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Technical challenges for future accelerators

Lucio Rossi
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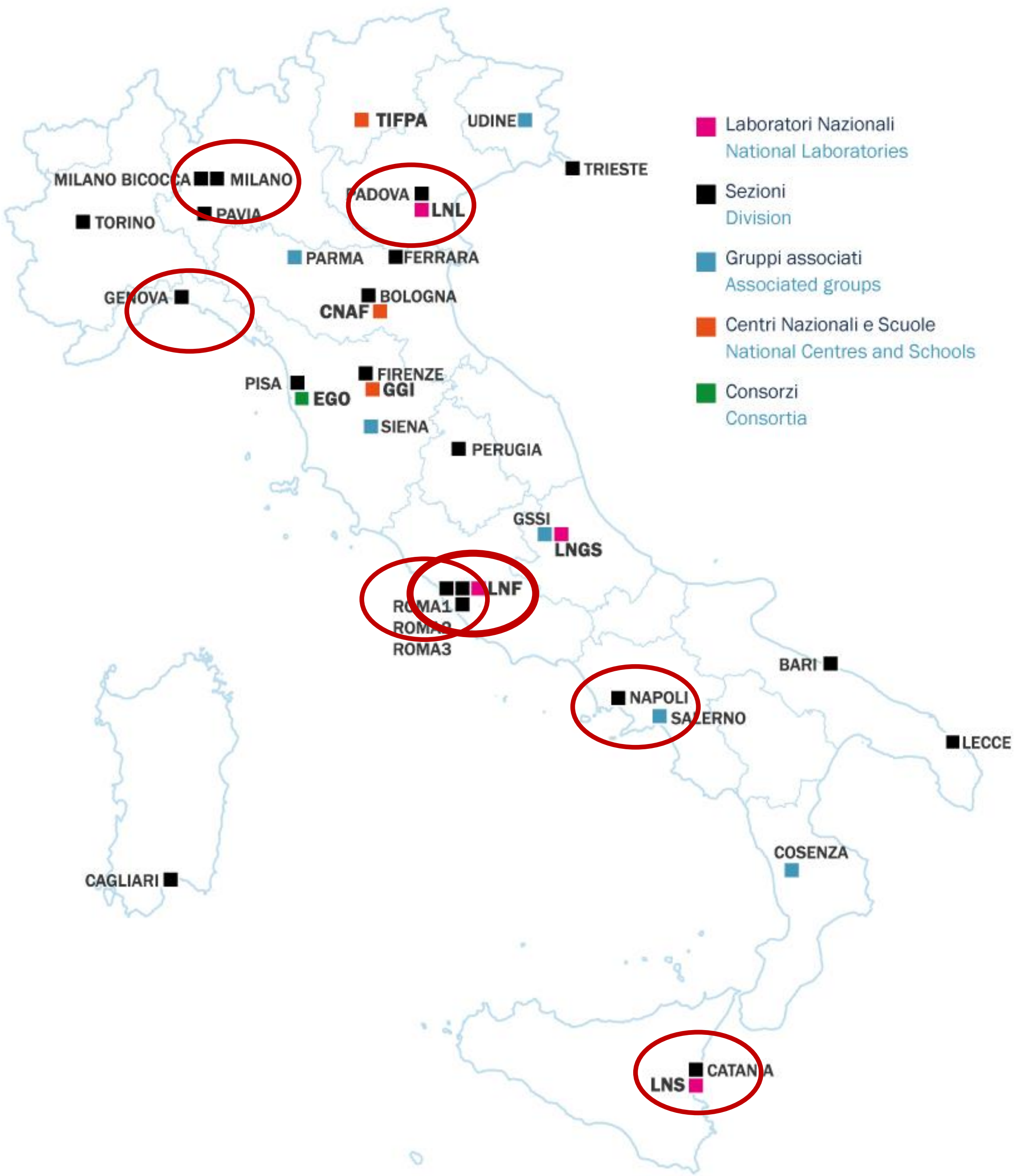
Coordinator of INFN committee for Science & Technology of Accelerators

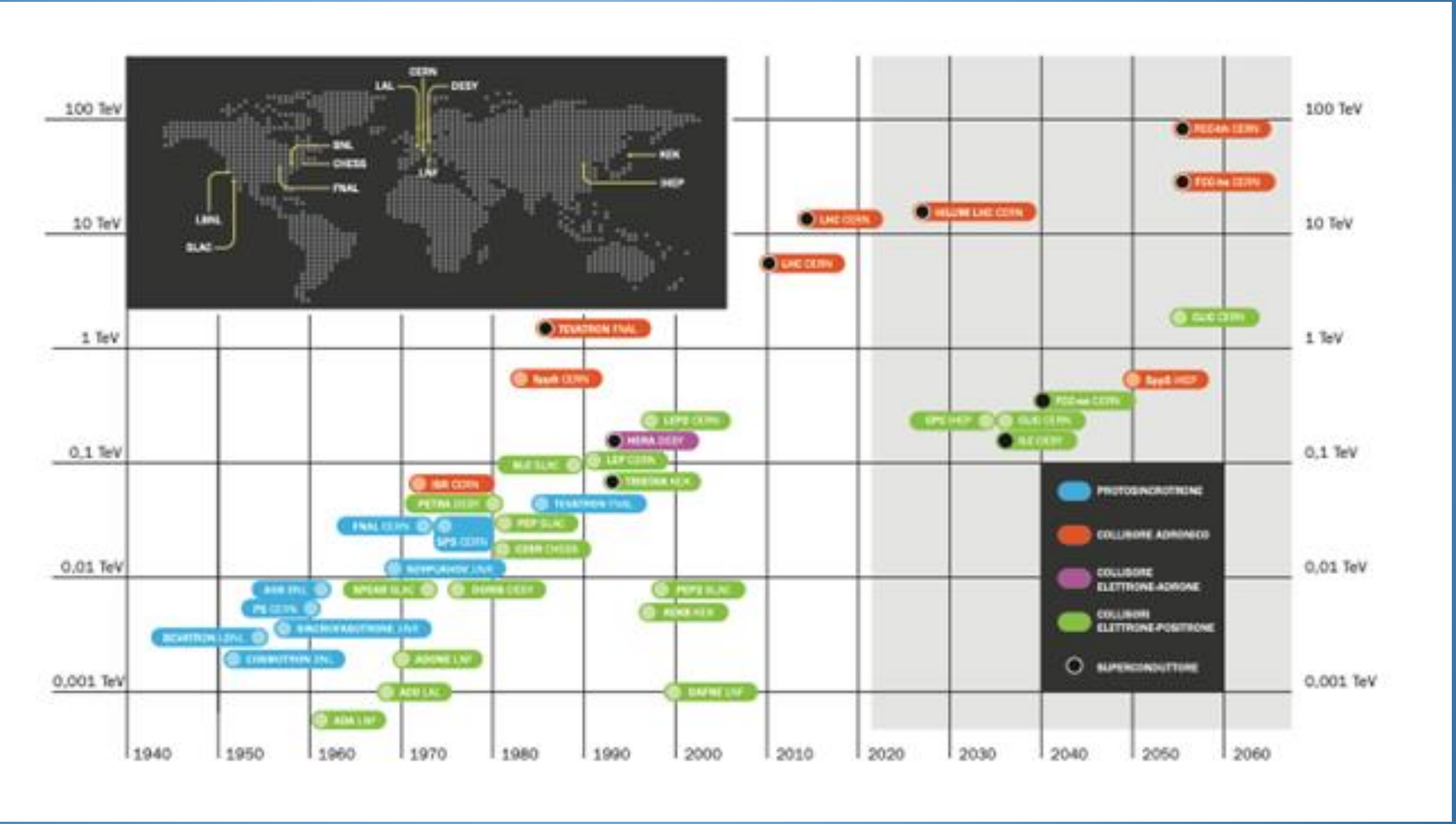
Acknoledgement: Akra Yamamaoto, KEK and CERN, (Granada-ESUPP workshop)

Comitato nazionale
Scienza e Tecnologia degli Acceleratori

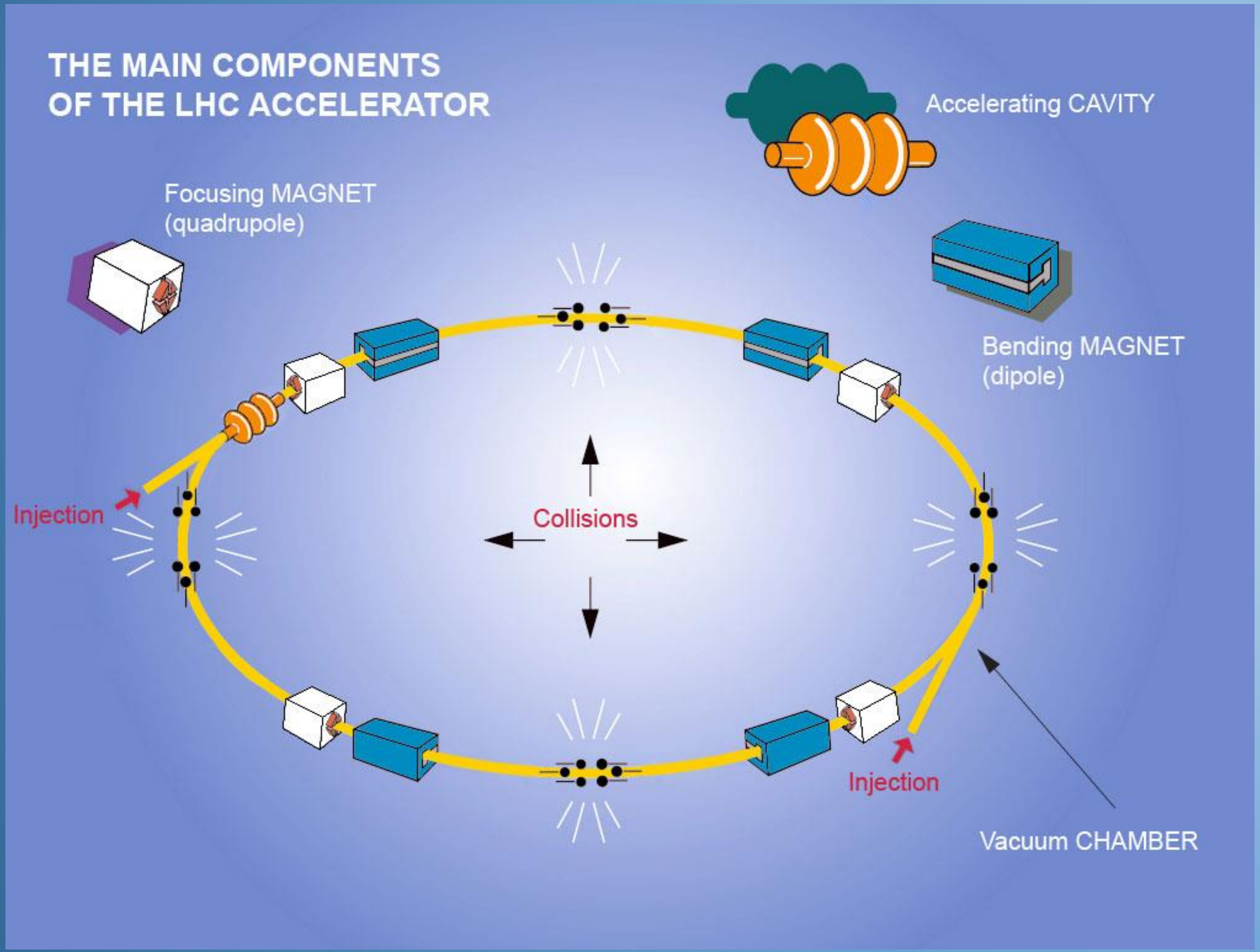
- Established in summer 2020 by INFN President
- Scope
  - Connection a “rather diversified and territorially-spread” community
  - Promote networking
  - Support international and national CALLS
  - Support to INFN management for new projects and strategic lines
- Website : type accleratpri.infn.it → https://acceleratori.infn.it/it/
  - type accelerators.infn.it and the english version should appear https://acceleratori.infn.it/en/
- Mapping of competence : structured DB
- Mapping industry relation



