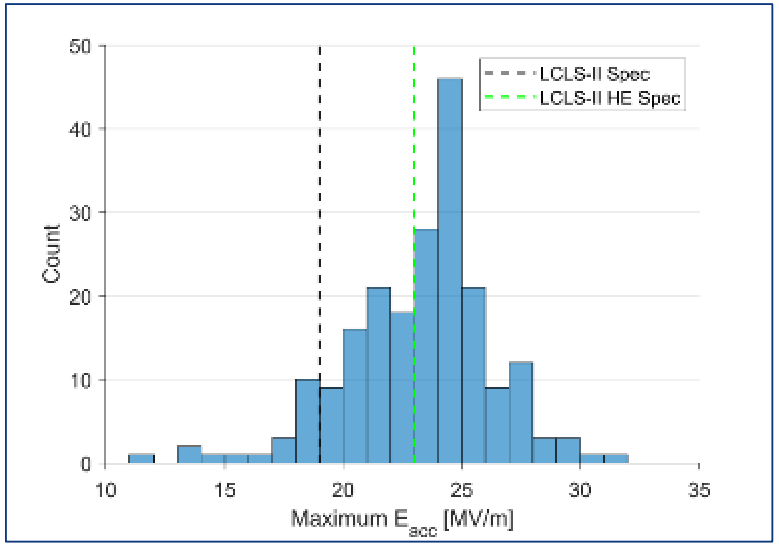


- 98% of cavities *with improved processes* passed LCLS-II specification
- Average quench field of ~23 MV/m

LCLS-II will be the 1st operational machine using N-doping !

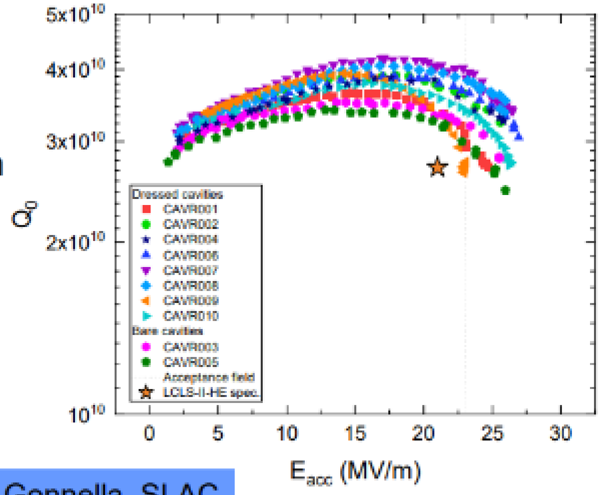
LCLS-II (4 GeV) upgrade = LCLS-II HE (8 GeV)





vCM Cavity Results – *New Cavity recipe for LCLS-II-HE*

- New N-doping protocol (2N0 + improved EP) successfully transferred to industry
- Vertical test completed for 10 vCM cavities fabricated and processed in industry
- Performance exceeded specification with average **Q0=3.6e10 and Eacc=25.6 MV/m**
- 8 fully dressed cavities are ready to be assembled in the vCM

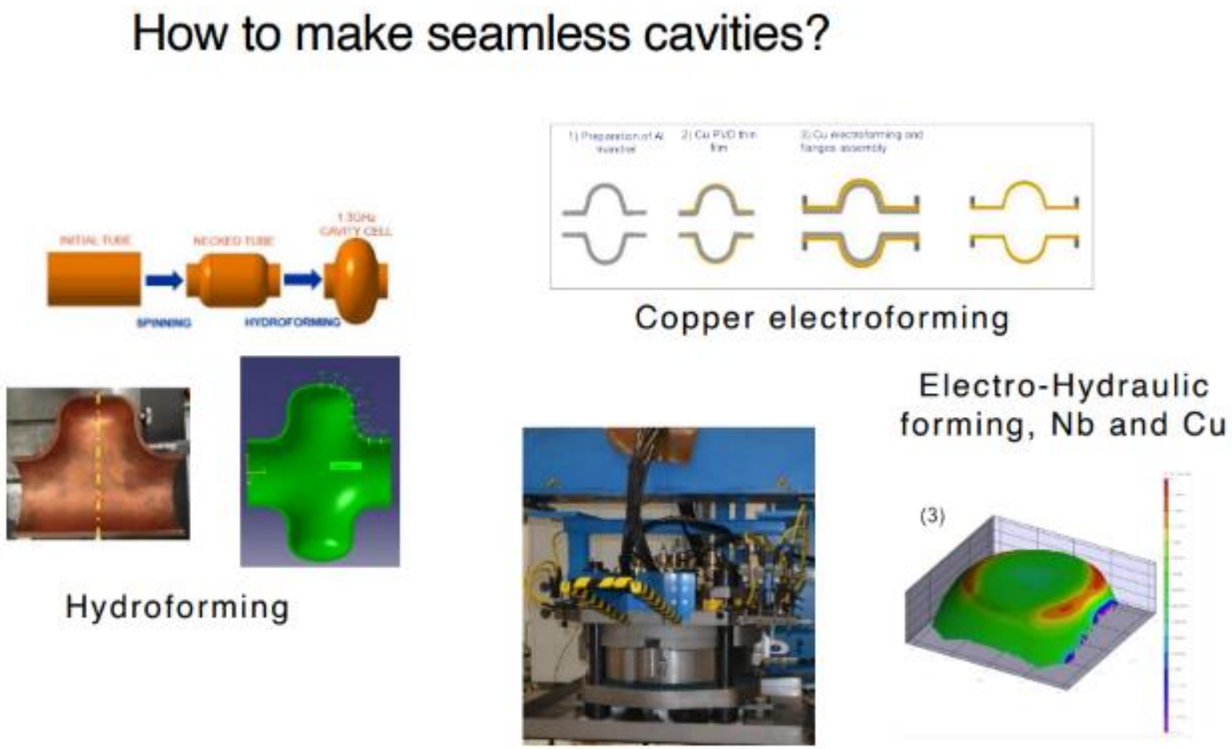


AWLC 2020 M. Ross 20 Oct 2020

Dan Gonnella, SLAC

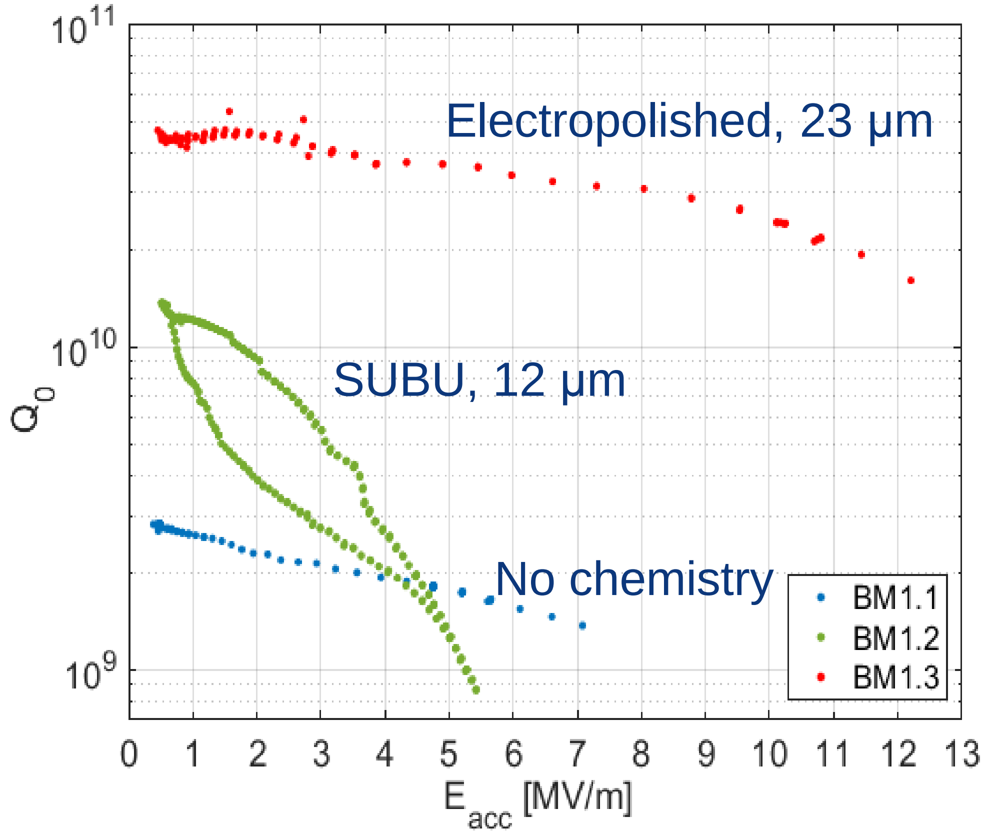
Why not Niobium on Copper ?

- At cryogenic temperatures copper is a much better head conductor than Niobium, which makes more quench resistant.
- It is also mechanically more stable and cheaper to produce than Niobium.
- Combining the thermo-mechanical characteristics of copper with a tunable superconducting layer seems like a winning combination, provided that you can make a near-perfect film.



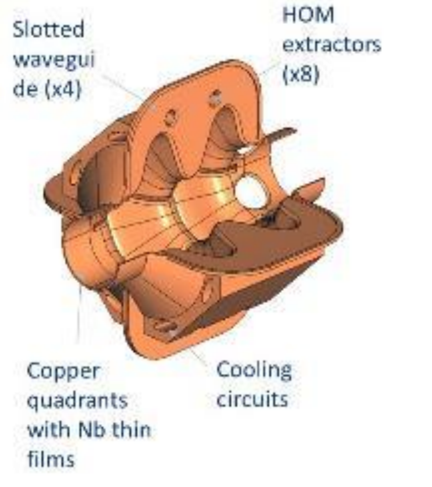
Breakthrough on thin-film SRF technology

- Test of a seamless 1.3 GHz copper cavity with Nb coating at 1.85 K.
- **The test results are comparable with the performance of bulk Niobium cavities: high Q-value and little Q-slope.**
- These results gave the proof that cost-efficient thin film technology has a lot of unrealised potential.
- R&D continues to extend the field reach and to use higher temperature superconductors (Nb3Sn, Vn3Si).
- Key technology for FCC and other high-current accelerators.



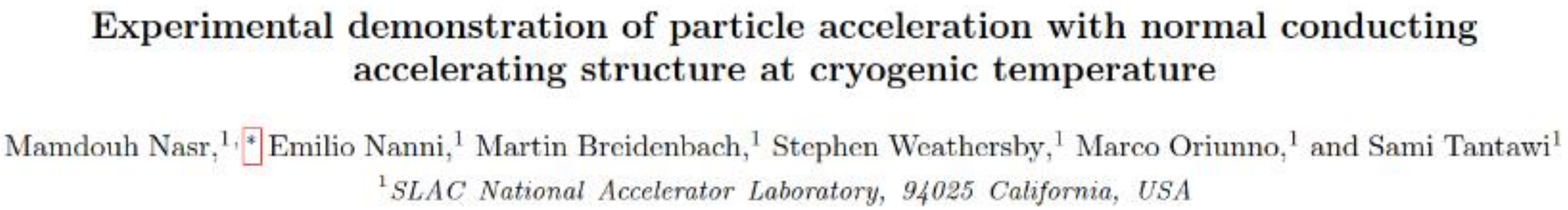
Superconducting slotted Waveguide ELLiptical cavity (SWELL):

A combination of CLIC technology (slotted waveguide HOM damping) and SRF (elliptical cavities) using technology developed for LEP, LHC and HIE-ISOLDE (Nb on Cu coating).
Made of 4 independent quadrants, machined out of bulk pieces and clamped together.
Easy coating of quadrants.
Cryogenic cooling channels are drilled into the copper instead of building dedicated helium tanks.
No assembly joints in high electromagnetic field regions: potential for high performance.



Courtesy Frank Gerigk

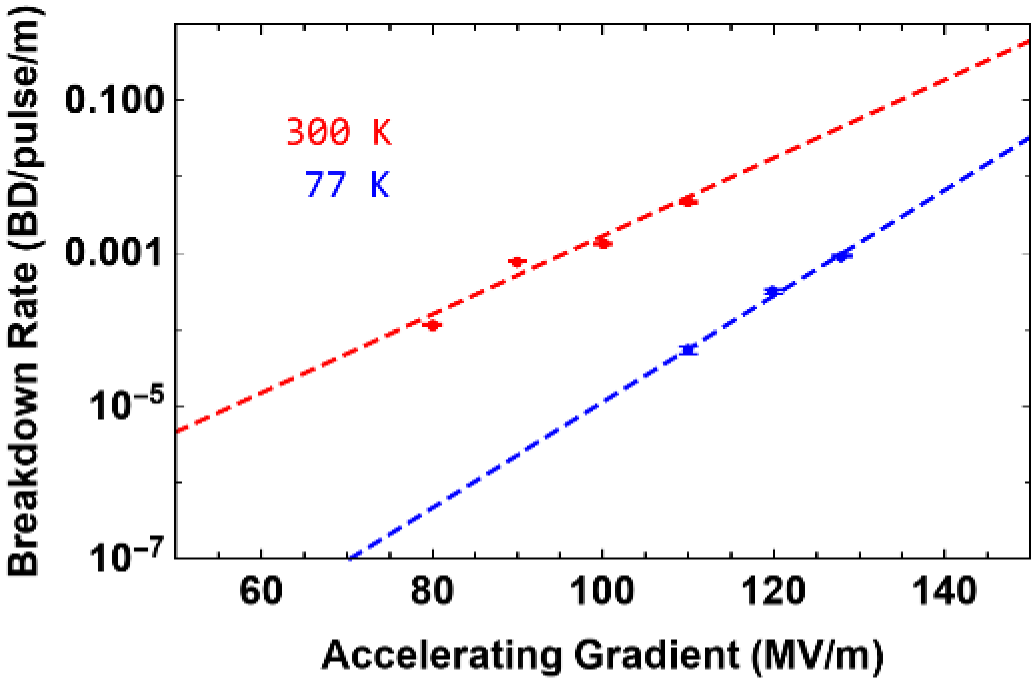
Cool Copper Cavities (C^3) (Liquid nitrogen)

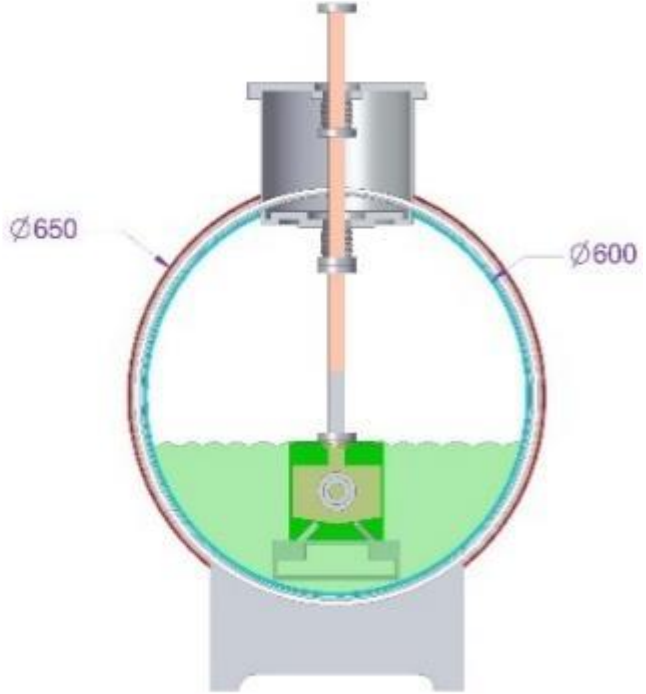

Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature

Mamdouh Nasr,[1,*] Emilio Nanni,[1] Martin Breidenbach,[1] Stephen Weathersby,[1] Marco Oriunno,[1] and Sami Tantawi[1]

[1]*SLAC National Accelerator Laboratory, 94025 California, USA*

arXiv:2011.00391v1 [physics.acc-ph] 1 Nov 2020

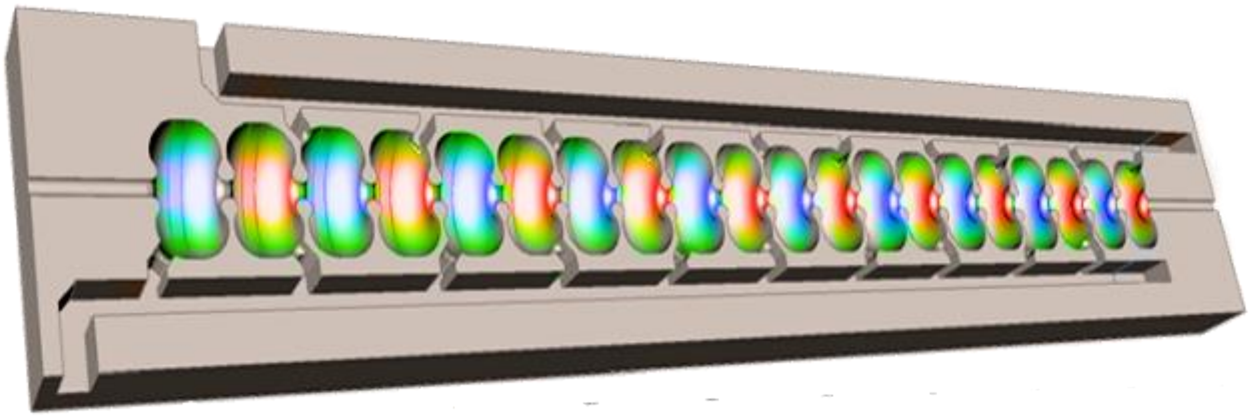




Courtesy Emilio Nanni

Cool Copper Collider – C^3

250 GeV e+/e- initially
and upgrade to 550 GeV with
~8 km in length



C^3 : A "Cool" Route to the Higgs Boson and Beyond

MEI BAI, TIM BARKLOW, RAINER BARTOLDUS, MARTIN BREIDENBACH*, PHILIPPE GRENIER, ZHIRONG HUANG, MICHAEL KAGAN, ZENGHAI LI, THOMAS W. MARKIEWICZ, EMILIO A. NANNI*, MAMDOUH NASR, CHO-KUEN NG, MARCO ORIUNNO, MICHAEL E. PESKIN*, THOMAS G. RIZZO, ARIEL G. SCHWARTZMAN, DONG SU, SAMI TANTAWI, CATERINA VERNIERI*, GLEN WHITE, CHARLES C. YOUNG

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VLADIMIR SHILTSEV

Fermi National Accelerator Laboratory, Batavia IL 60510-5011

ABSTRACT

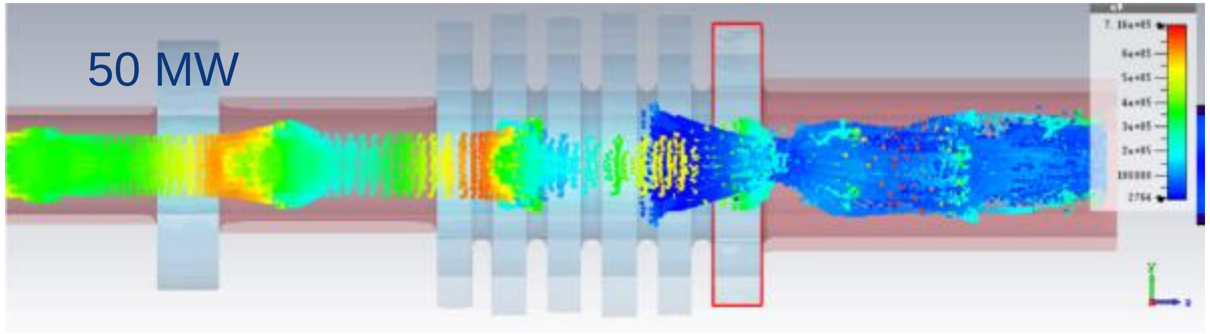
We present a proposal for a cold copper distributed coupling accelerator that can provide a rapid route to precision Higgs physics with a compact 8 km footprint. This proposal is based on recent advances that increase the efficiency and operating gradient of a normal conducting accelerator. This technology also provides an e^+e^- collider path to physics at multi-TeV energies. In this article, we describe our vision for this technology and the near-term R&D program needed to pursue it.

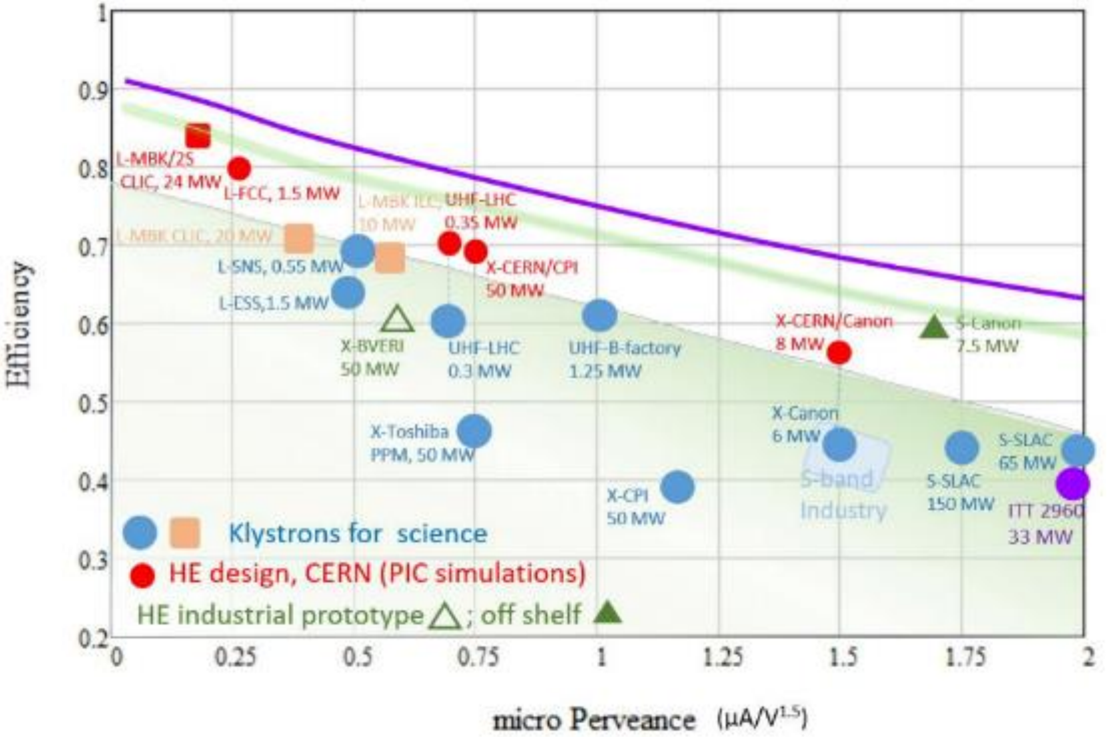
ArXiv 2110.15800 (2021)

High-efficiency klystron project

- **After 8 decades of klystron technology, new R&D to push significantly their efficiency**
- **Higher power efficiency will be mandatory for all future HEP projects.**

- 2 industry collaborations ongoing (1 pending):
  - Thales: A plug-and-play replacement of the LHC klystrons, which will increase the power output from 300 to 350 kW, while maintaining the same input power (expected 2023).
  - X-band klystron with Canon (test in July 2022): 8 MW
  - X-band with CPI (under discussion): 50 MW, design delivered.



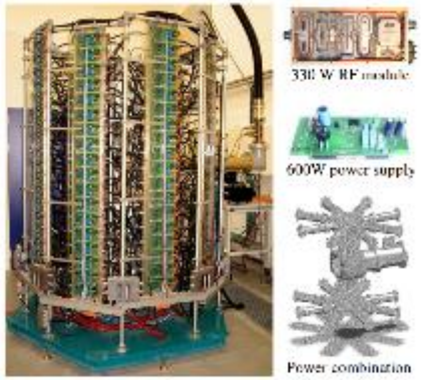


Courtesy I. Syratchev

Pushing the power of solid state power amplifier (SSPA)

SSPAs start to replace tube-based technology and have the potential to increase the MTBF of RF systems.

SSPA systems with several hundred kW RF power are now available for various accelerator fields.

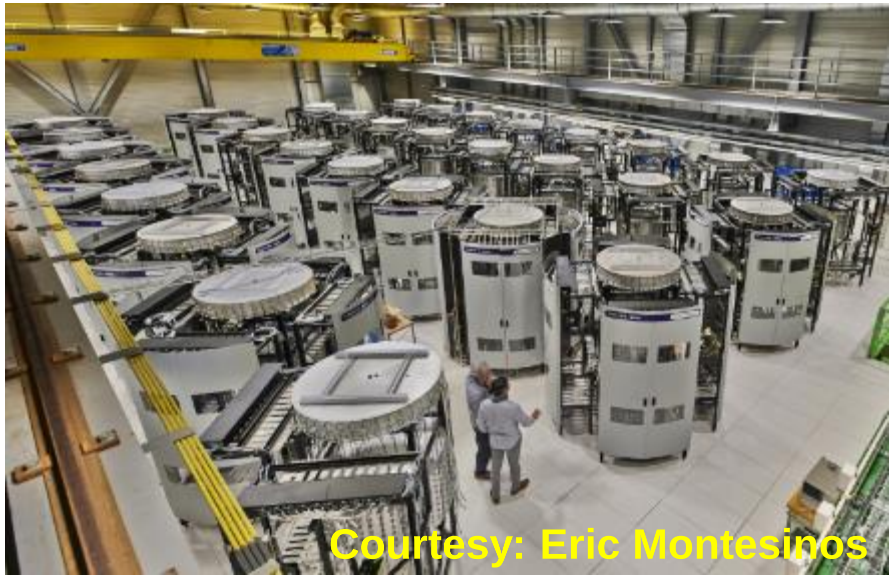


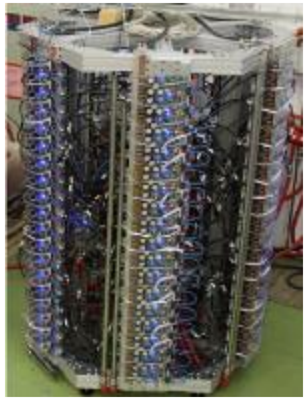
35 kW SSPA (352 MHz)
of the SOLEIL Booster
(commissioned in July 2005)

SOLEIL Storage Ring : 4x45 kW, SSPA
(operation from 2006)

LCLS-II: 3.8 kW 1.3 GHz
(284 units)

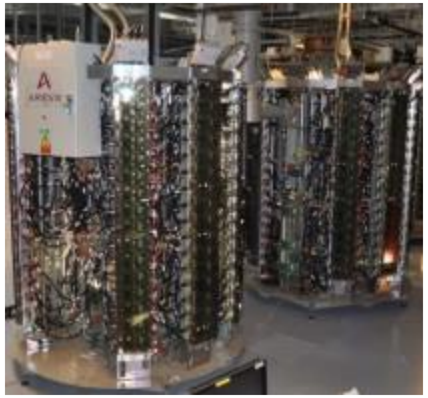
CERN SPS (Thales): 32 x 140 kW = 4 MW
successfully commissioned (in 2021)
3.2 MW peak power and 1.5 MW CW at 200 MHz.