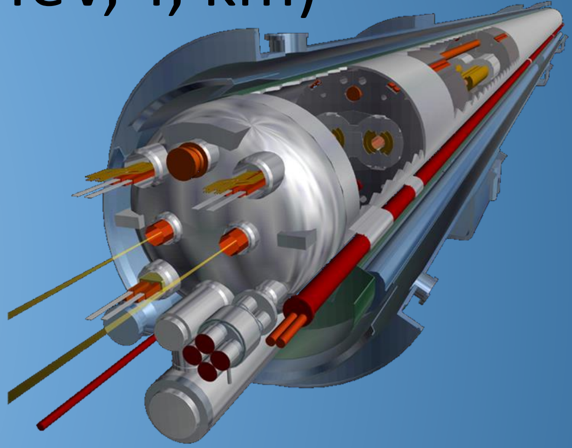
A “Revised” Livingstone Plot



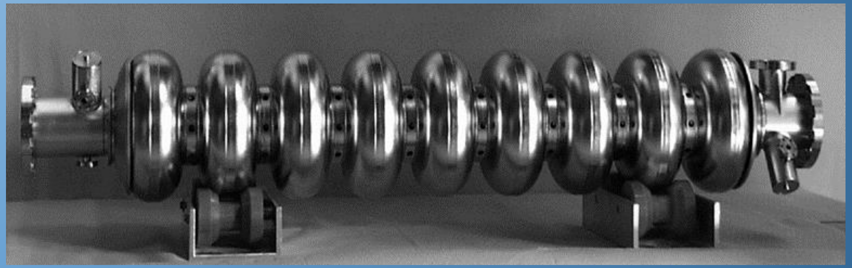
To push the energy frontier



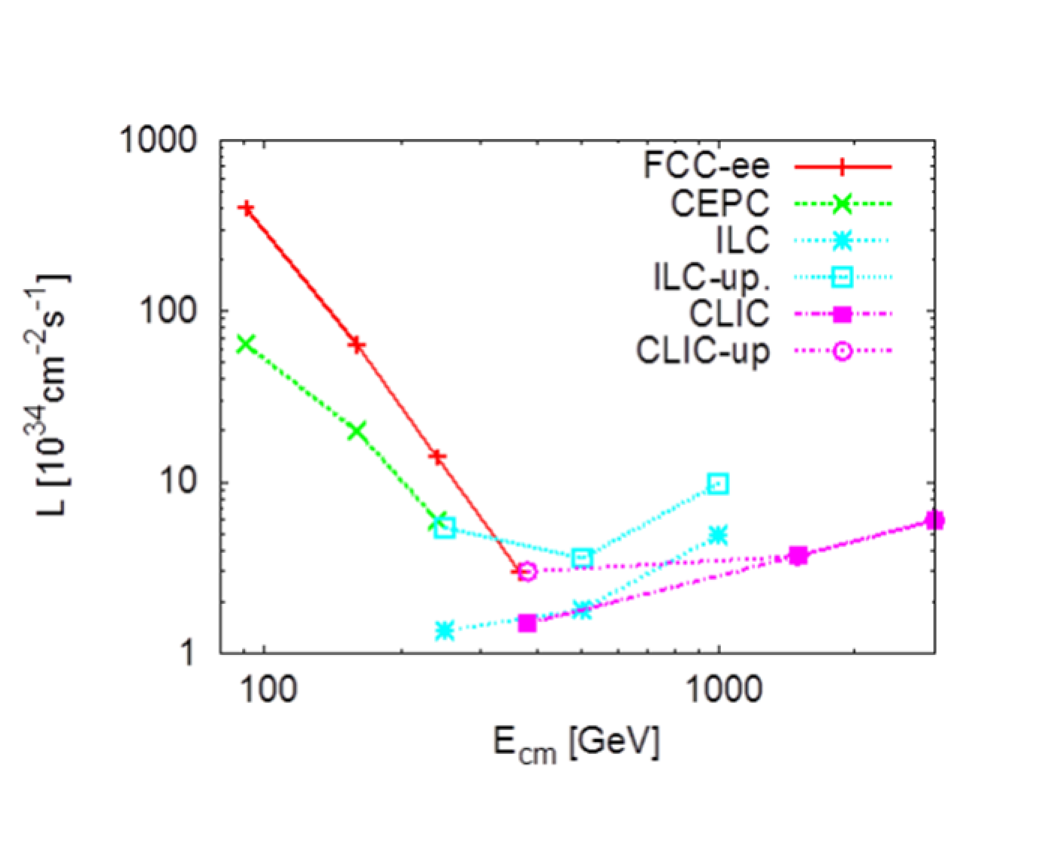
- E ≈ 0.3 B R [TeV, T, km]

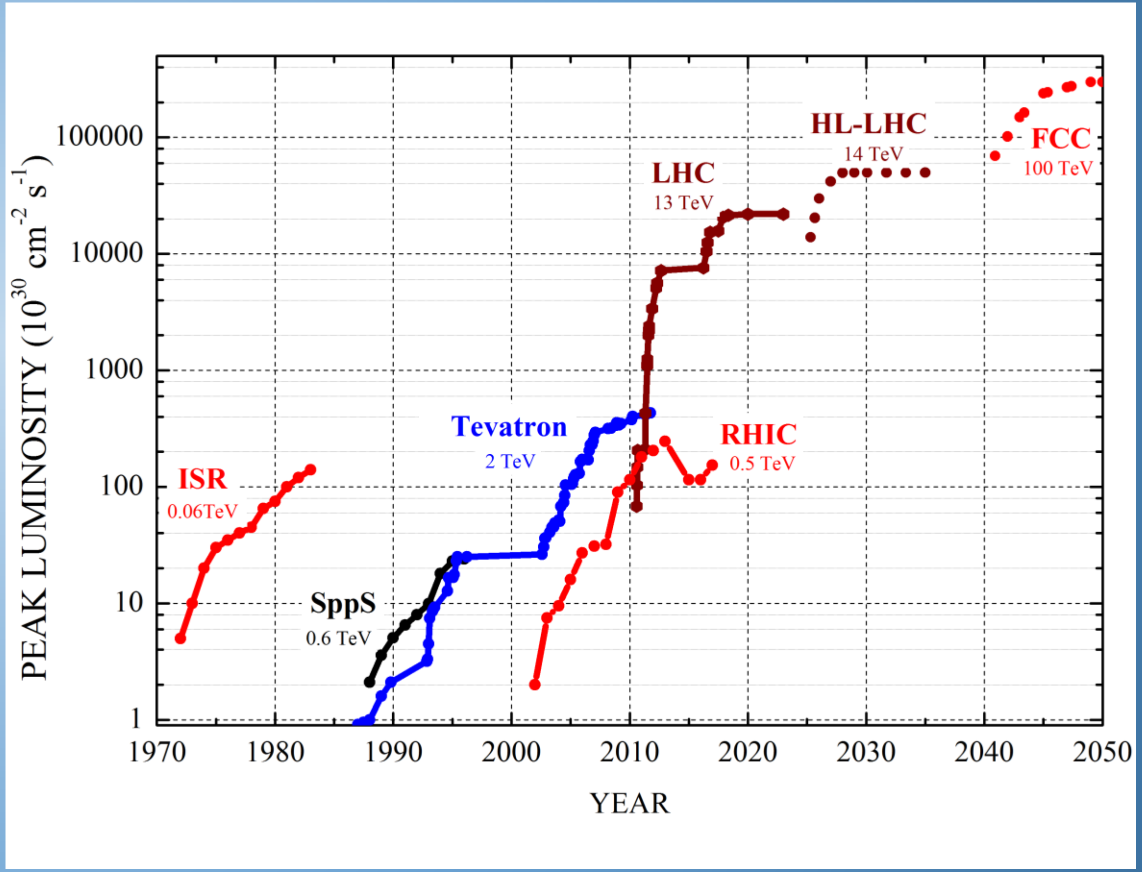


- E = E L [GeV, MV/m, km]

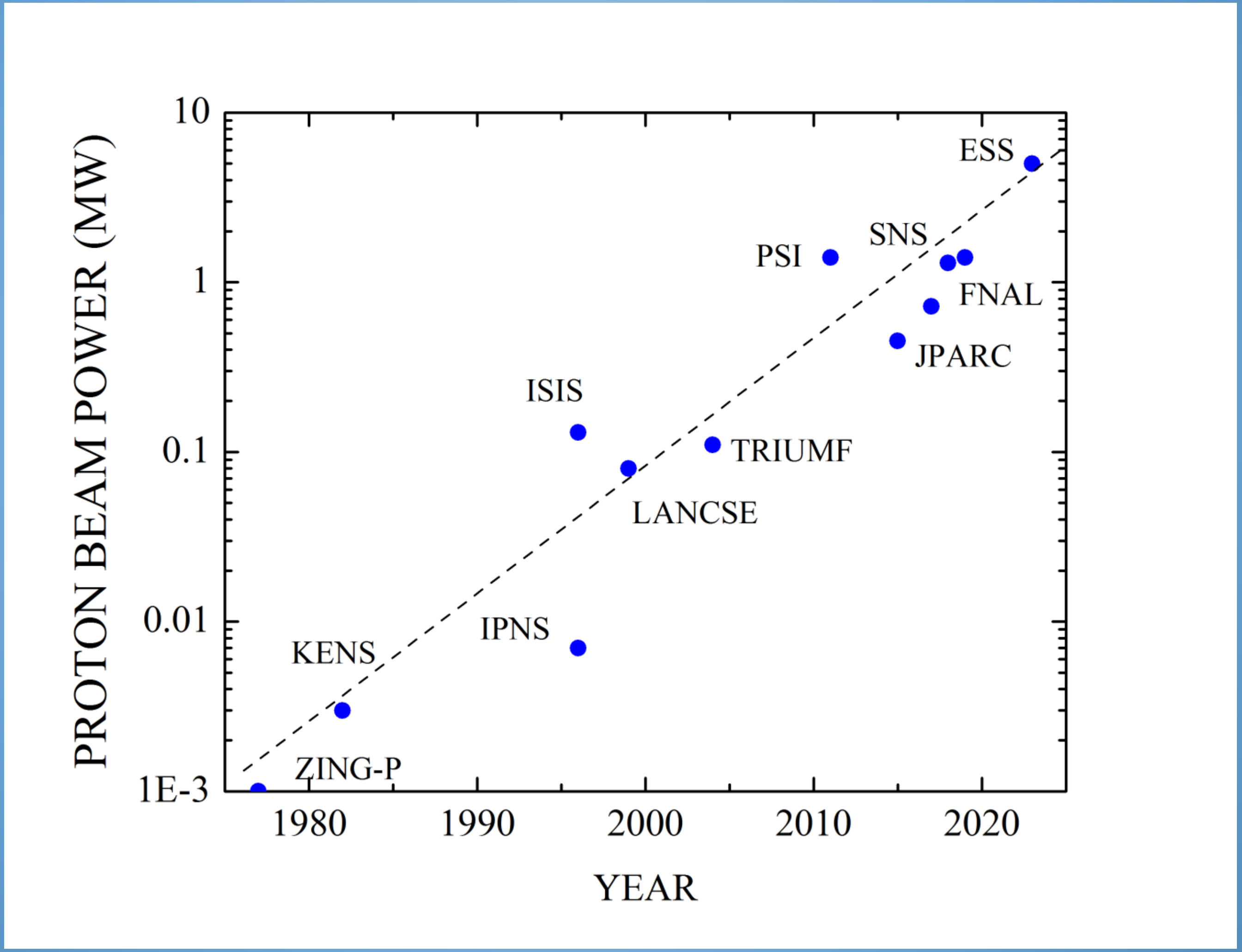


Energy is not all… Luminosity counts

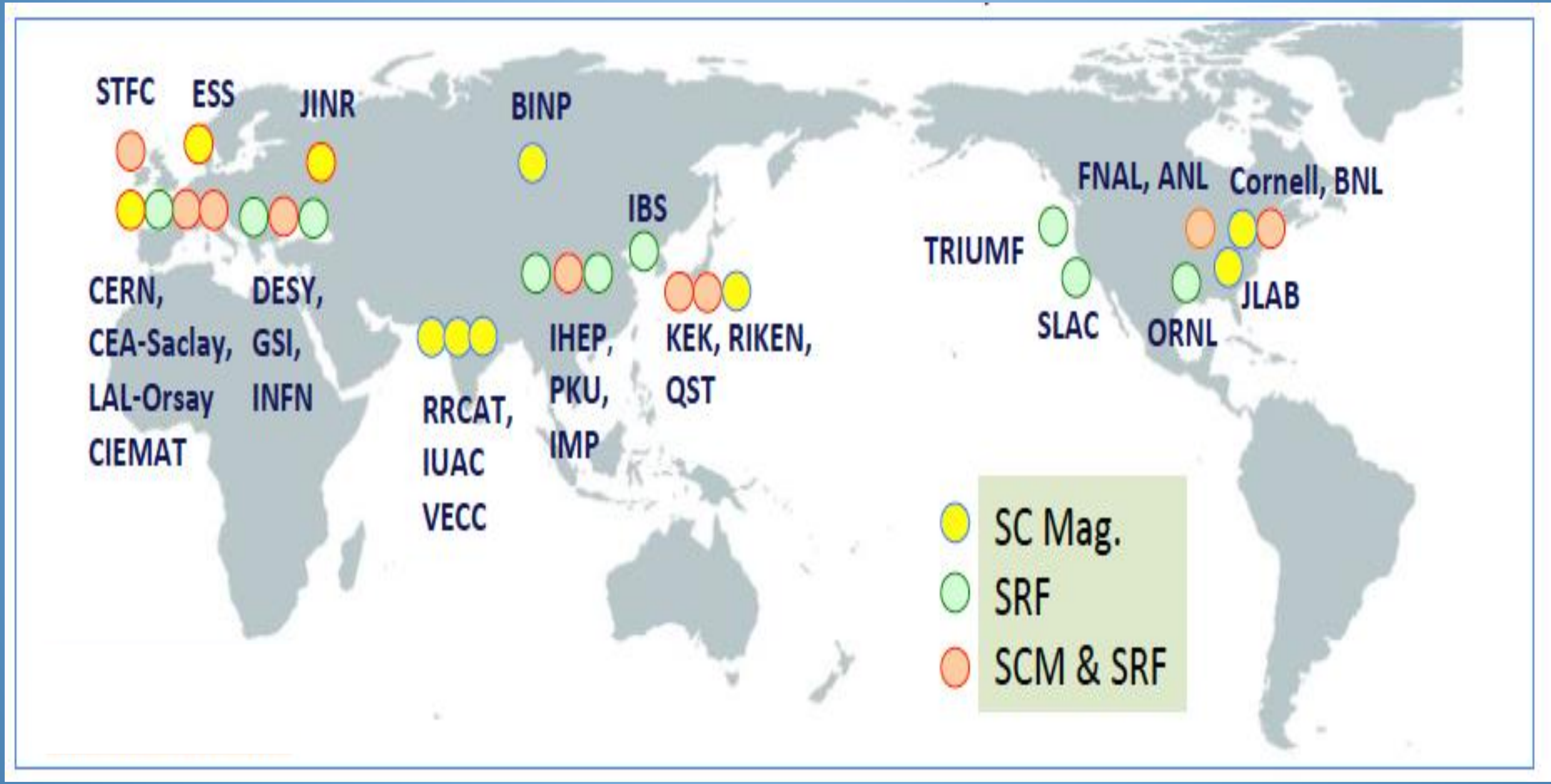




The intensity frontier



SC Magnets and SRF cavites are widely spread



Accelerator Technologies advanced in Particle Physics

Type	Acclerator	Op. Years	Beam Energy (TeV)	B [T]	E [MV/m]	Pioneering/Key Technology
CC hh	**Tevatron**	1983-2011	2 x 0.5	**4 T**		Superconducting Magnet (SCM)
	HERA	1990 -2007		**4.68 T**		SCM industry-manufac., e-p Collider,
	RHIC	2000 ~		**3.46 T**		SCM – low cost
	SPS **LHC** **HL-LHC**	1981-1991 2008 ~ Under constr.	2 x 0.42 2 x (6.5 >> 7)	**(NC mag.)** **7.8T -->8.4** **11~12**		P-bar Stochastic cooling **SCM (NbTi) at 1.8 K, SRF** **SCM (Nb_3Sn), SRF-CC, e-cooling**
CC ee	**TRISTAN**	1986-1995	2 x 0.03		**5**	**SRF** (Nb-bulk), SCM-IR-Quad (NbTi)
	LEP	1989-2000	2 x 0.55		**5**	**SRF** (Nb-Coating) , SCM-IRQ
	KEKB **Super-KEKB**	1998~2010 2018 ~	0.002+0.008 0.004+0.007		**5** **5**	Luminosity, **SRF** Crabbing, SCM-IRQ Luminosity, Nano-beam, SCM-IRQ
LC ee	**SLC/PEP-II**	1988/98~2009	2 x 0.5			**Normal conducting RF**
	(Eu-XFEL)	(2018 ~)	(0.0175)		**(23.6)**	**SRF HG** **(Nb-bulk)**

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Value [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10~20 (0.4 / 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 (~ 40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	< 5.3 > (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

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Major Technical Challenges:

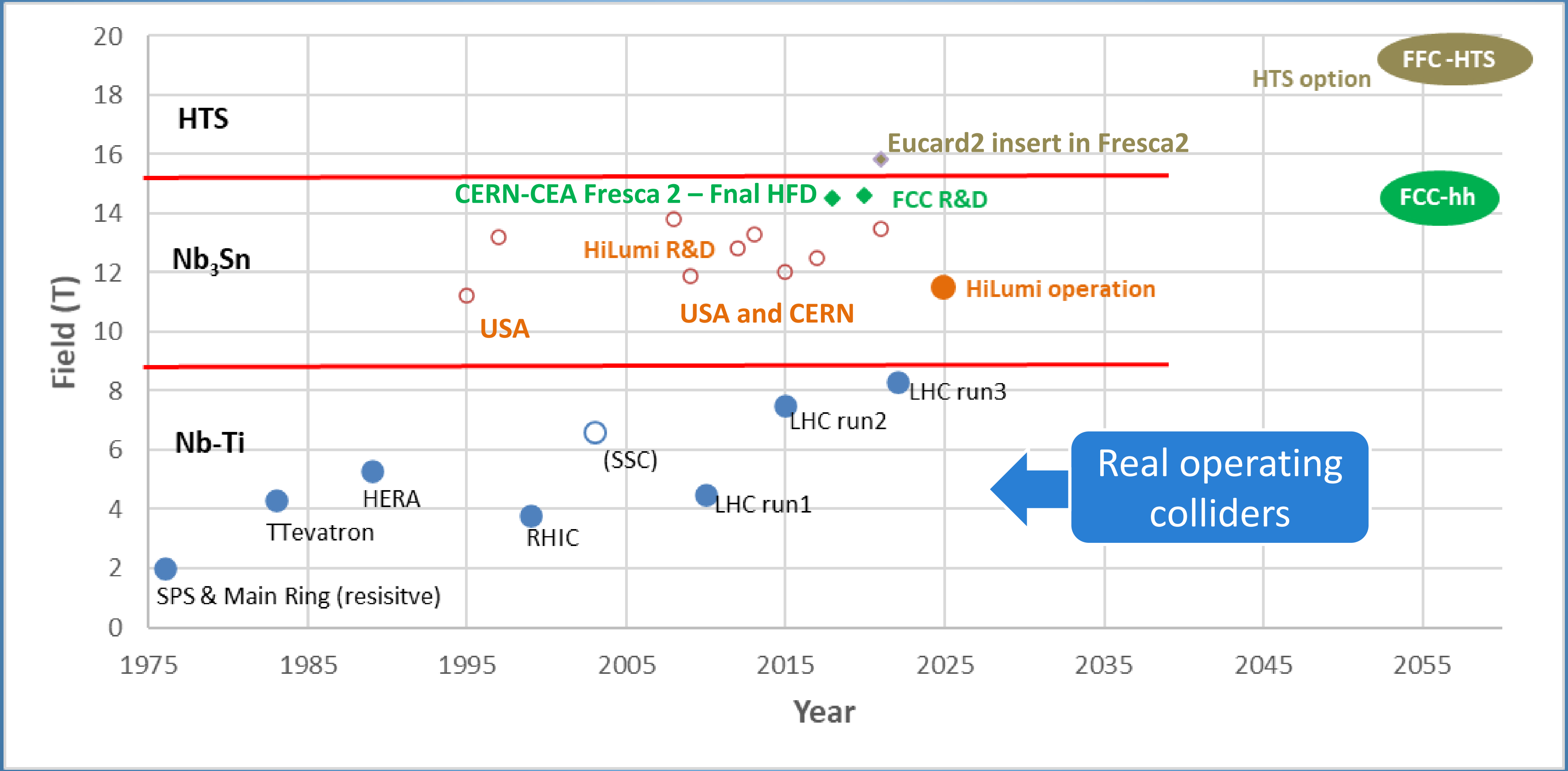
Hadron Colliders:

- High-field magnets - protection
- Energy management

Lepton Colliders:

- SRF cavity: High-G and Hig-Q
- NRF acc. Struct.: large scale, alignment, tolerance
- Energy management

Evolution of max magnetic field in hadron collider, past and future



Circular hadron colliders: FCC-hh and SppC

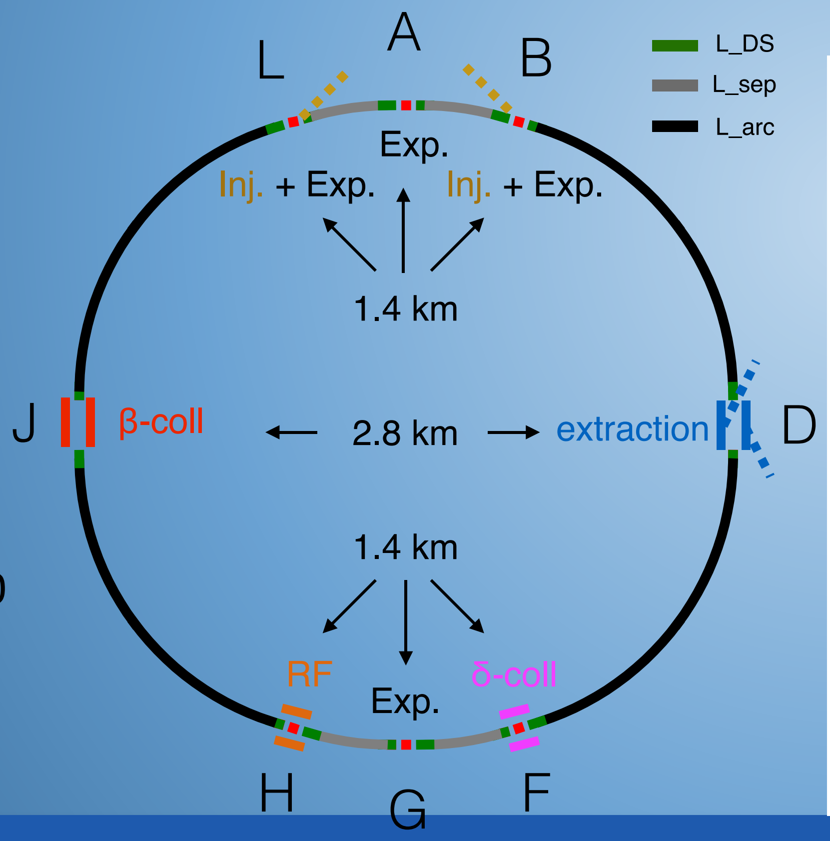
circumference ~100 km, two high-luminosity experiments up to 3 (1) x 10^{35} $cm^{-2}s^{-1}$, two additional experiments possibly combined with injection section, collimation insertions (betatron and momentum cleaning), extraction/dump insertion, RF insertion,