SLS 60 kW 500 MHz

LNLS 2x 50 kW 476 MHz



ESRF 2x75 kW 352 MHz

Outline

Advanced Technologies:

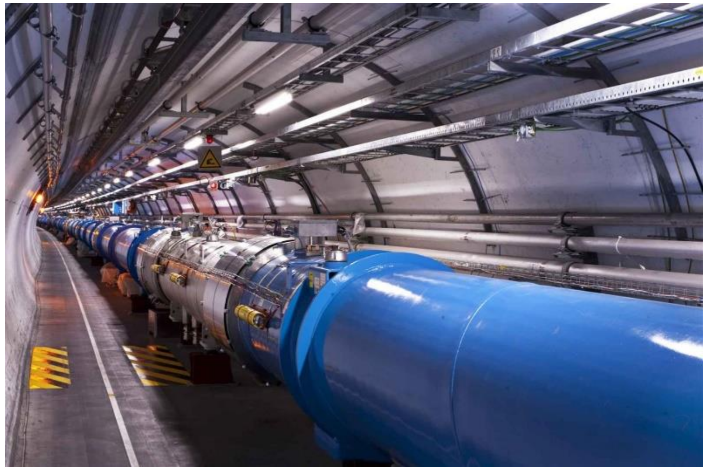
- Superconducting magnets
- Superconducting RF
- **Cryogenics** (see Steffen Grohmann's presentation)

- Materials and beam intercepting devices (BID)
- Vacuum system

Advanced Concepts

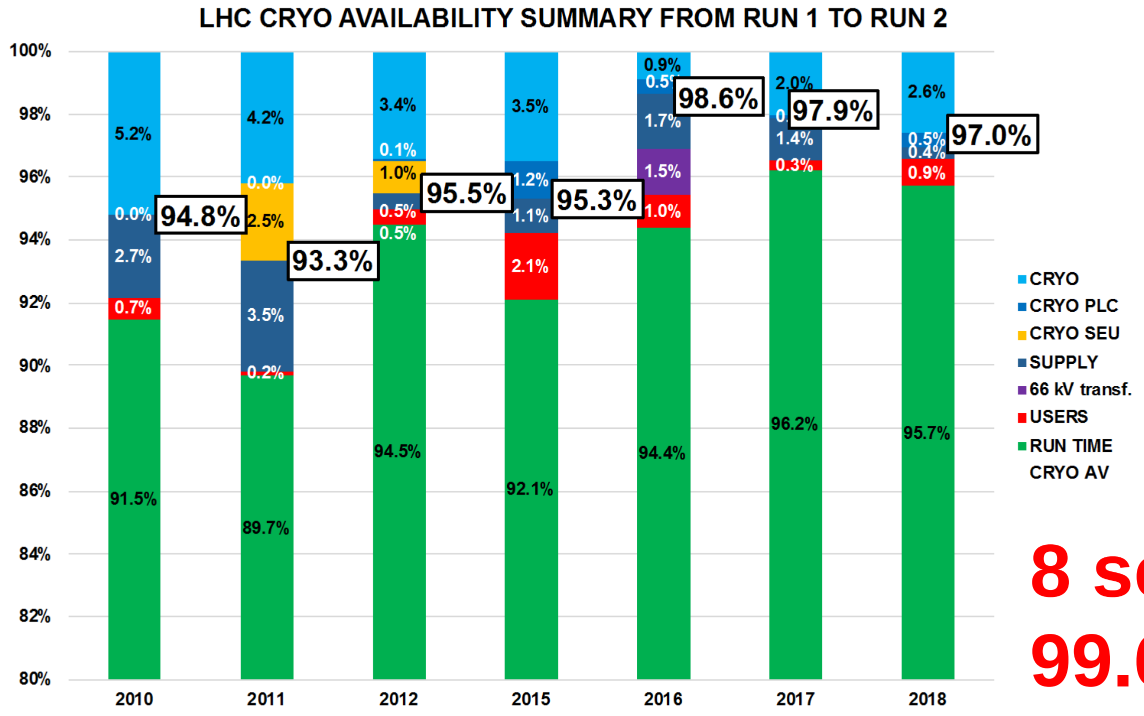
- Beam-driven Plasma Wakefield Acceleration (PWFA)

Cryogenics : large power



LHC 36’000 tons of cold mass at 1.9 K

LHe inventory : 130 tons

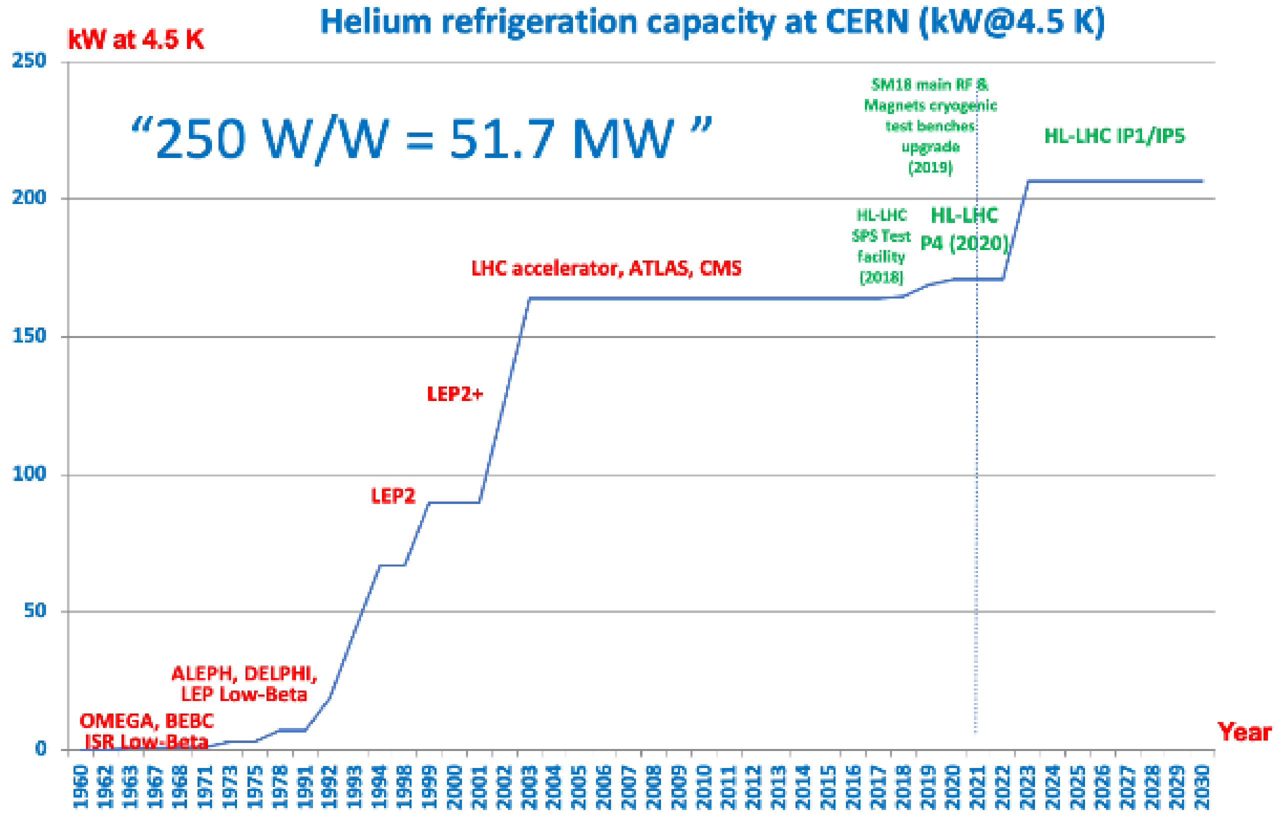


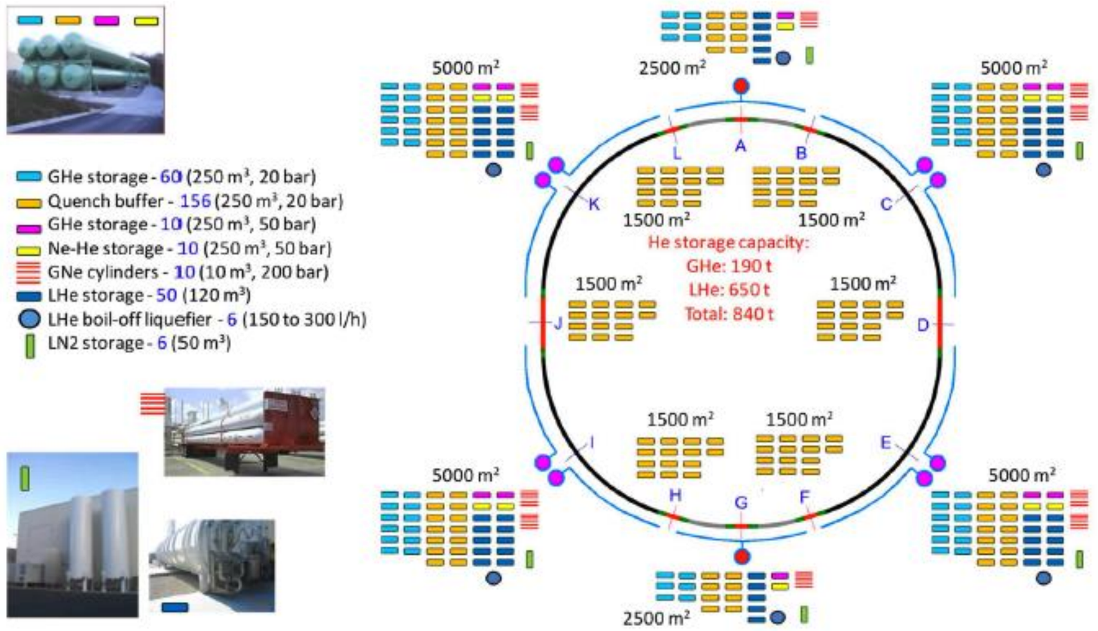
8 sectors

99.6 % per sector

Cryogenics : large power (refrigeration & energy)

HL-LHC: 210 kW @ 4.5 K
Approx. 52 MW electrical consumption

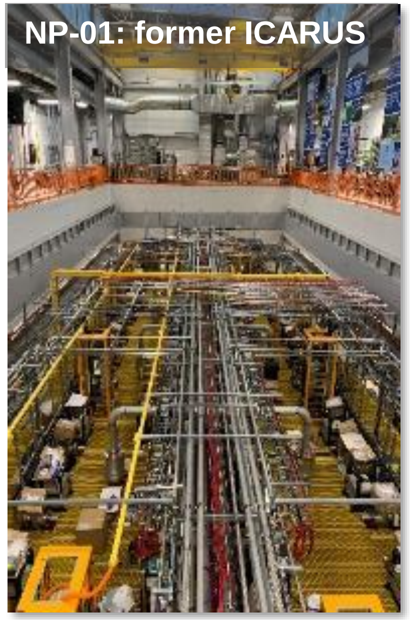




Towards the challenge of the FCC- hh:
230’000 tons of cold mass
LHe inventory = 880 tons

Helium cryogenics: 1.1 MW @ 4.5 K
Approx. 275 MW electrical consumption

Neutrino platform facilities (CERN & US); LArgon



At CERN:

- NP02/NP04 : liquid argon single/double phase prototype neutrino detector installed and operated; liquid argon volume 550 m^3/600 m^3 respectively

At Fermilab, US (proximity cryogenics from CERN):

- NP01: former ICARUS detector (600 m^3 of liquid argon) installed as far detector: in operation
- NP03: near detector (300 m^3 of liquid argon) ; to be commissioned

Now start working on the LBNF/DUNE proximity cryogenics in US: cooling and re-condensing gaseous argon, purification and recirculation of LAr (70kt)

Cryostats (inner dimensions, liquid and gas): 65m x 15m x 15m (next slide…)

Courtesy Johan Bremer

Outline

Advanced Technologies:
- **Superconducting magnets**
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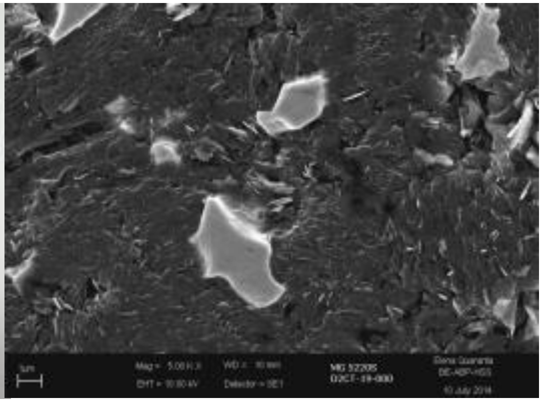
- **Vacuum system**

Advanced Concepts

- **Beam-driven Plasma Wakefield Acceleration** (PWFA)

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.