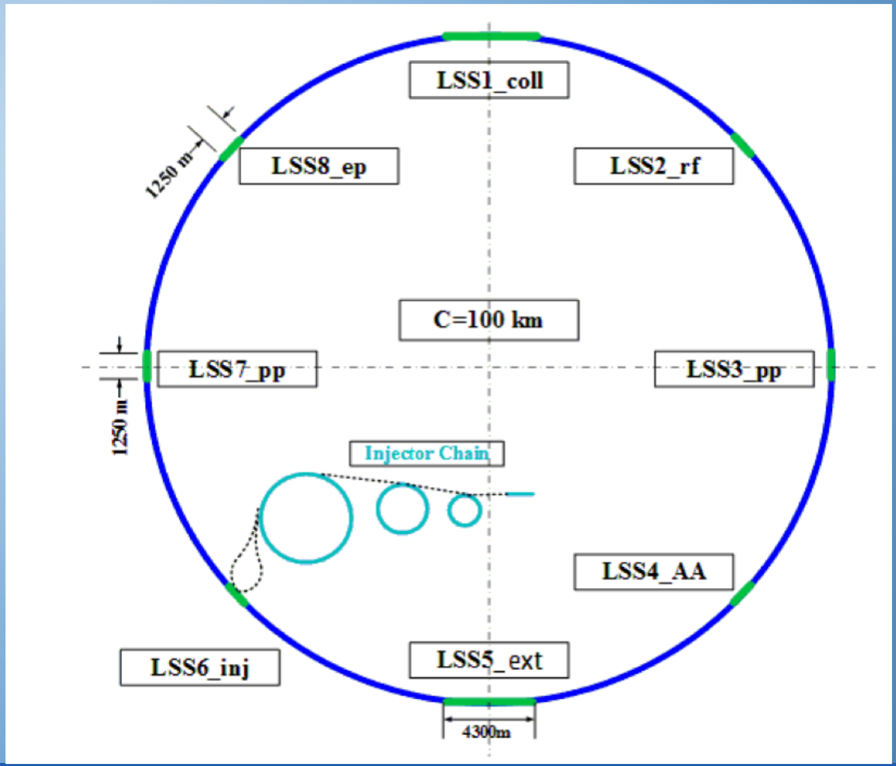
values in brackets refer to CEPC

FCC-hh

based on existing CERN injector chain,

Luminosity goal ~20 ab-1 per main IP within 25 years





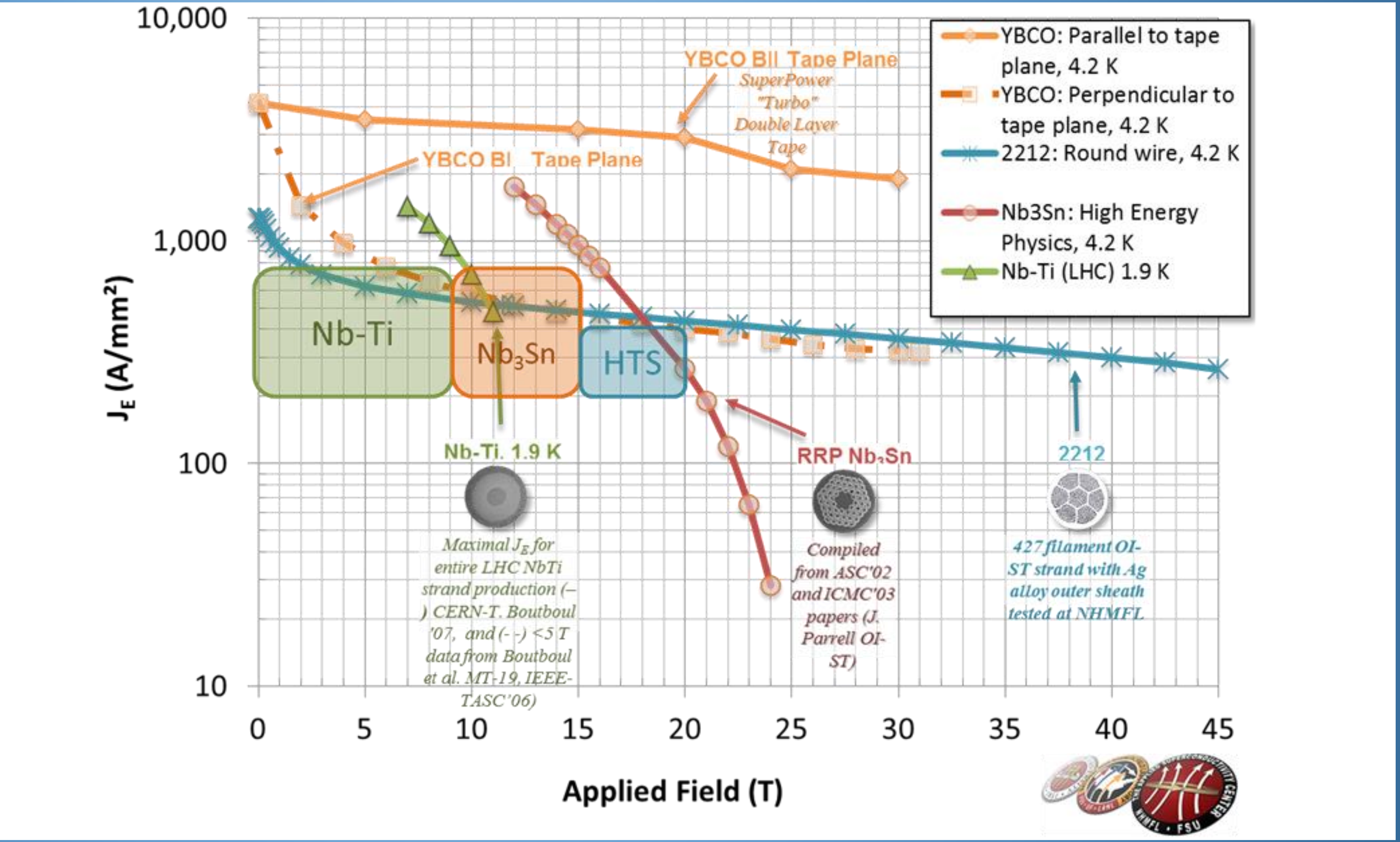
SppC

new injector chain,

simultaneous operation with e+e- collider

The key for Sc magnets: SUPERCONDUCTOR

A SC magnet cannot be better than its superconductor…
But it can be much worst…

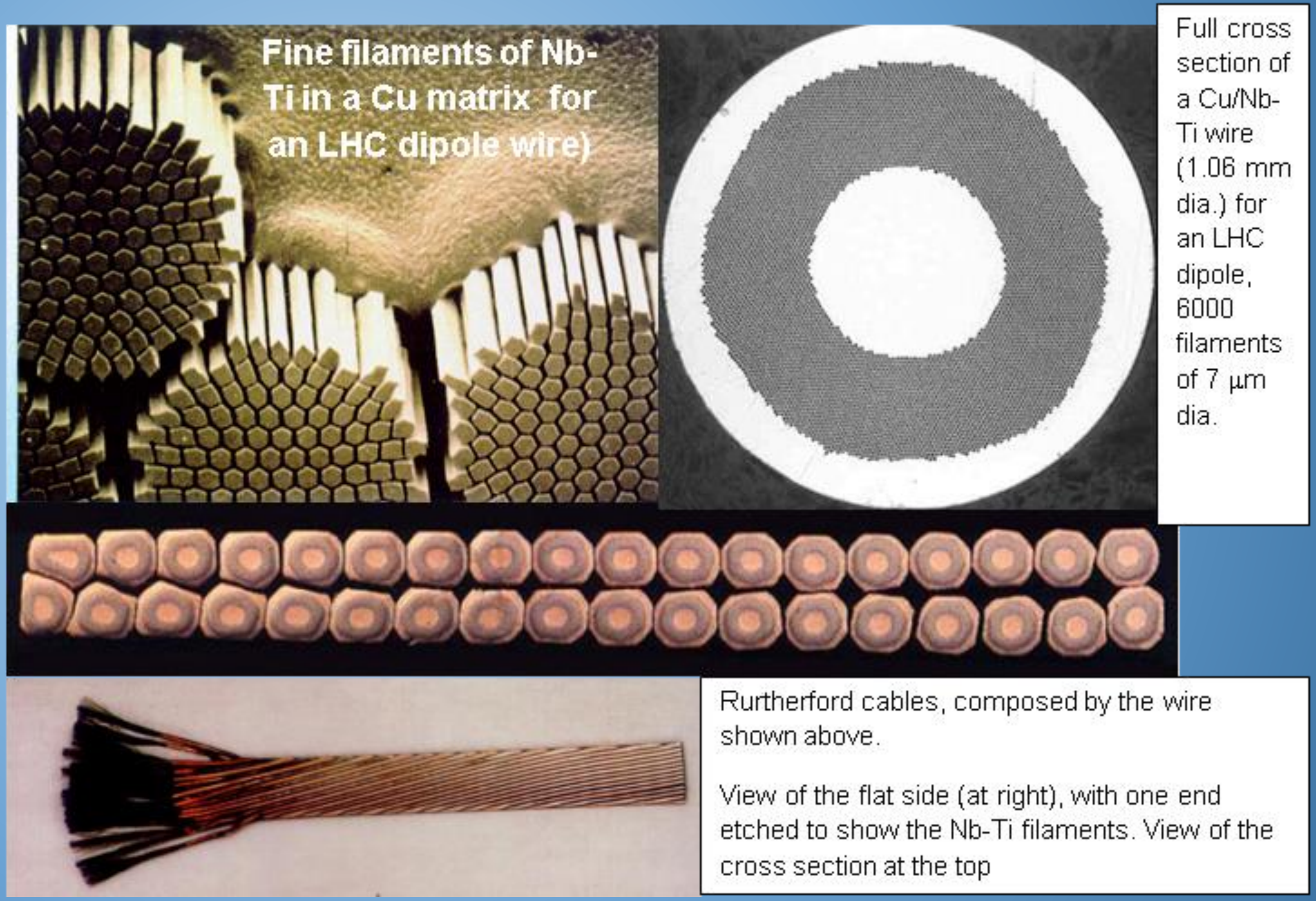


The perfection of the LHC Nb-Ti

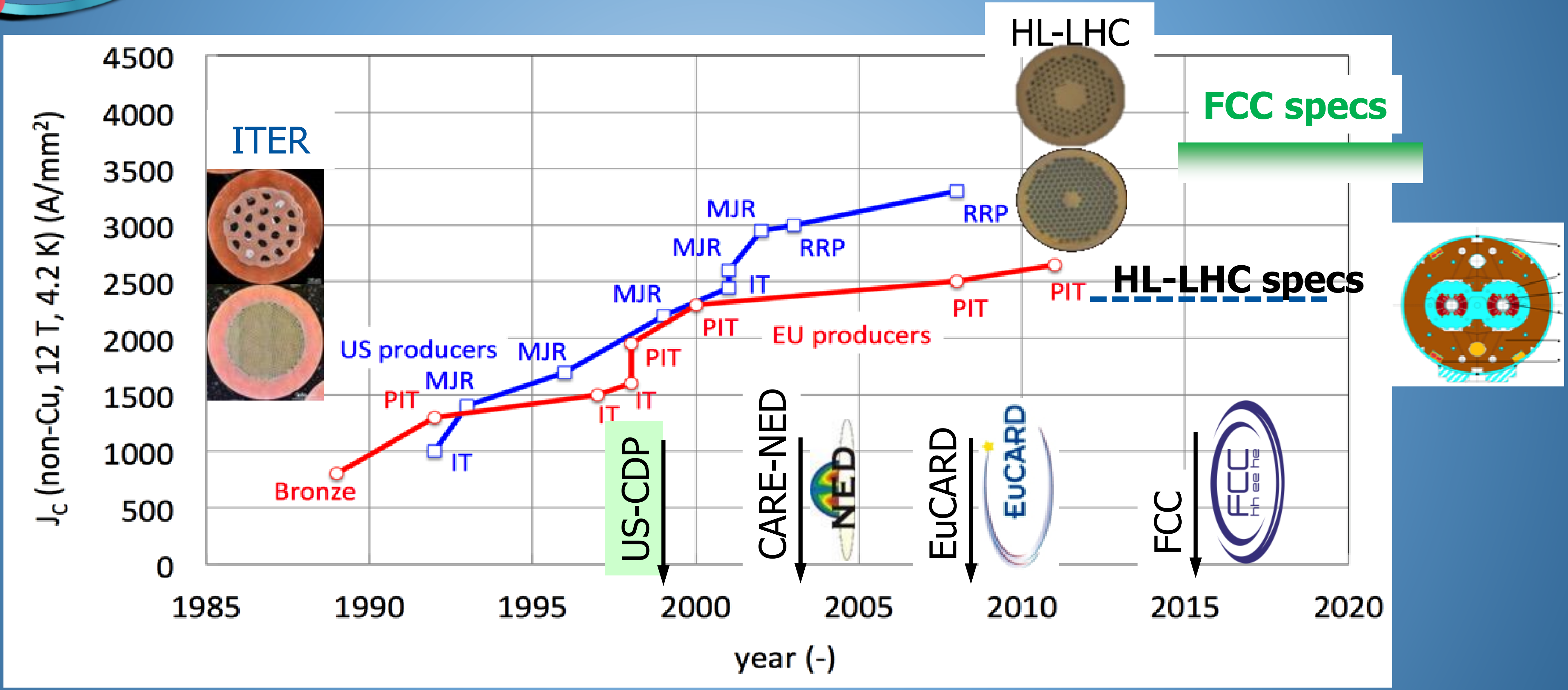
There are 300,000 km of 1 mm SC wire in the LHC , arrangd in 7,000 km of Rutherford cable

Each wire contains 5-7,000 6 μm Nb-Ti filaments … 1 μm spaced!

> 2 billions km of filaments → eight the round trip Earth-Sun!



How Nb_3Sn is developing

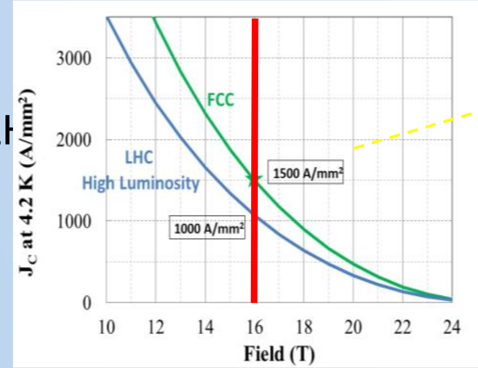


Progress of HEP Nb_3Sn

- **A**rtificial **P**inning **C**enter (**APC**) approach reached: **J_c** (16T, 4.2K) **~ 1500 A/mm²**
- **Mas-Production** and **cost-reduction** is yet to come !!

Main development Target:

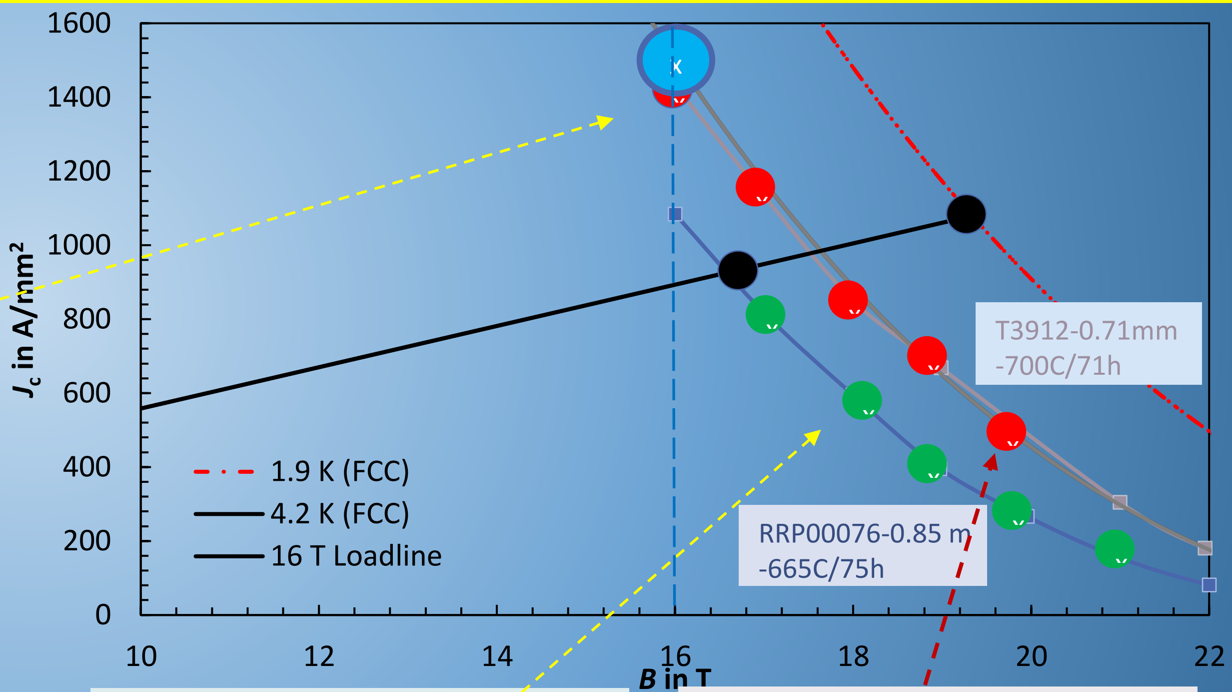
- **J_c (16T, 4.2K) > 1500 A/mm²**
  - 50% higher than HL-LHC



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
- US-DOE-MDP, Fermilab

A. Ballrino et al., ASC-2018, DOI 10.1 109/IEEE TASC-2019, 2896469.

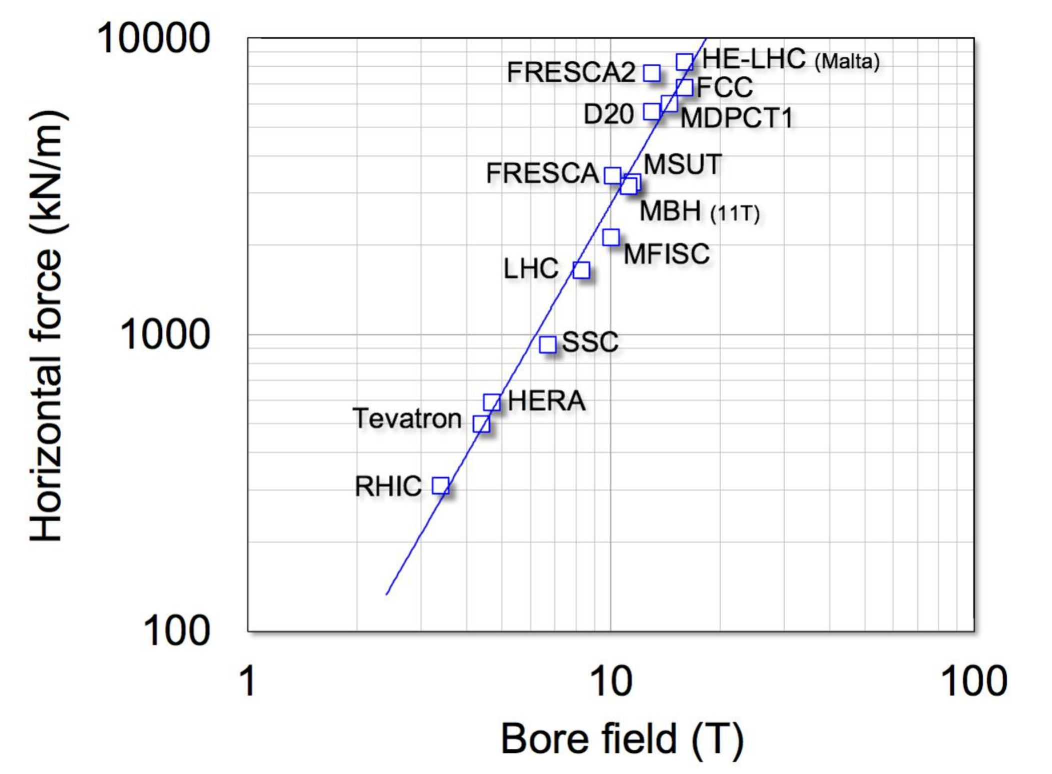


- Achieved by a ternary approach: K. Saito/T. Ogitsu et al. (JASTEC/KEK)

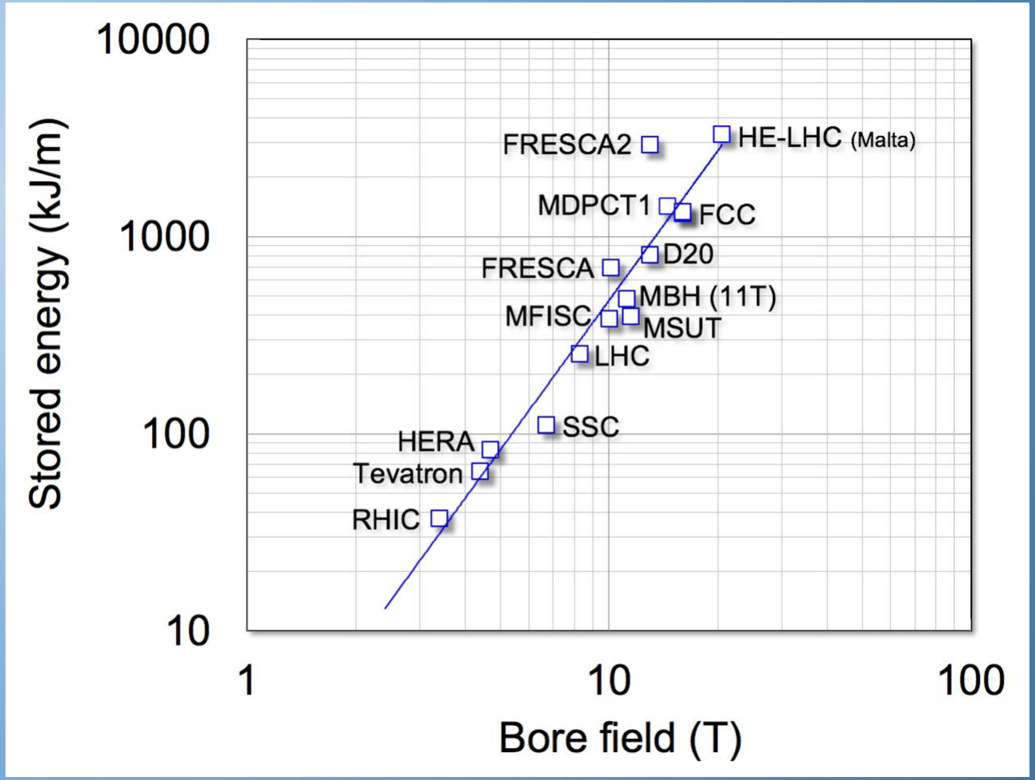
● Achieved by APC approach: X. Xu et al (Fermilab)

Main indicators for magnets scales as $\propto B^2$

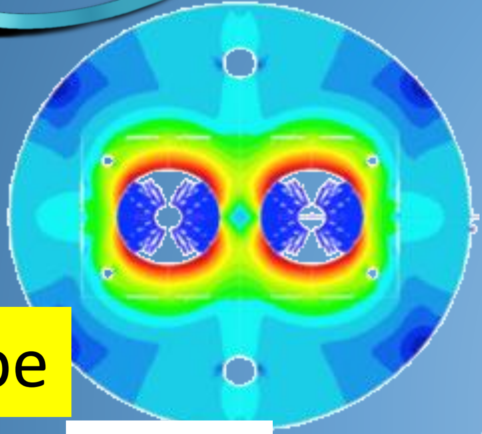
Compilation of e.m forces for various dipoles operating or future



Compilation of the stored energy for various dipoles operating or future

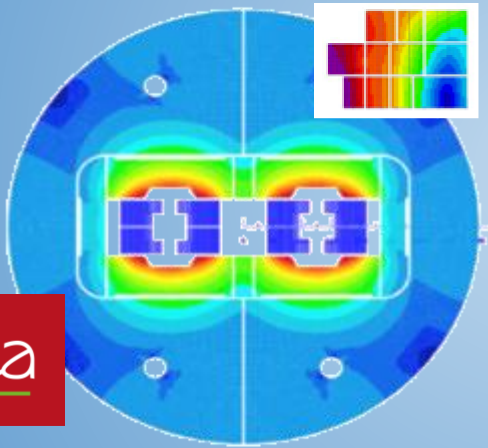


Cos-θ

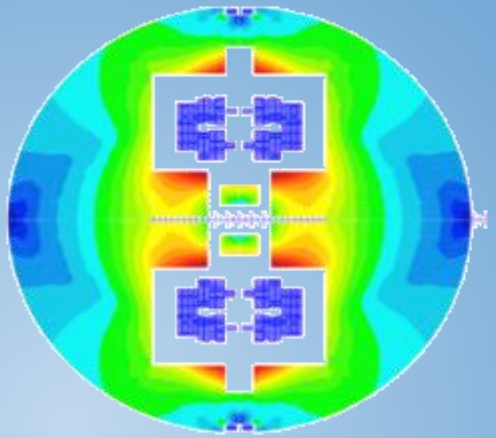


EuroCirCol
A key to New Physics

Blocks



Common coils



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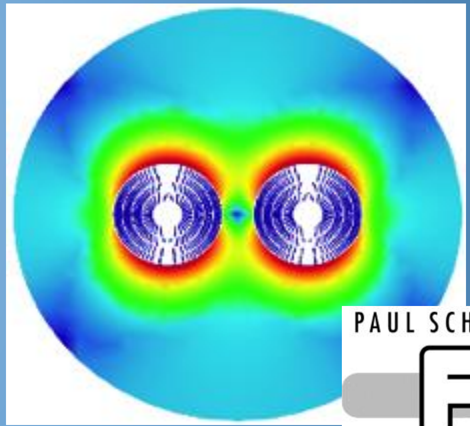
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CHART2
Swiss Acc. Research & Technology

Canted Cos-θ (CCT)



PAUL SCHERRER INSTITUT
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Europe