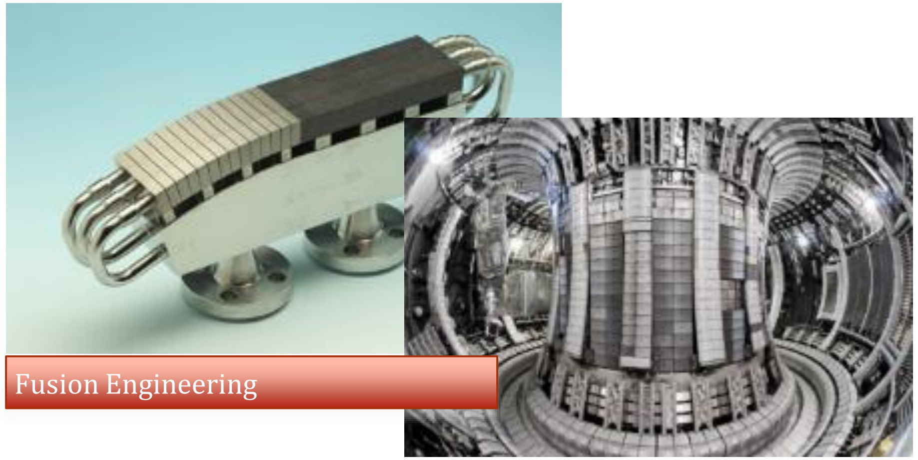


MoGr Key Properties	
Density [g/cm^3]	2.5
Melting Point T_m [°C]	~2500
CTE [10^{-6} K^{-1}]	~1
Thermal Conductivity [W/mK]	770
Electrical Conductivity [MS/m]	~1

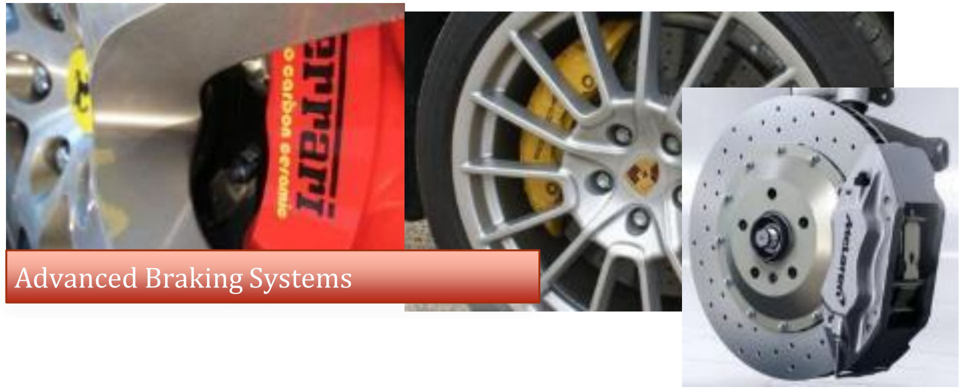
- Understanding of **unexplored conditions** call for state-of-the-art numerical simulations complemented by advanced tests in dedicated facilities

Courtesy Stefano Redaelli

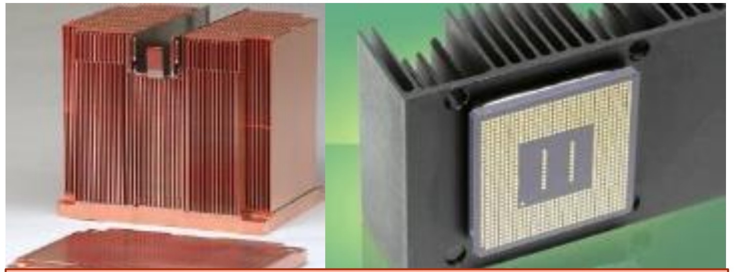
Applications of MoGr



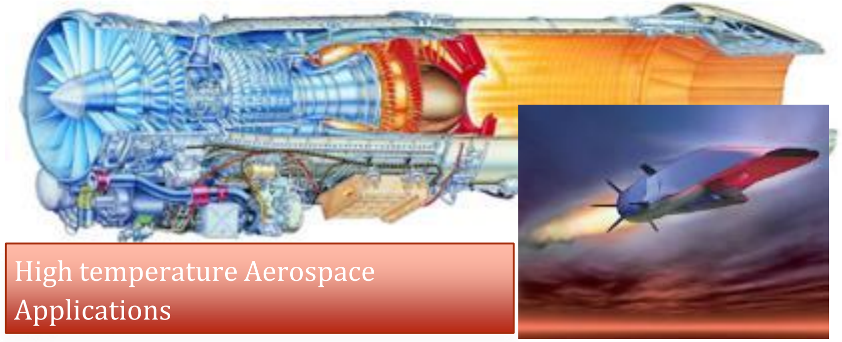
Fusion Engineering



Advanced Braking Systems



Thermal Management for High Power Electronics



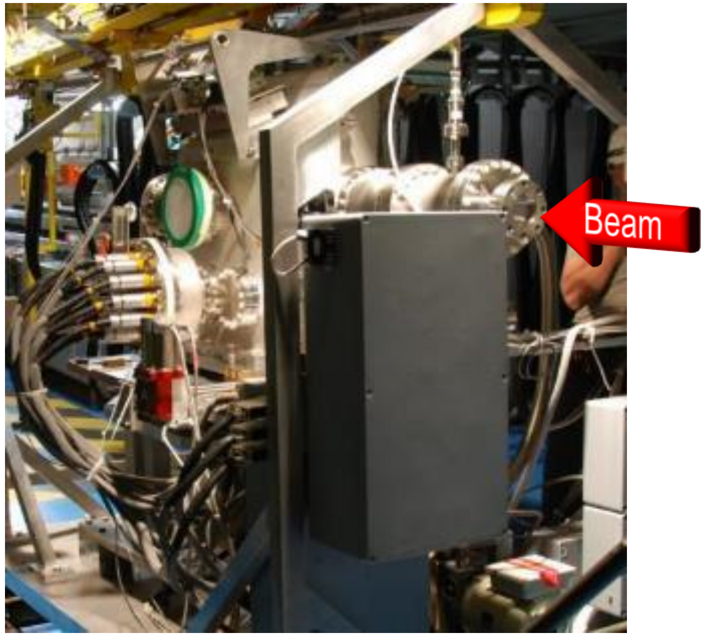
High temperature Aerospace Applications

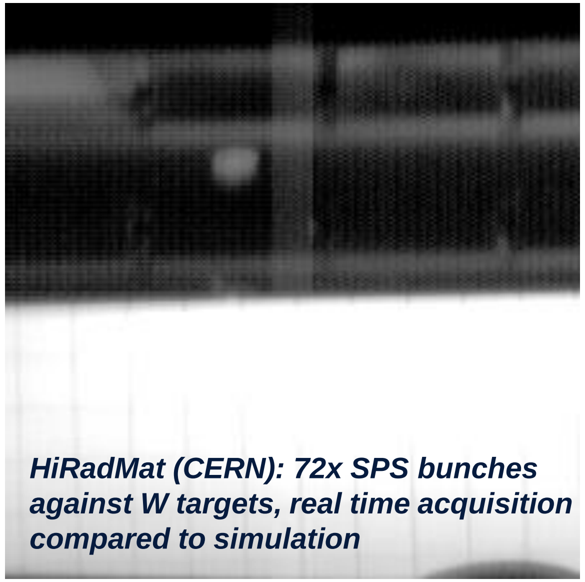
Solar Energy Applications

Potential range of applications can be further expanded thanks to the tailoring possibilities of Molybdenum-Graphite composites …

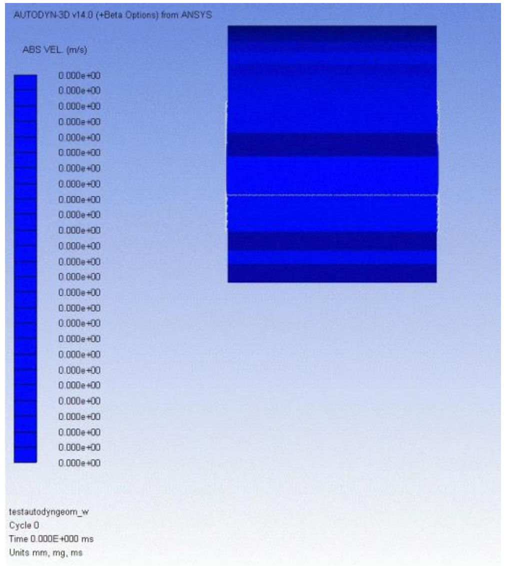
e.g. HiRadMat Experiments

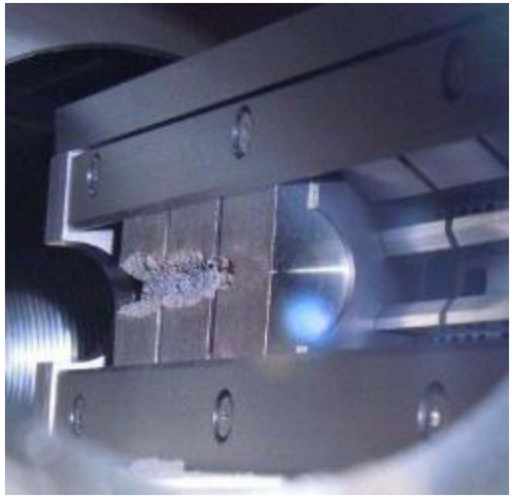
- Test of complete devices and materials under extreme beam impact conditions with comprehensive acquisition systems.
- Benchmark of experimental measurements with results of state-of-the-art numerical codes





HiRadMat (CERN): 72x SPS bunches against W targets, real time acquisition compared to simulation





Tungsten target, impact of 72x SPS bunches

Beam Intercepting Device

A beam intercepting device is a component that intercepts particle beams for diverse purposes, such as
- Production of secondary particles: **target**
- Protection of sensitive equipment: **collimator**
- Safe disposal: **dump**

Challenges

- Devices must be able to withstand operation and accident scenarios & protect delicate equipment
- Sometimes employed as “last line of defence” against component damage
- Operational teams rely heavily on dependable components, whose failure often leads to long period of downtime
- Usually, the most radioactive components in an accelerator complex (cool down, ALARA)

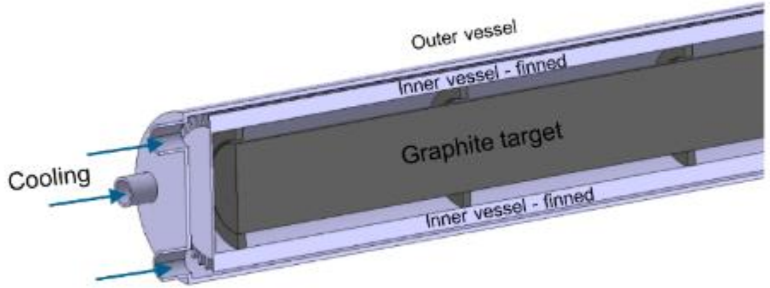
- Ultra High Vacuum requirements (10^{-10} mbar)
- Movable parts with extremely high precision and flatness requirements
- High energy densities (several kJ/cm^3/pulse)
- High power densities (±MW/cm^3)

- Impedance (especially for colliders)
- Radiation damage and modification of thermo-physical properties
- Final radioactive waste packaging and disposal

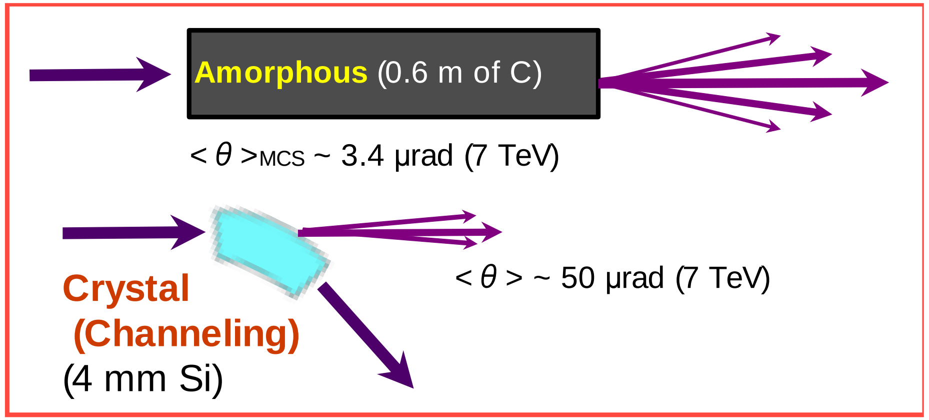
Courtesy Marco Calviani

Target activities

- Graphite
  - Workhorse for Target and beam intercepting device
  - Possible solution if beam power up to 1.5/2 MW max
- Packed bed target (also an option for ±2 MW)
- Fluidised tungsten
  - Advanced design, additional offline testing to validate technology
- Liquid metal technologies (pure, eutectics, etc.)
  .- Technologies developed already for nuclear industry – being investigated by recently established start-ups
- Hg target to be considered ?



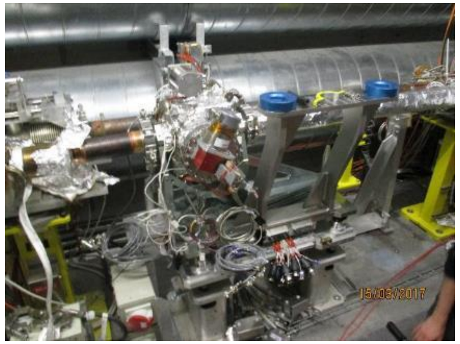
Advanced collimation – bent crystals



Bent crystals allow bending high-energy particles trapped between lattice planes, with reduced nuclear interactions compared to amorphous scatterers.