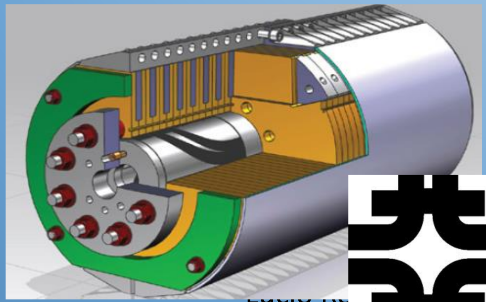
INFN

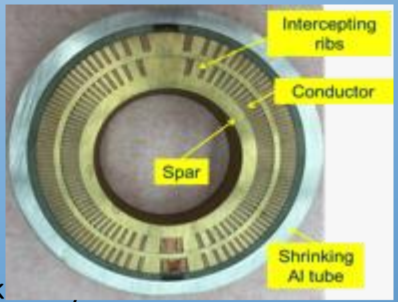
cea

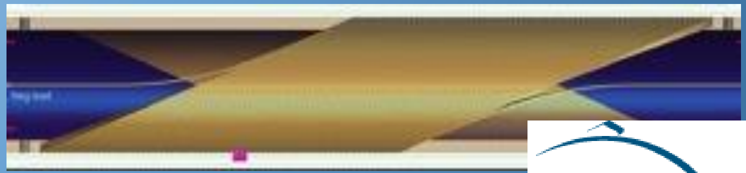
US

U.S. MAGNET DEVELOPMENT PROGRAM

Cos-θ



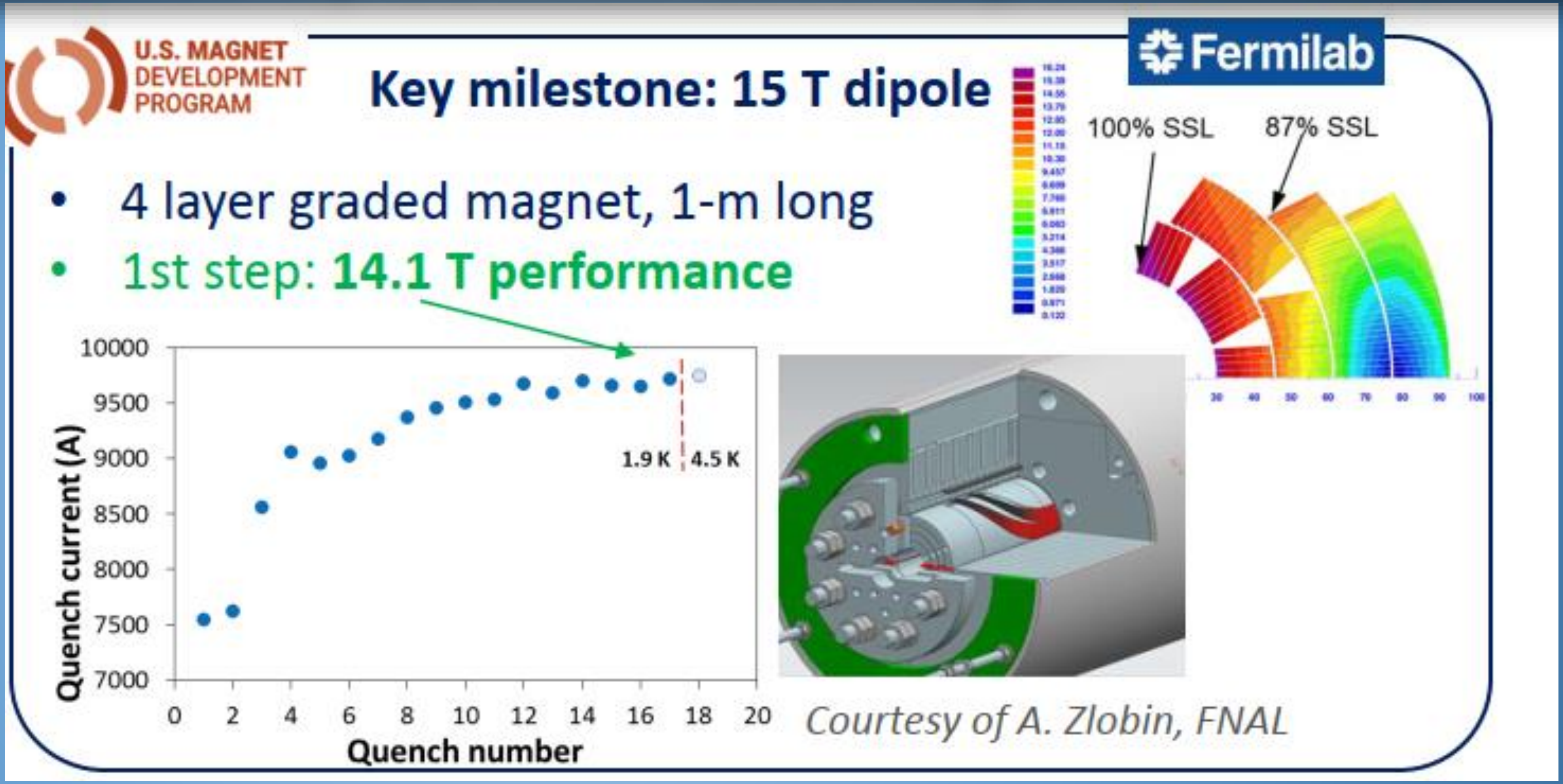




CCT,
Pioneering work at

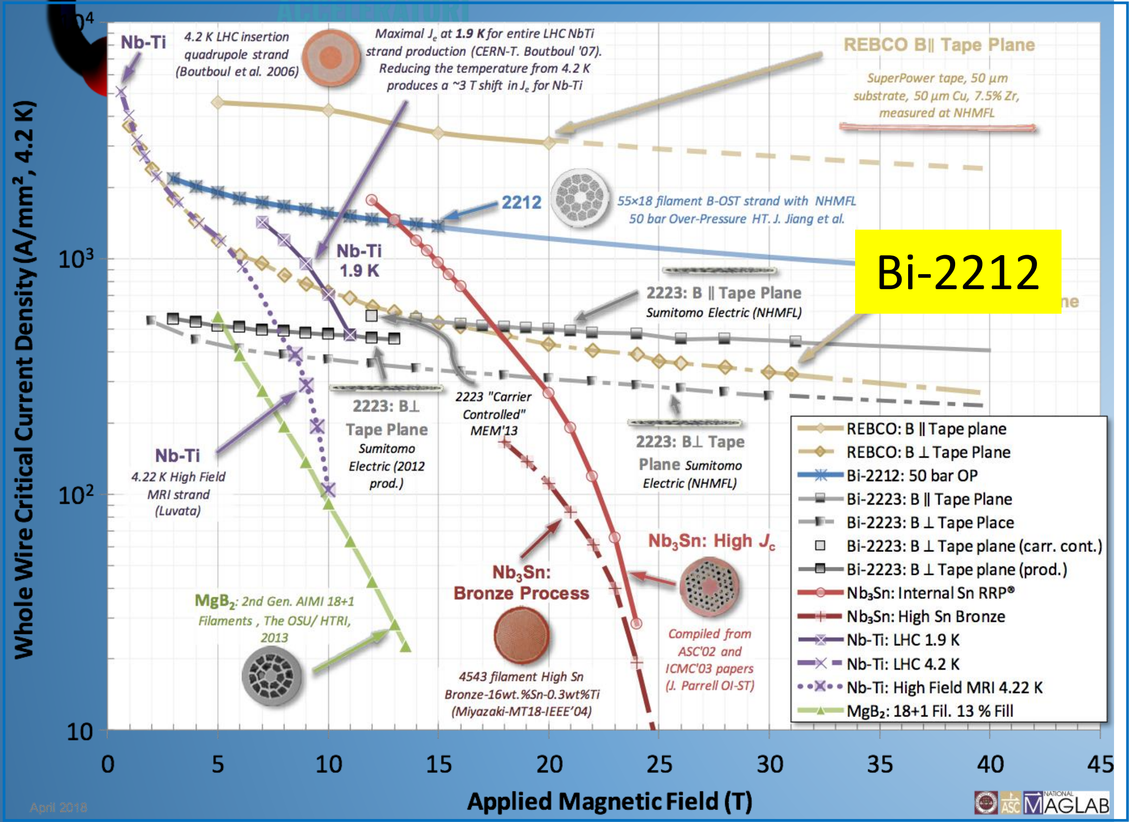
BERKELEY LAB

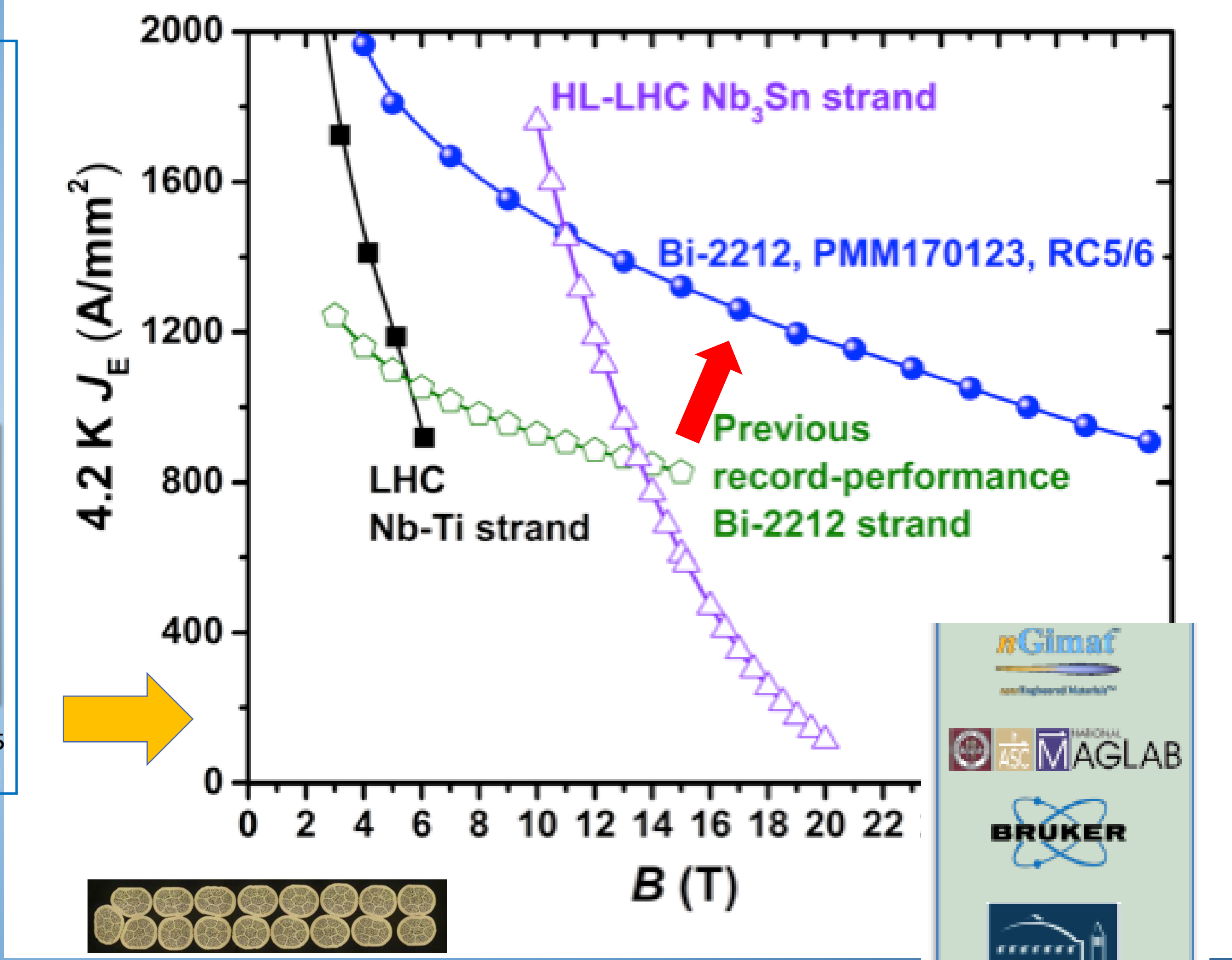
Recent very successful 14 T magnet reached by US MDP $\cos\vartheta$ dipole at FNAL



But the route is long… at > 15 T the magnet failed… a 16 T 100 km accelerator is not yet at hand...
In May 2020 in Budapest the new ESPP whas been approved…
Now the roadmap is being discussed by LDG to be presented to CERN Council next weeks…

HTS, focusing on Bi2212 in the US



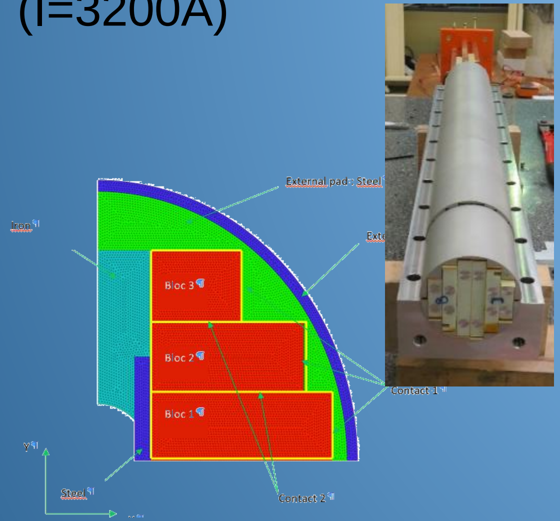


Application expected for CCT by using B2212

Three HTS/Rebco Inserts (CERN-Europe Cooperation)