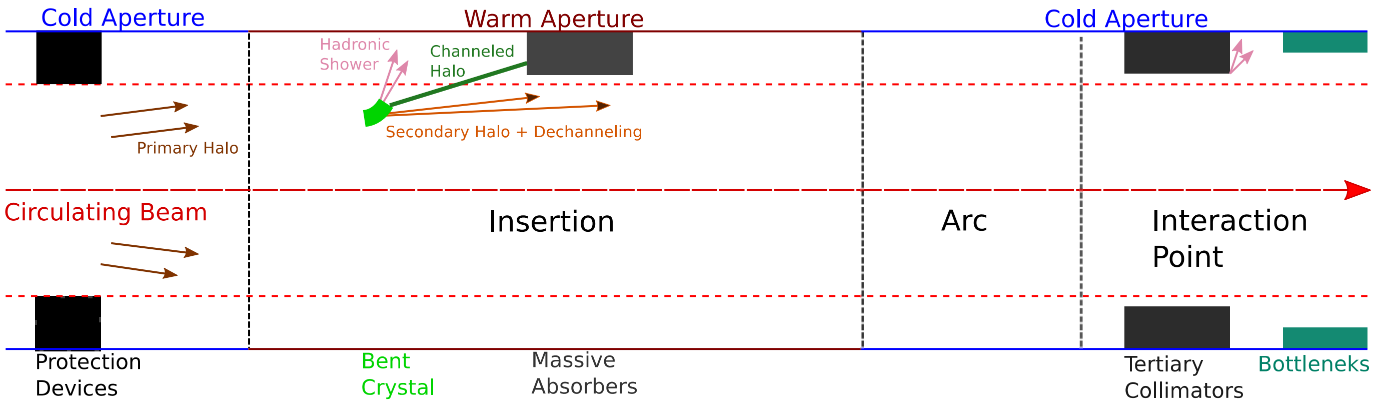
With 50 µrad of bending in 4 mm the crystals produce the effect of an equivalent 310 T field

LHC crystal collimators (ion operation)



In recent years, attention has been turned to crystal collimation:
Primaries are replaced by **bent crystals that steer all halo particles onto a single absorber**

1. Improved collimation cleaning
   (especially for ions)
2. Reduce impedance
   (less collimators at larger gaps)



Courtesy Marco Calviani

Outline

Advanced Technologies:
- Superconducting magnets
- Superconducting RF
- Cryogenics (see Steffen Grohmann's presentation)

- Materials and beam intercepting devices (BID)
- **Vacuum system**

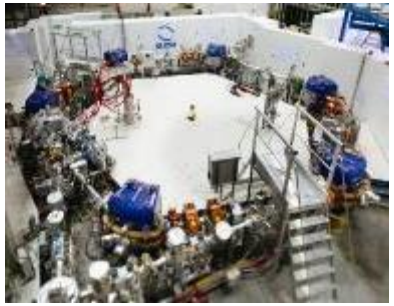
Advanced Concepts
- Beam-driven Plasma Wakefield Acceleration (PWFA)

Vacuum levels of accelerators: CERN case

Linac4 <2*10^{-7} mbar*

PSB <5*10^{-8} mbar*

PS <2*10^{-8} mbar*



ELENA <4*10^{-12} mbar

* After 24 h pumpdown

SPS LSS <10^{-7} mbar*

LHC arcs <10^{-8} mbar

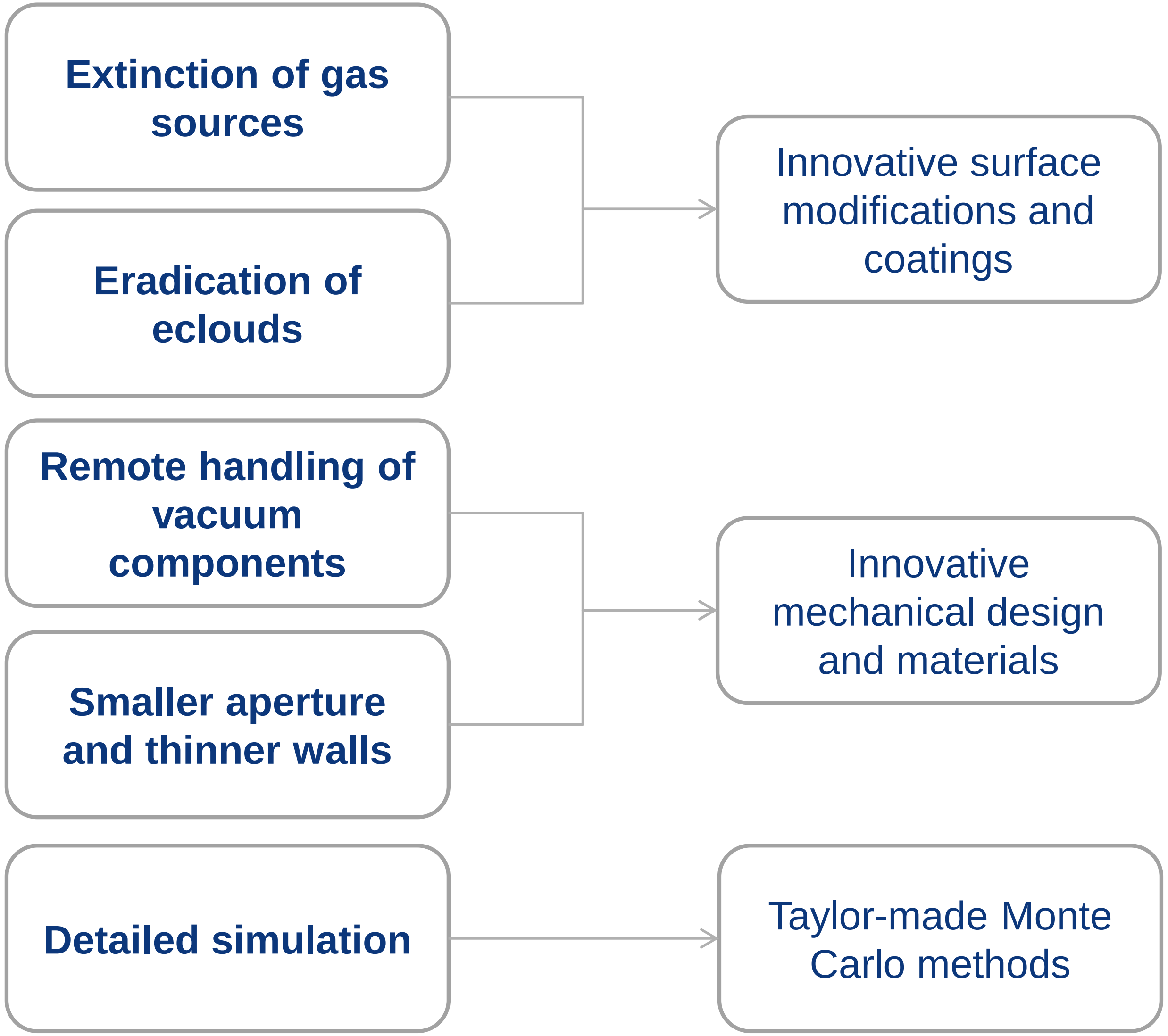
LHC LSS <10^{-10} mbar

Unbaked systems TMP, ion pumps, Ti sublimators	Cryogenic systems Cryopumping	Baked systems Ion pumps, NEG coating

127 km long vacuum system, 99.98% availability at end of LHC run-2

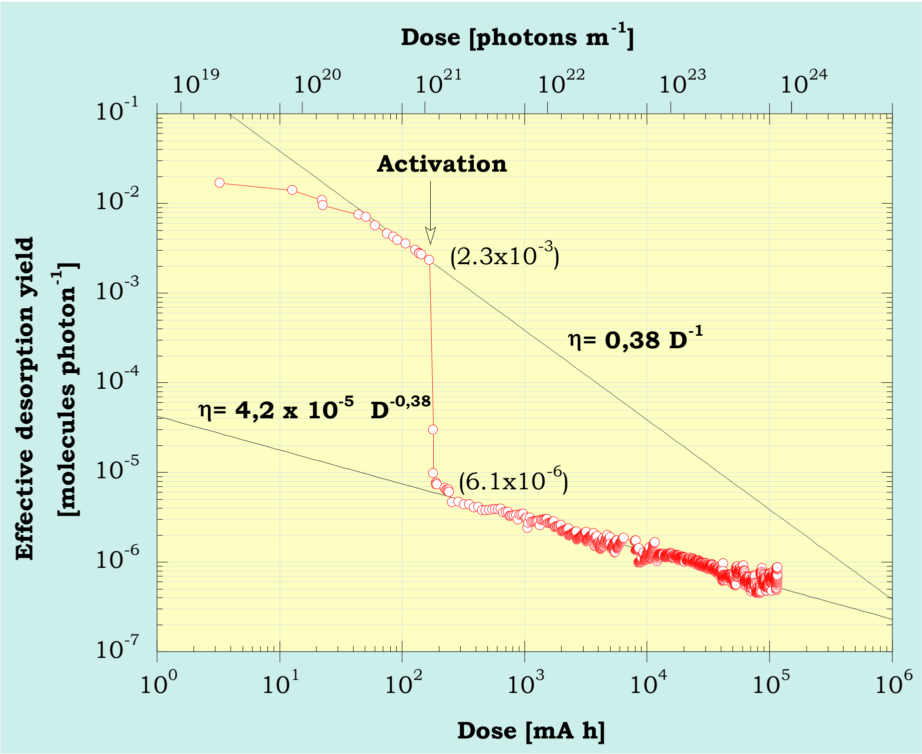
Courtesy Paolo Chiggiato

Trend in vacuum technology for particle accelerators



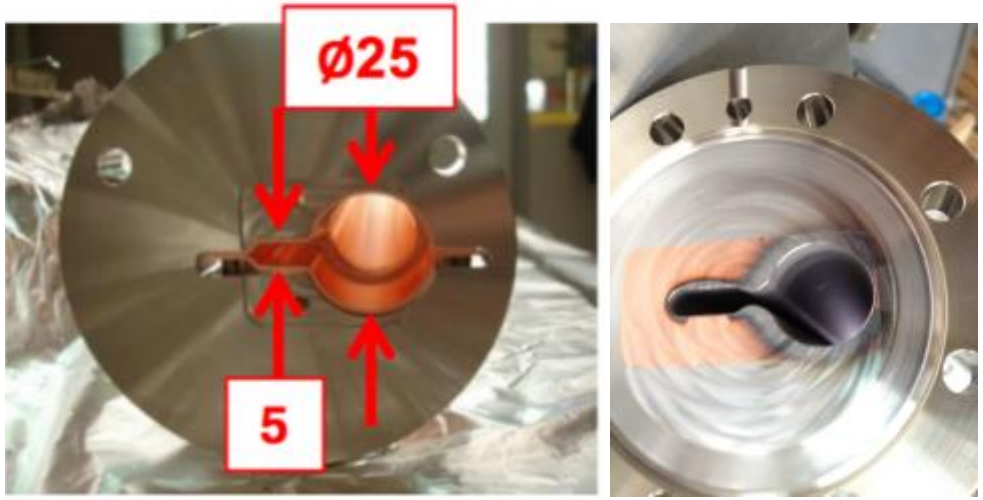
Courtesy Paolo Chiggiato

Extinction of gas sources



Reduction of synchrotron-radiation desorption yield after NEG activation

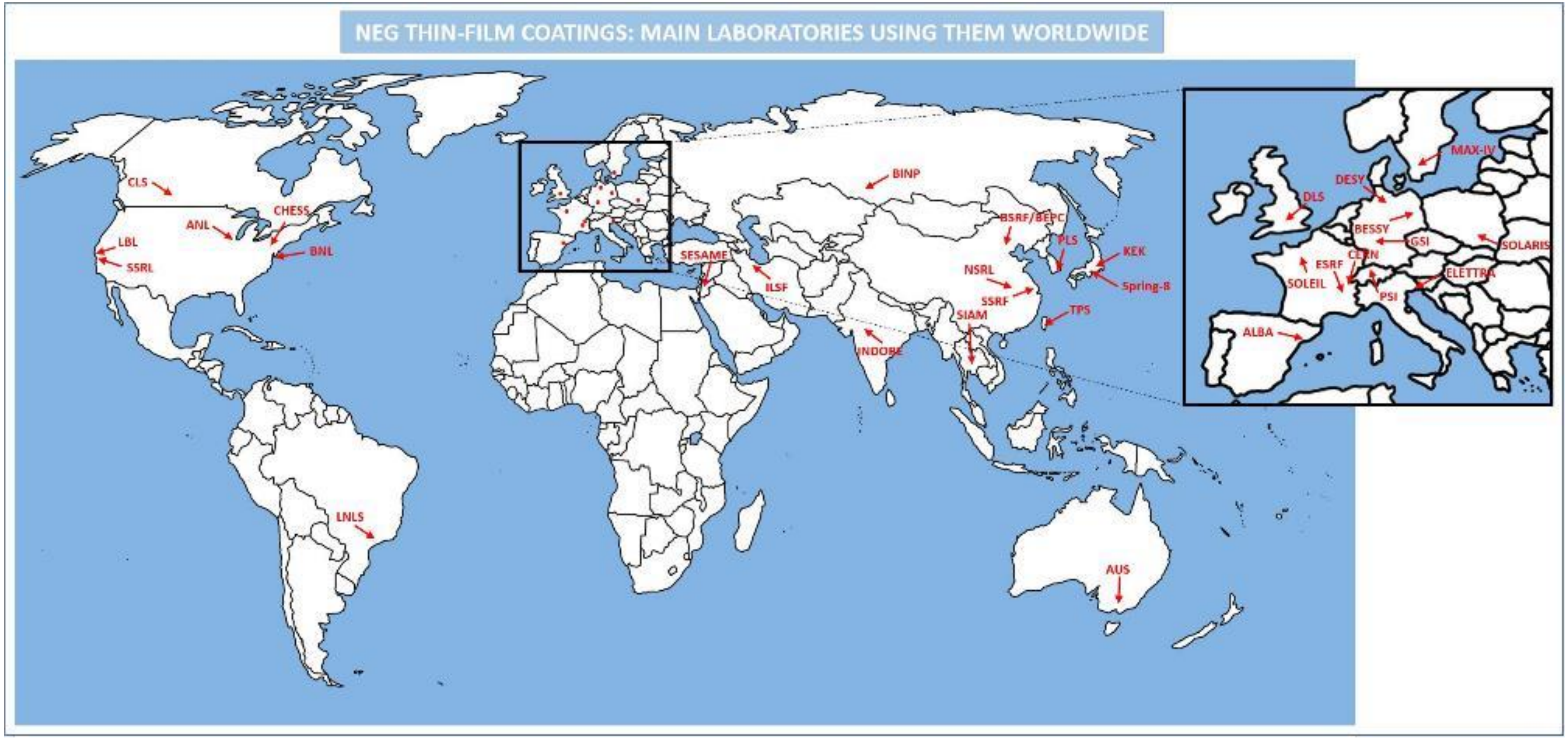
- **Non Evaporable Getter (NEG) thin film coatings transform beampipes into pumps.**
- After activation at 180°C, they provide very low beam induced desorption and low secondary electron yield.
- e.g more than 1500 vacuum chambers coated at CERN.