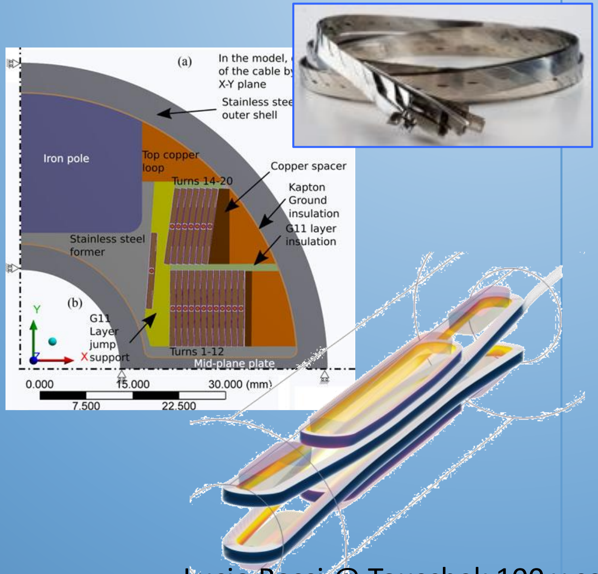
<u>EuCARD1: insert</u> (CEA-CNRS-CERN),

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



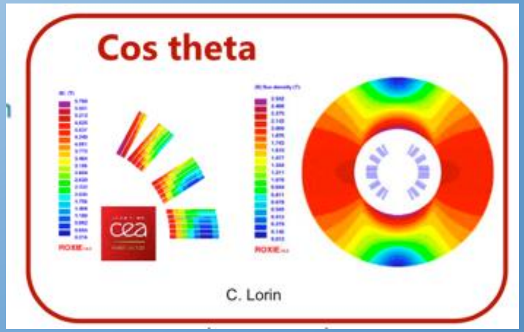
<u>EuCARD2: Feather-M2</u> (CERN),

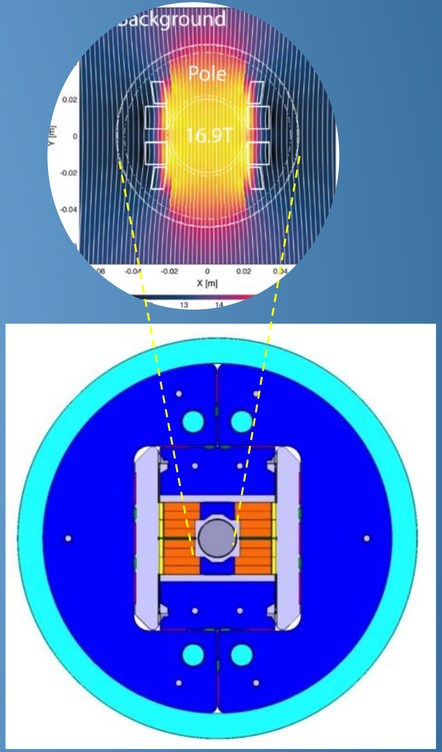
flared Ends coil
ReBCO, Roebel cable,
stand alone tested Apr 2017:
Reached 3.37 T @ 4.2K (I=6500A)



<u>EuCARD2: cosΘ insert</u> (CEA),

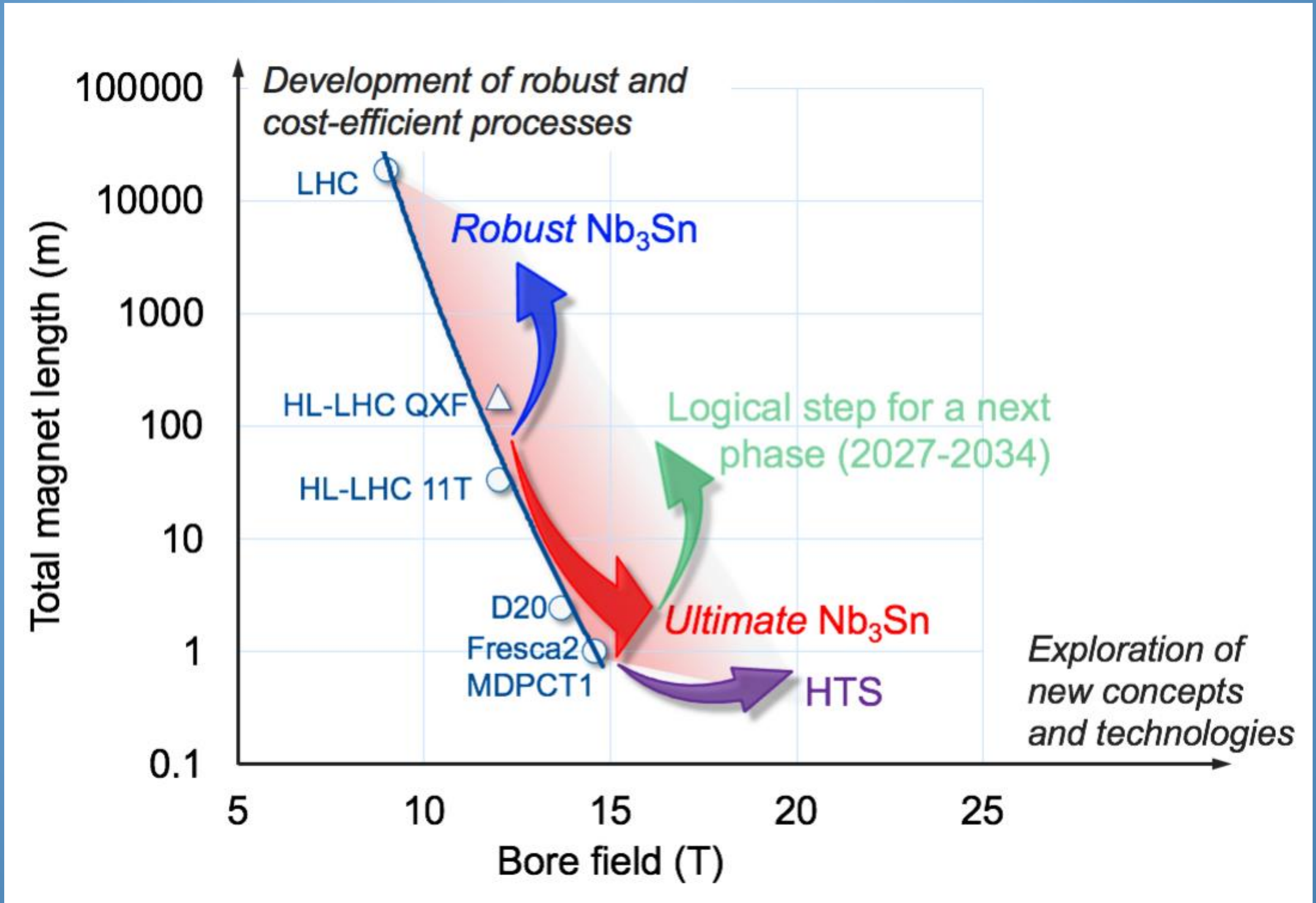
cosΘ coil,
ReBCO, Roebel cable,
being fabricated,
stand alone test in autumn 2019





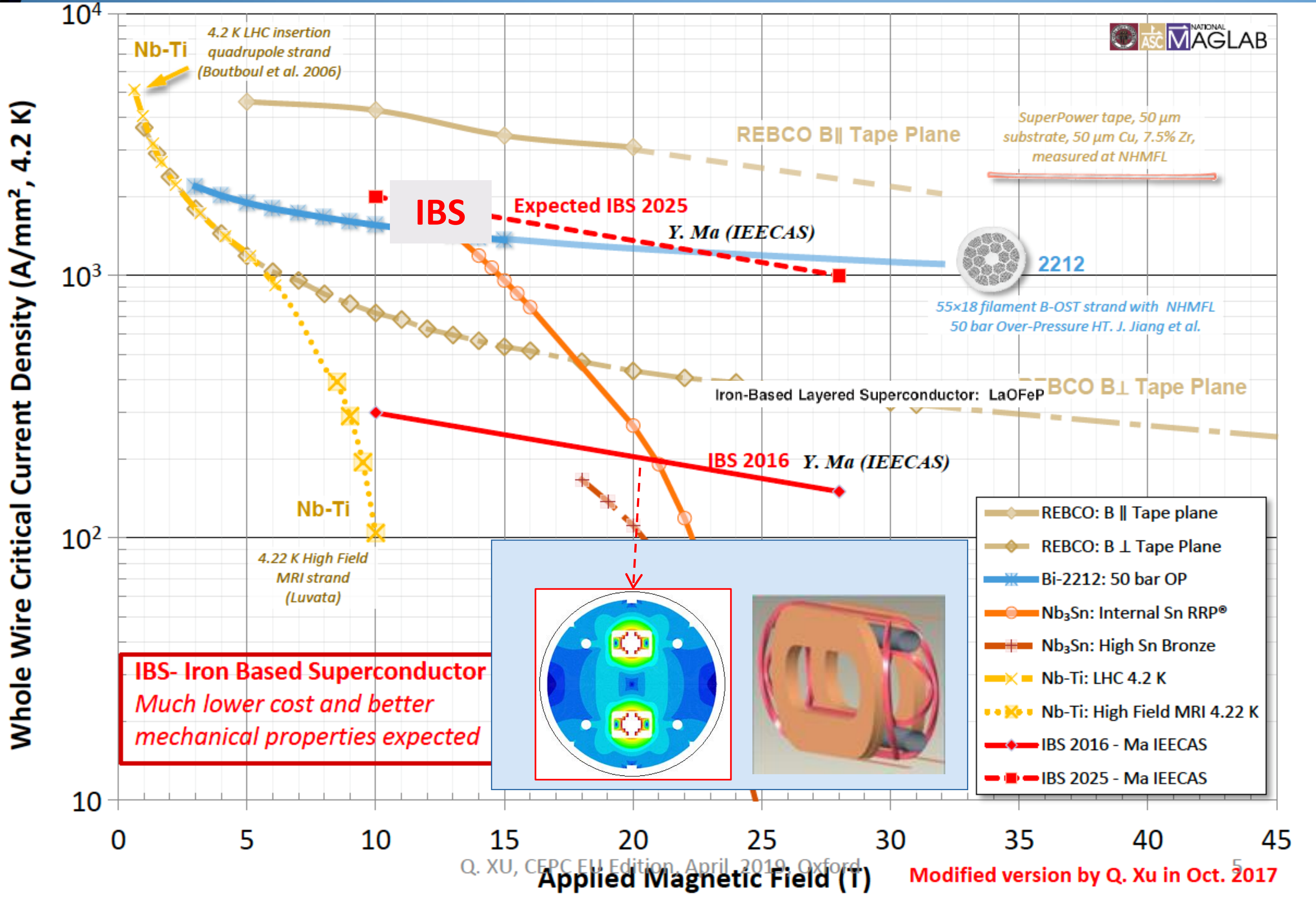
Eucard2+ HTS-insert tested in 2019:
3÷5 + 13÷15 = 16 T
Good not except.