MAX IV vacuum chamber: before and after NEG coating

NEG thin film coatings

The Ti-Zr-V NEG thin film is being studied and used by an increasing number of particle accelerators worldwide:

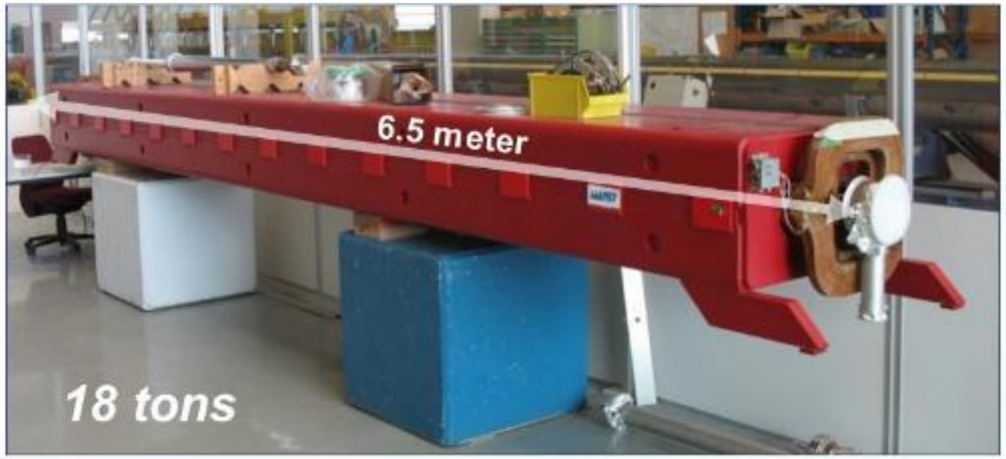


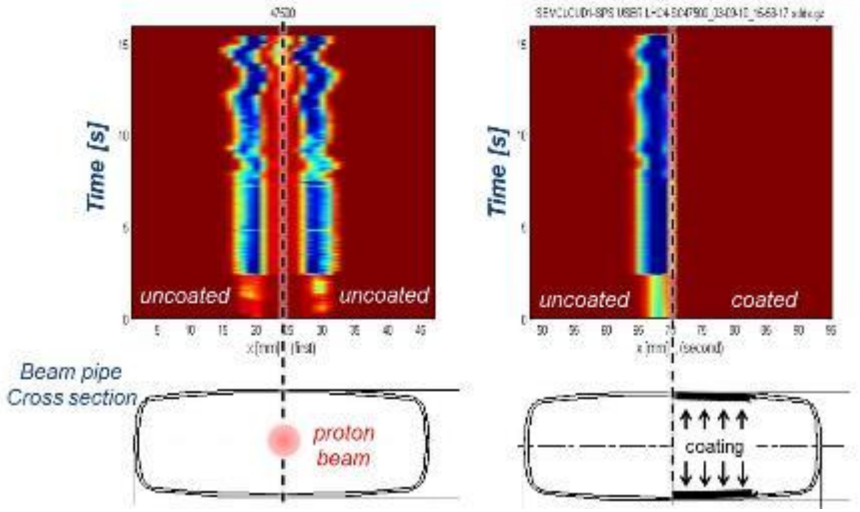
Courtesy Paolo Chiggiato and Roberto Kersevan

Eradication of eclouds: carbon coatings

The carbon coatings are produced by sputtering in order to keep a low hydrogen partial pressure during the deposition.

Different sputtering configurations have been developed to cope with the constrains of the beam pipes to be coated.

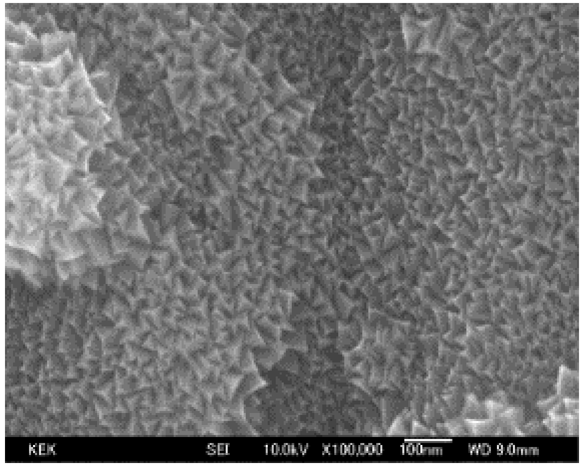




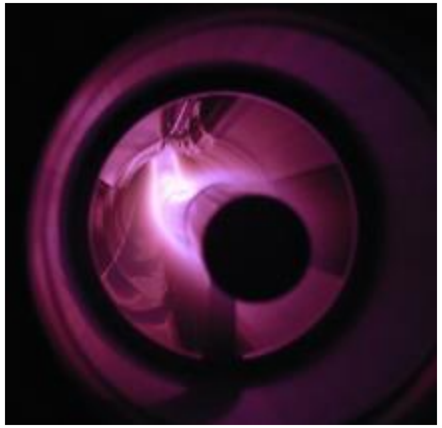
e.g DC Hollow Cathode sputtering used for the dipoles of the CERN Super Proton Synchrotron.

Eradication of eclouds: TiN at KEK

- **More than 1300 vacuum chambers have been TiN (Titanium Nitride) coated at KEK.**
- **TiN allows the conditioning of Al beampipes to SEY values < 1**



Electron microscopic image of TiN coating

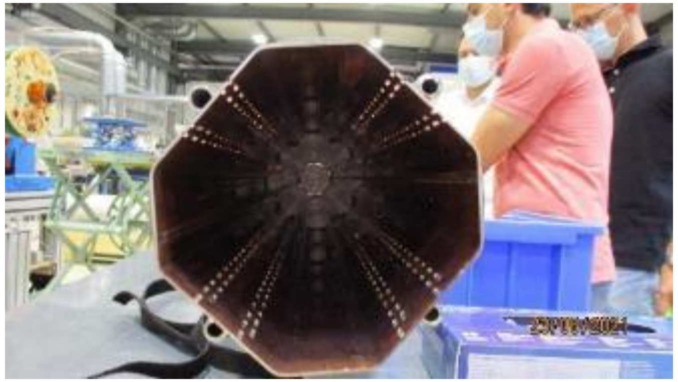


KEK's TiN coating facility

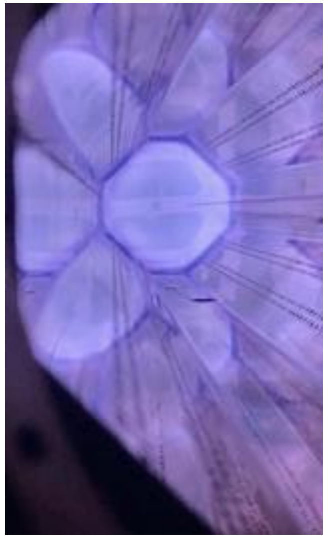
Courtesy of Kyo Shibata san

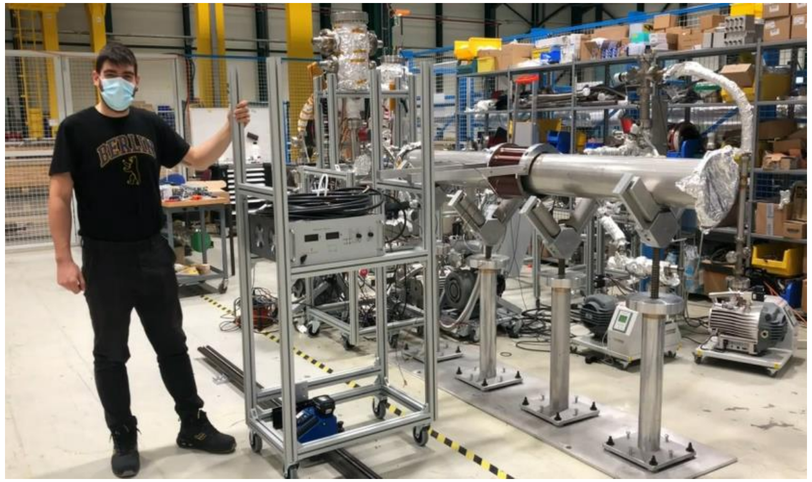
Beam-screen a-C coating - Vacuum of High-Luminosity LHC

a-C films withstand magnet quenchs at nominal HL-LHC current

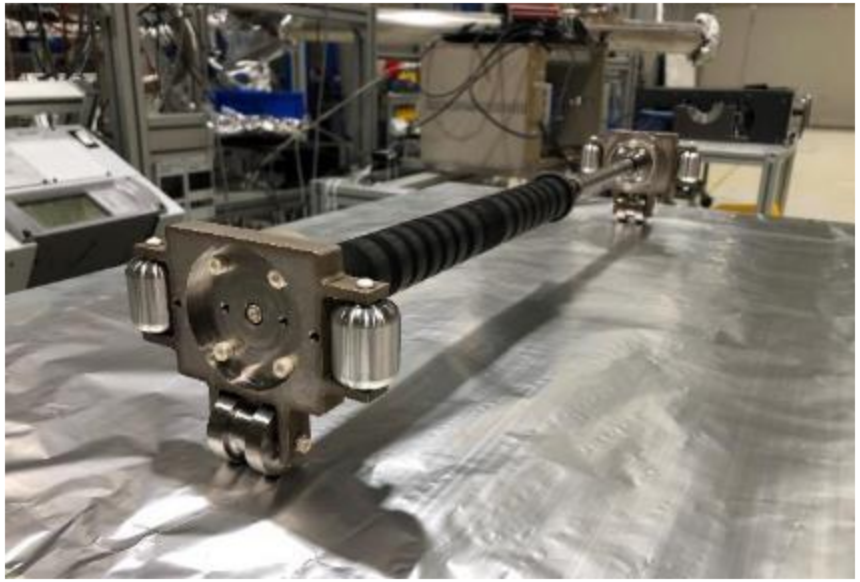


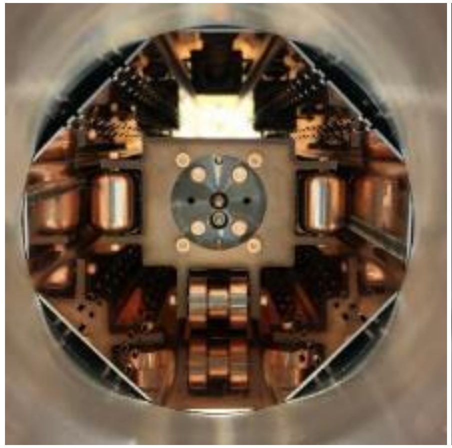
Ion etching with movable solenoid

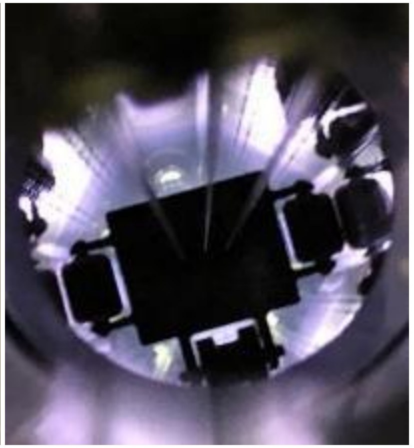




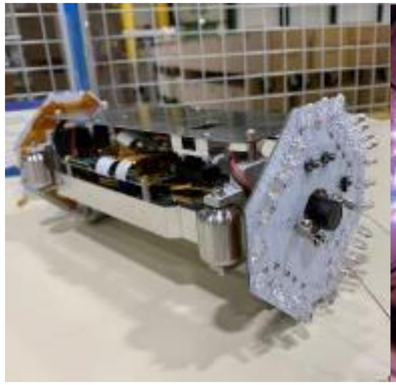
Sputtering device





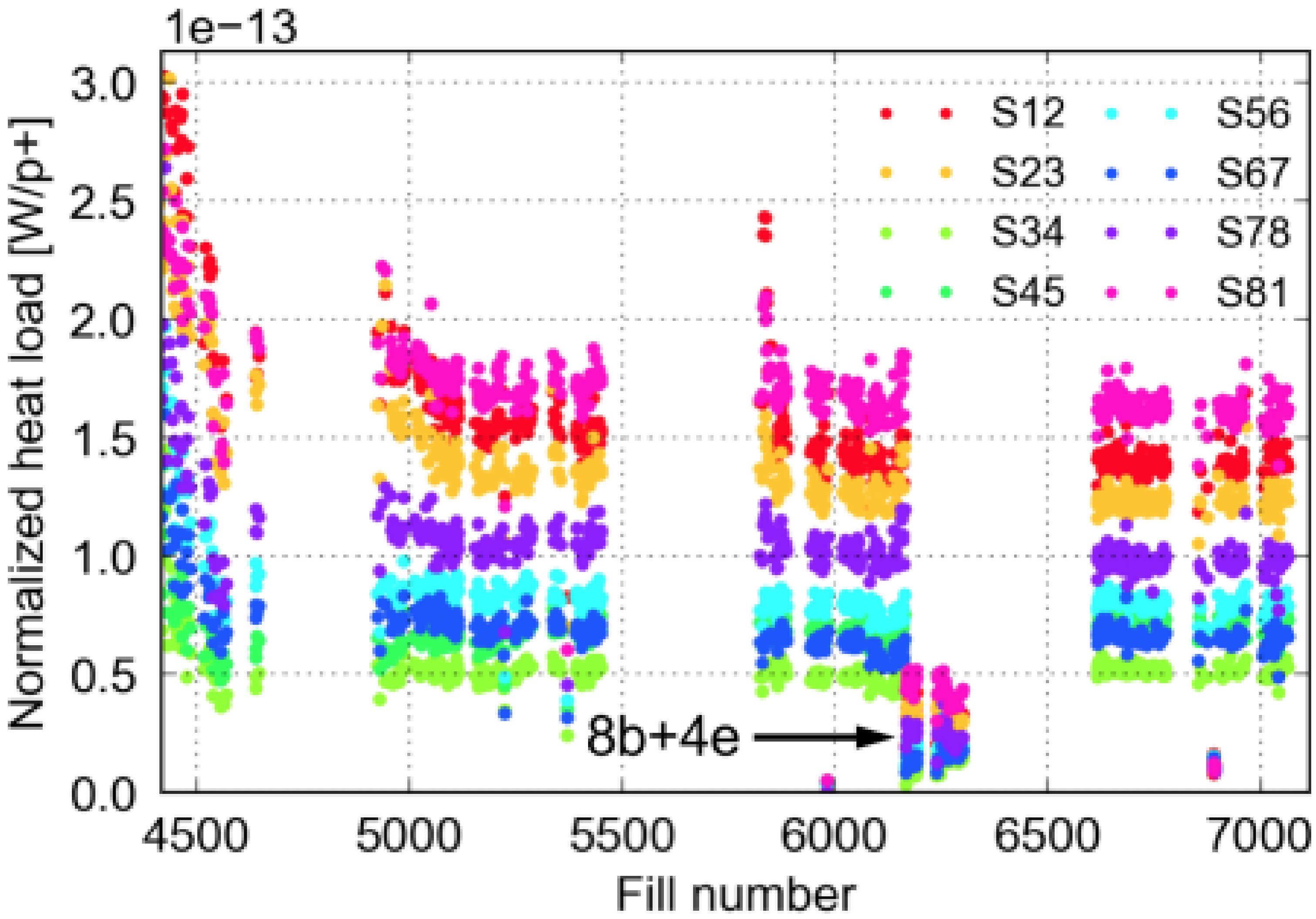


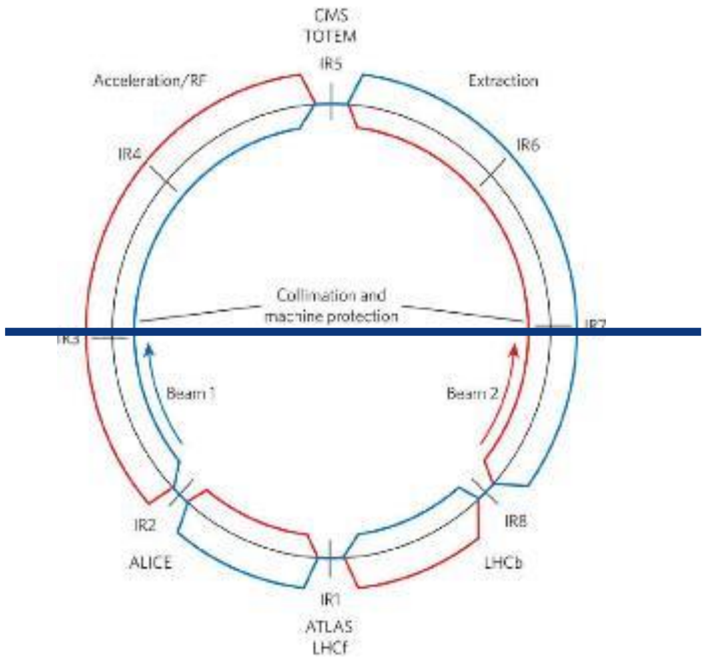
Optical inspection device



Courtesy Paolo Chiggiato

Anomalous heat load in LHC’s arcs

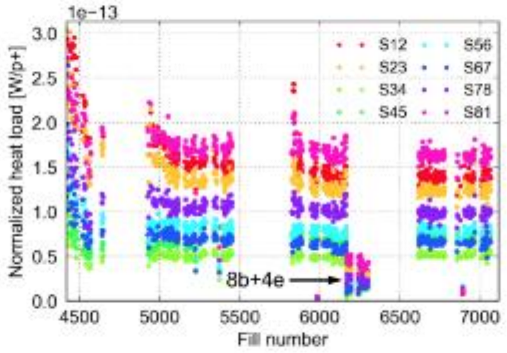




Sector 3-2
Sector 2-1
Sector 1-8
Sector 8-7

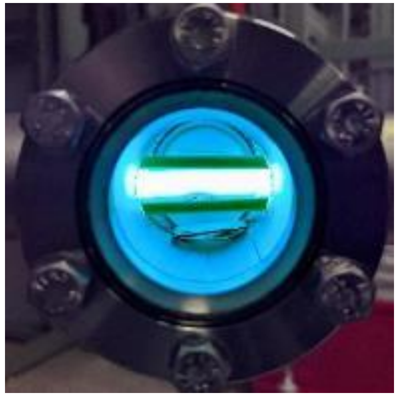
Higher ???

Anomalous heat load in LHC's arcs: in-situ treatment for mitigation

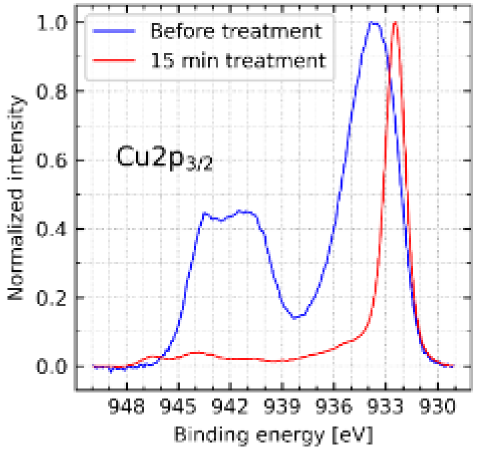


UV gas assisted

- 1 bar (static) of Forming Gas (N_2-H_2 95%-5%)
- UV lamp: 185 nm and 254 nm



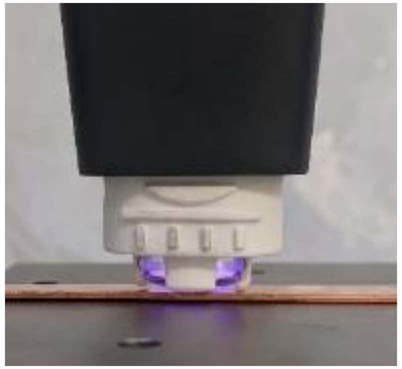
Full reduction in 15', but…
→ resulting heating acceptable for LHC?
→ check by fitting the UV lamp in a beam screen mockup



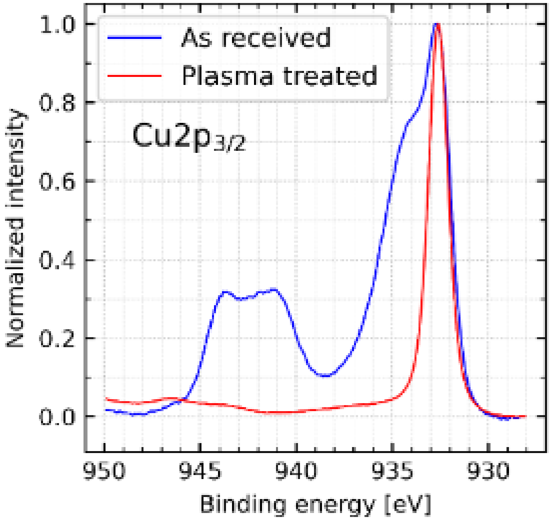
Will all this avoid to rebuild CuO?

Cold plasma treatment

- commercial (Relyon Plasma) atmospheric plasma source



Full reduction in 5', flushing in working gas
→ needs development to be implemented in a beam screen

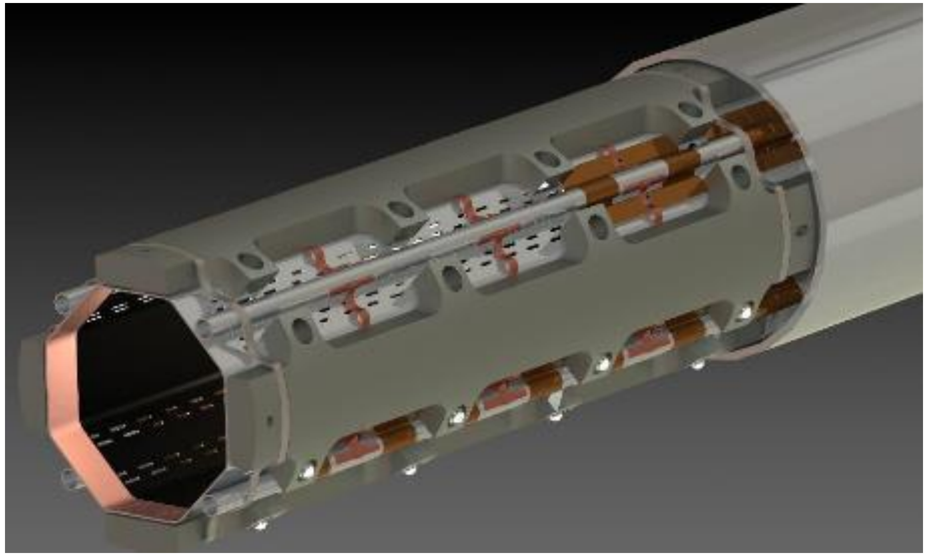


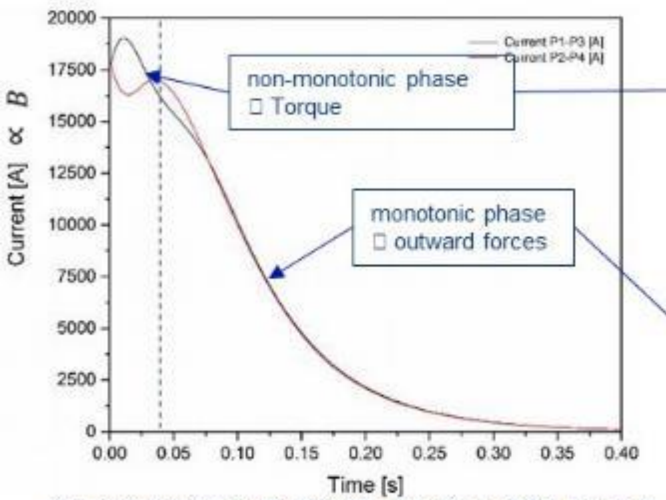
More and more complex shielded beam screen

Vacuum of High-Luminosity LHC: new triplet magnets

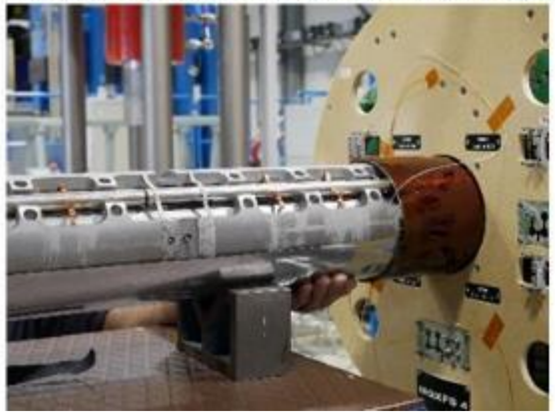
The shielded beam screen must withstand the Lorentz forces induced by Eddy current during a magnet quench.

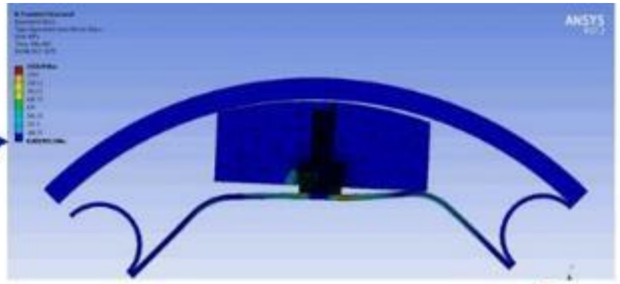
Magnetic forces around **30 tons/m/quadrant** develop in the shielded beam screens.

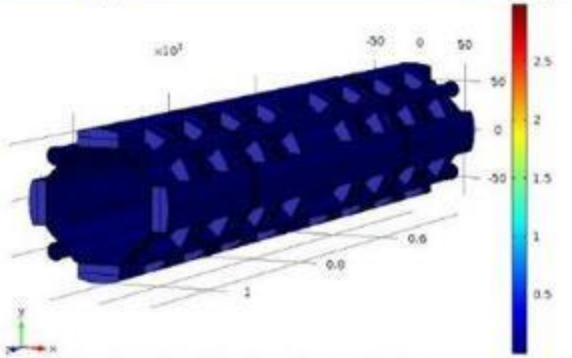




Current discharge at ultimate operation of the magnet







Mechanical behaviour during a quench

Simulations have been validated with a shielded beam screen prototype done on purpose for mechanical behaviour assessment during a quench.

Courtesy Paolo Chiggiato

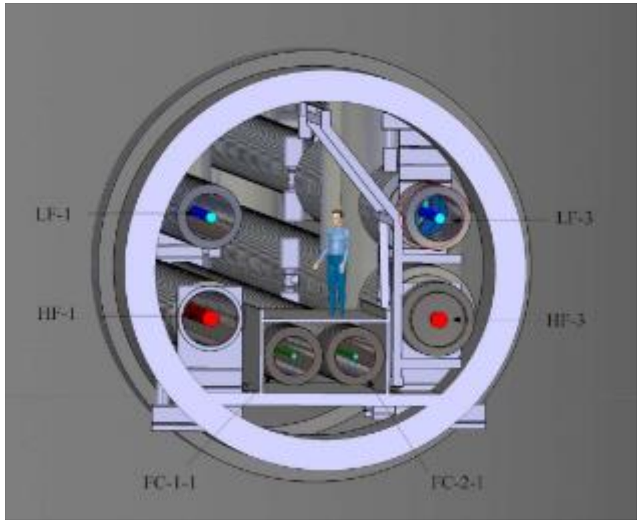
Services for the Physics Community

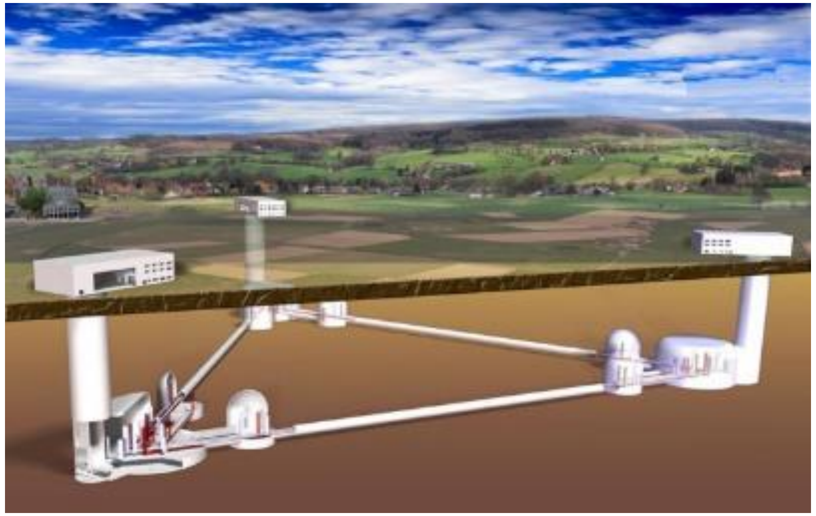
Leak detection

Leak detection for ARIA project

Courtesy Paolo Chiggiato

Vacuum for next-generation Gravitational Waves Telescopes





Vacuum & mechanical requirements of the Einstein Telescope (ET)'s arms

Items	Requirements	Comment
Pipe diameter	**1.2 m**	Exact value not yet decided
Total length	**120 km**	3 arms of 10 km, 4 pipes per arm
Hydrogen partial pressure	**order of 10^{-10} mbar**	
Water vapour partial pressure	< 5×10^{-11} mbar	
Hydrocarbon partial pressures	< 10^{-14} mbar	
Lifetime	50 years	

Vacuum for next-generation Gravitational Waves Telescopes

The main challenge is a significant reduction of the costs with respect to the scaled-up solution of the present GWT (LIGO, VIRGO, KAGRA).

Two, among others, possible directions of study:

Adapt gas pipelines to UHV requirements. This implies the use of mild steels and the treatments of surfaces against corrosion.

Use corrugated thin walls

Courtesy Paolo Chiggiato

Outline

Advanced Technologies:
- **Superconducting magnets**
- **Superconducting RF**
- **Cryogenics** (see Steffen Grohmann's presentation)

- **Materials and beam intercepting devices (BID)**
- **Vacuum system**

Advanced Concepts
- **Beam-driven Plasma Wakefield Acceleration (PWFA)**

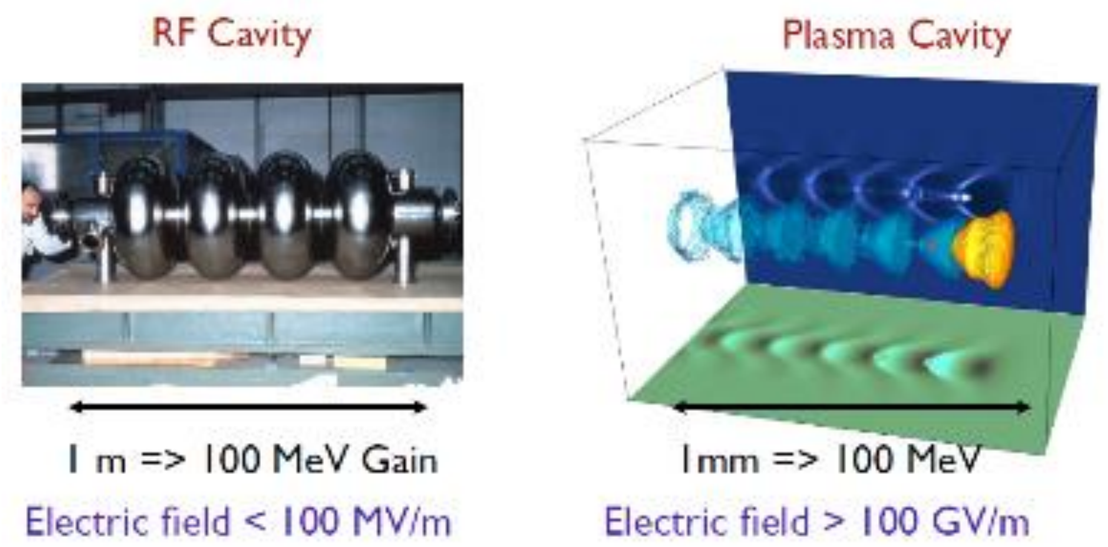
New acceleration techniques using lasers and plasmas

Accelerating field of today's RF cavities or microwave technology is **limited to ≈ 100 MV/m**

Several tens of kilometres for future linear colliders

Plasma can sustain up to **three orders of magnitude much higher gradient**

SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient



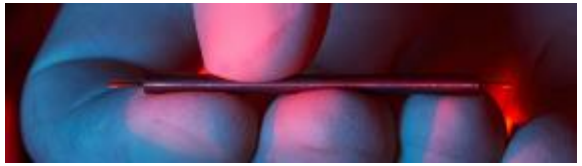
V. Malka et al., Science **298**, 1596 (2002)

Lasers can produce huge transverse electric fields (TV/m !)

Can we convert the transverse fields into longitudinal and use them for acceleration?

(1) Micro/Nano-Accelerators

Send THz Laser into Dielectric Waveguide (Micro-Accelerator)



The «accelerator on a chip»

(2) Plasma Accelerators

Use a plasma to convert the transverse electrical field of the laser (or the space charge force of a beam driver) into a longitudinal electrical field, by creating plasma waves.

Courtesy of Maurizio Vretenar

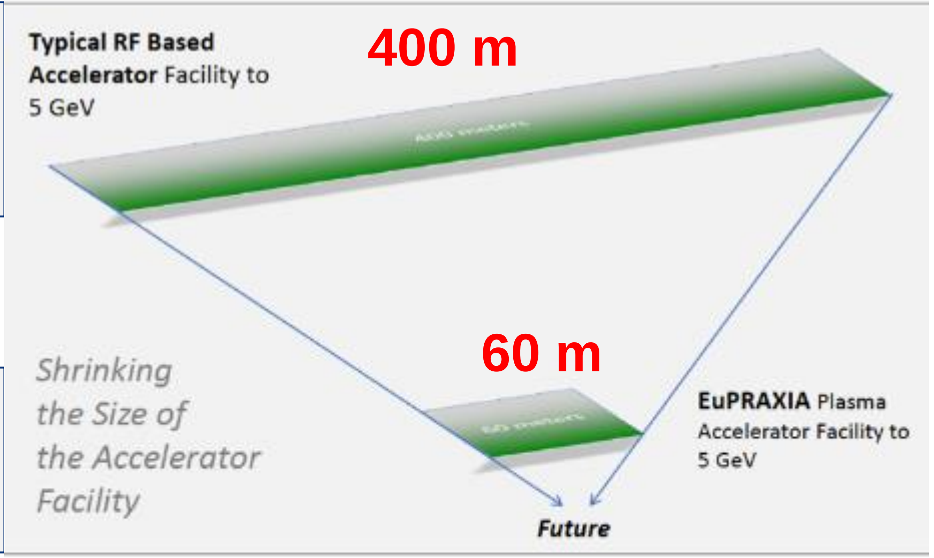
European Plasma Research Accelerator with eXcellence In Applications

European ESFRI Project on Accelerator Innovation

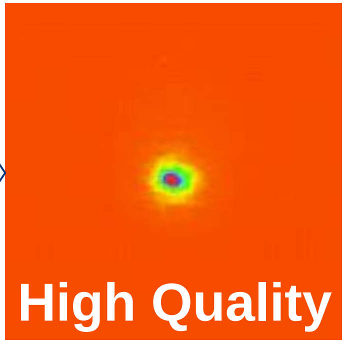
http://www.eupraxia-project.eu/

RF Particle Accelerators
> 30,000 operational – many serve for Health
30 million Volt per meter
RF: 90 years of success story for society

Plasma Particle Accelerators
first user facility to be realized
100 billion Volt per meter



600+ page CDR, 240 scientists contributed



Placed on 2021 ESFRI Roadmap new RI due to compactness and cost-efficiency – ultra-fast science bringing new capabilities to institutes, hospitals, universities, industry, countries.

Courtesy of Ralf Assmann

Conclusion

Many important domains of accelerator technologies not mentioned (or too quickly): cryogenics (e.g. Nelium Ne-He,...), magnetic horn, beam instrumentation, beam dump sytem, quench protection, power converters and modulators, control systems, R2E, remote handling, nano-positionning,...

Multiple synergies and interest in common R&D activities, for nuclear science and astrophysics, and also with fusion (ITER,…), energy domain, manufacturing techniques, space applications, medical applications, ...

Global collaborations on future accelerators will lead to **technological breakthroughs** and R&D on **new concepts.**

From 2010, global thinking on "Energy at Research Infrastructures"

Workshop Energy for Sustainable Science

2011, ESS - Lund (S)
2013, CERN (CH)
2015, DESY - Hambourg (D)
2017, ELI-NP - Bucharest (RO)
2019, PSI - Villigen (CH)

Energy Management

To share experience between representatives from various research laboratories **strategies, goals and institutional practice to advance environmental sustainability at their research facilities and research campus with particular emphasis on energy savings and energy efficiency measures**

There will be no future large-scale science project without an energy management component and an incentive for energy efficiency and Research infrastructures do not want to represent an energy issue for society. But wish to contribute to good practices and solutions for the future !

A selection of specific programs for consolidating existing infrastructures is a way to put into practice these good intentions, and to acquire expertise with proven references.

CERN

EUROPEAN SPALLATION SOURCE

ERF European Association of National Research Facilities Open to International Access

6th Workshop: Energy for Sustainable Science at Research Infrastructure (ESSRI) : 29-30 September 2022 – ESRF – Grenoble (France)

29-30 September 2022 REGISTRATION OPENS 1ST MAY
ESRF, Grenoble
Europe/Paris timezone

- Overview
- Committees
- Timetable
- Registration Instructions PLEASE READ!
- ESRF Registration Form
- Fees & Payment Information

Dwindling resources together with rising energy costs and climate change are all challenges faced by the next generation of large-scale research infrastructures. Indeed, the enhanced performance of proposed new facilities often comes with anticipated increased power consumption. Sustainable developments at research infrastructures will rely on mid- and long-term strategies for reliable, affordable and carbon-neutral energy supplies.

The ESRF (European Synchrotron Radiation Facility) is pleased to host the **Sixth Workshop on Energy for Sustainable Science at Research Infrastructures** on **29th and 30th September 2022** in Grenoble, France in collaboration with:

https://indico.esrf.fr/event/2/

Session Topics:
- energy efficient technologies
- energy management at research infrastructures
- sustainability of equipment, materials and resources
- energy management for projects

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"The task of the mind is to produce future"
Paul Valéry

Muchas gracias por su atención

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- Thanks all the colleagues who made their slides available
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