Now the road should be well defined: technology challenge but also robutsness



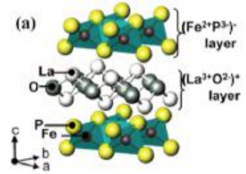
HTS/IBS SC and Magnet in China

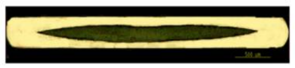
Courtesy, P. Lee, Q. Xu

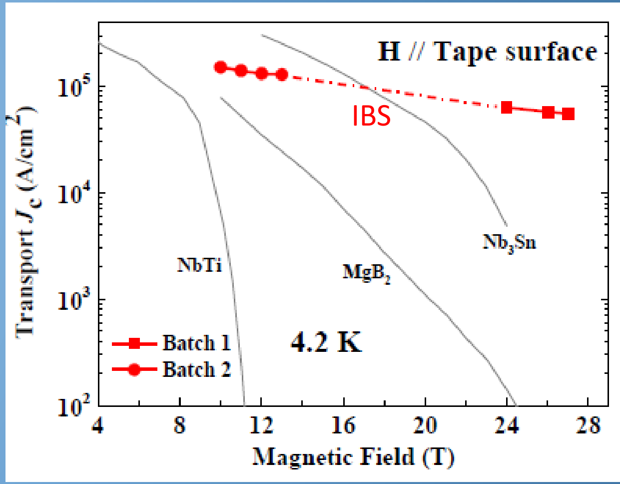


Y. Kamihara et al.,

Iron-Based Layered Superconductor: LaOFeP



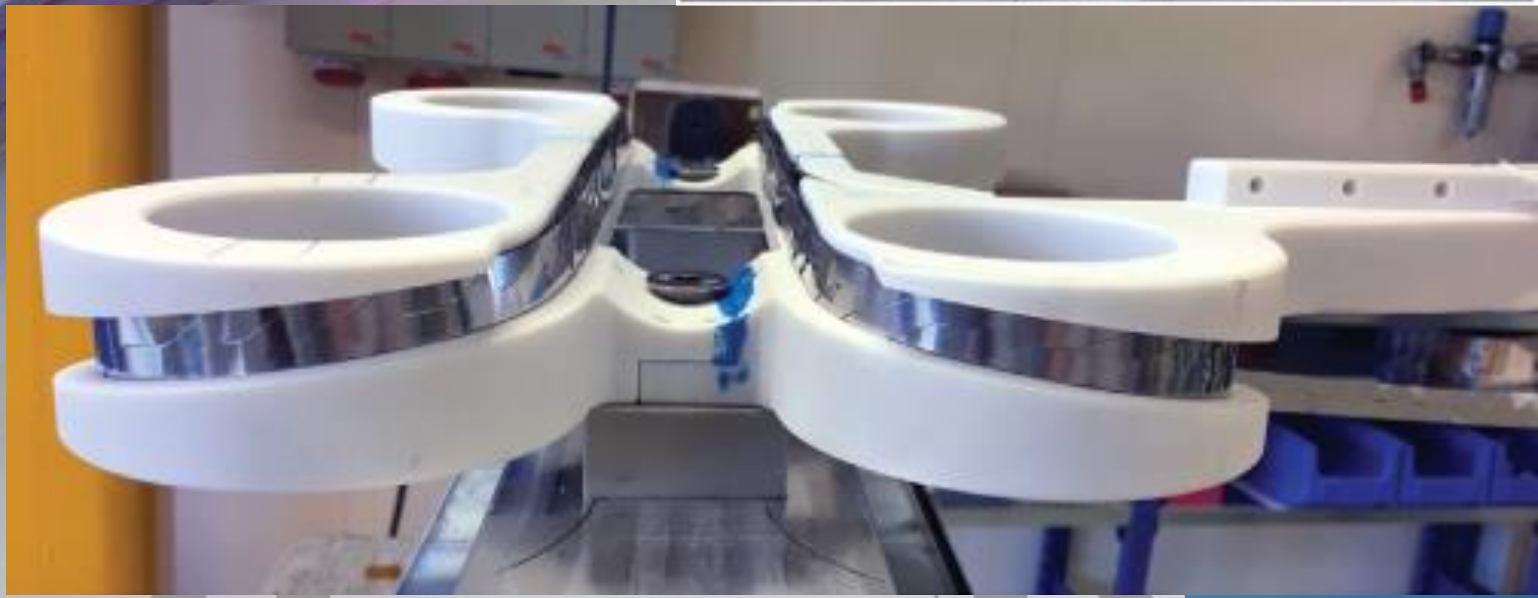




Y. Mao et al., Supercond. Sci. Technol. 31 (2018) 015017

Iron Based Superconductor (IBS) development in China toward 12 --> 24 T

Innovating: HTS magnets of the future … 20 tesla or more...



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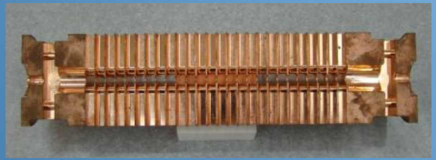
A. Yamamoto, 190512c

Courtesy: W. Wuensch

Normal | Super

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



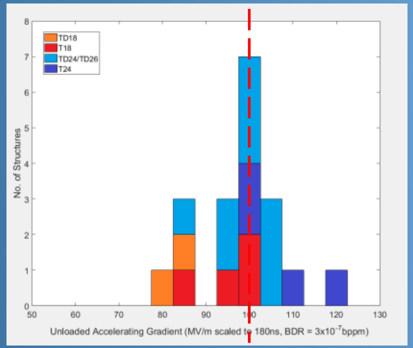
Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

Components:

Laboratory with commercial

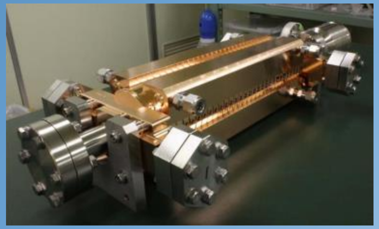
- Accelerating structures
- pulse compressors
- alignment
- Stabilization, etc.



~ 100 (+/-20) MV/m

Full commercial supply

- X-band klystrons
- solid state modulator,



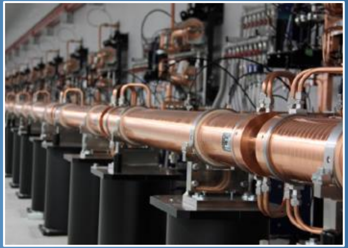
Systems Facilities:
(100 MeV-range)

- 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**
- **SwissXFEL (8 GeV)**

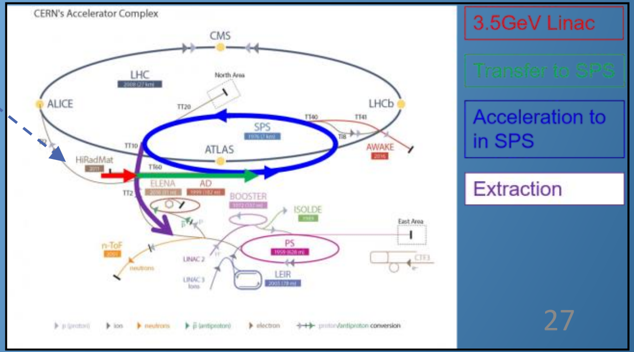


X-band (12 GHz)
GeV-range facilities

Planning:

- **Eu-Praxia**
- **e-SPS**
- **CompactLight**

CLIC



Advances in SRF Technology for Accelerators

<u>Progress (1988~)</u>
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

<u>In Operation: → # cavities</u>
- **SNS: 1 GeV**
- **CEBAF 12 GeV → 80**
- **ISAC-II, ARIEL**
- **Super-KEKB**
- **Eu-XFEL → 800**

<u>Under Construction:</u>
- **LCLS=II → 300**
- **FRIB → 340**
- **PIP-II → 115**
- **ESS→ 150**
- **Shine → 600**

<u>To be realized:</u>
- HL-LHC-Crab → 20
- EIC

- **ILC-250 → 8,000**
- FCC
- CEPC/SPPS

1980

2000

2020

> **2,000** SRF cavities realized, in last 10 years !

Courtesy: R. Geng,

Advances in L-band (~ 1GHz) SRF Cavity Gradient

Field Gradient

Surface

Material

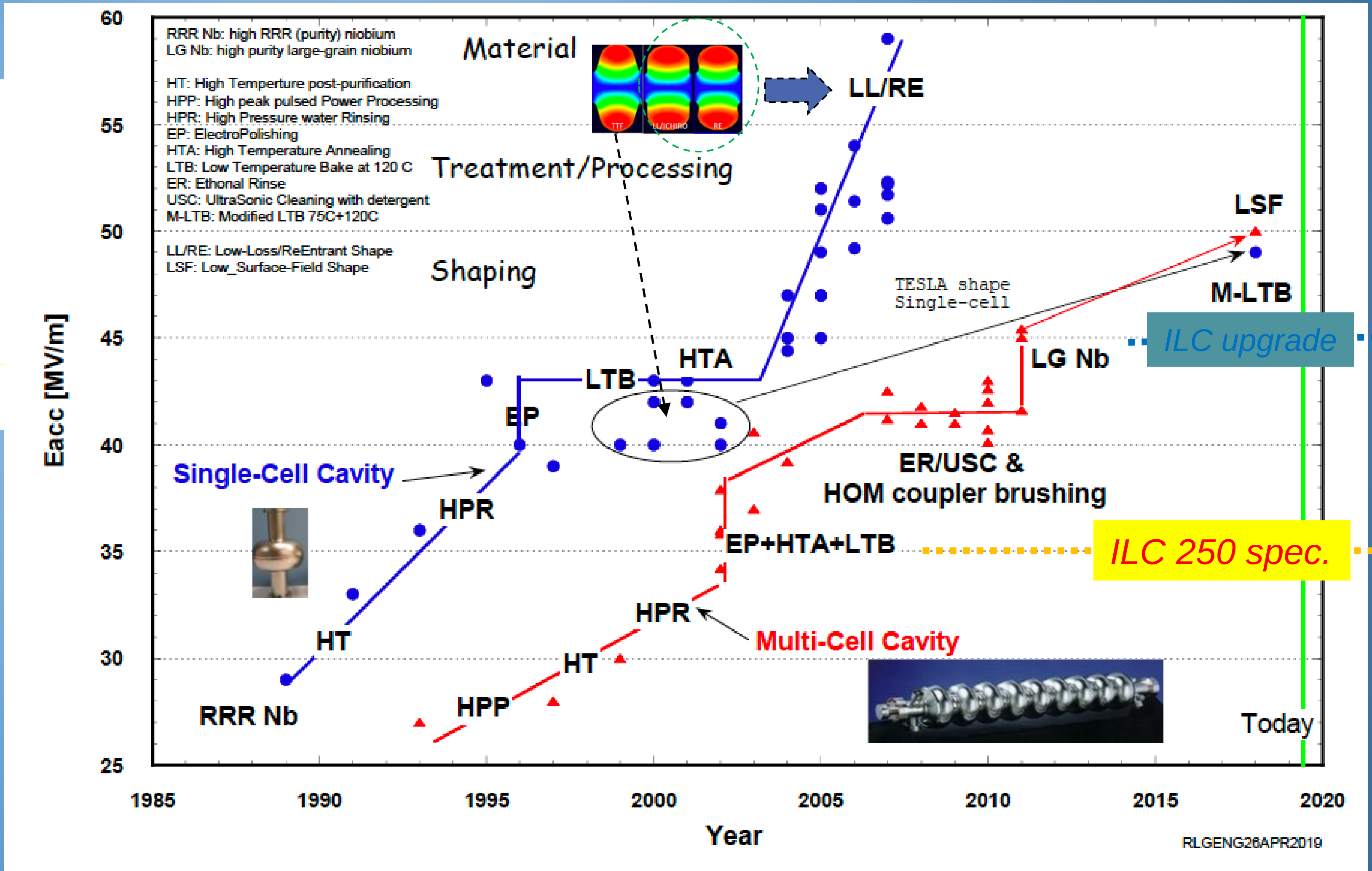
$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Thermal conductance

Surface,

Shape

See more, Appendix p.60.



European XFEL, successful in operation

URL: http://www.desy.de/news/news_search/index_eng.html

2018/07/17

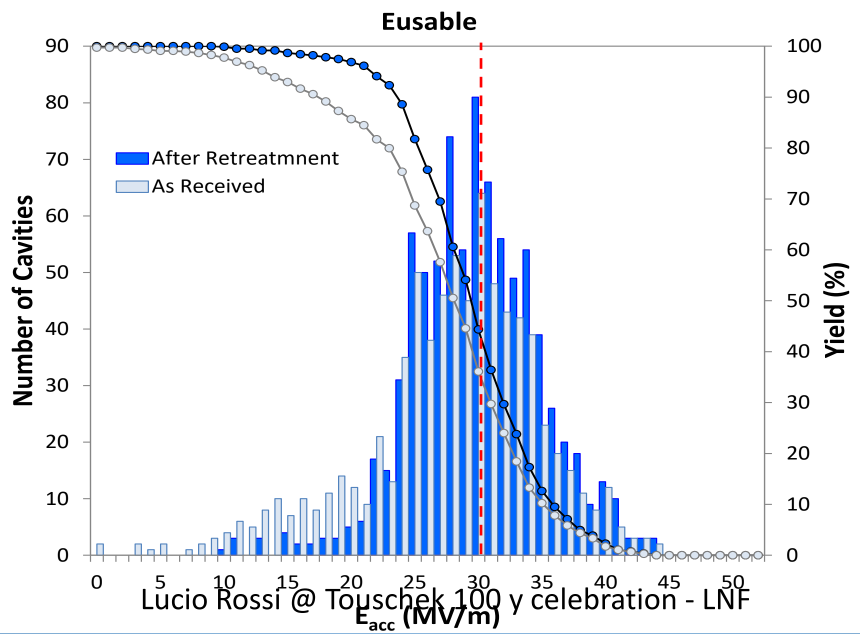
Back

European XFEL accelerator reaches its design energy

Accelerator accelerates electrons to 17.5 GeV for the first time

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)

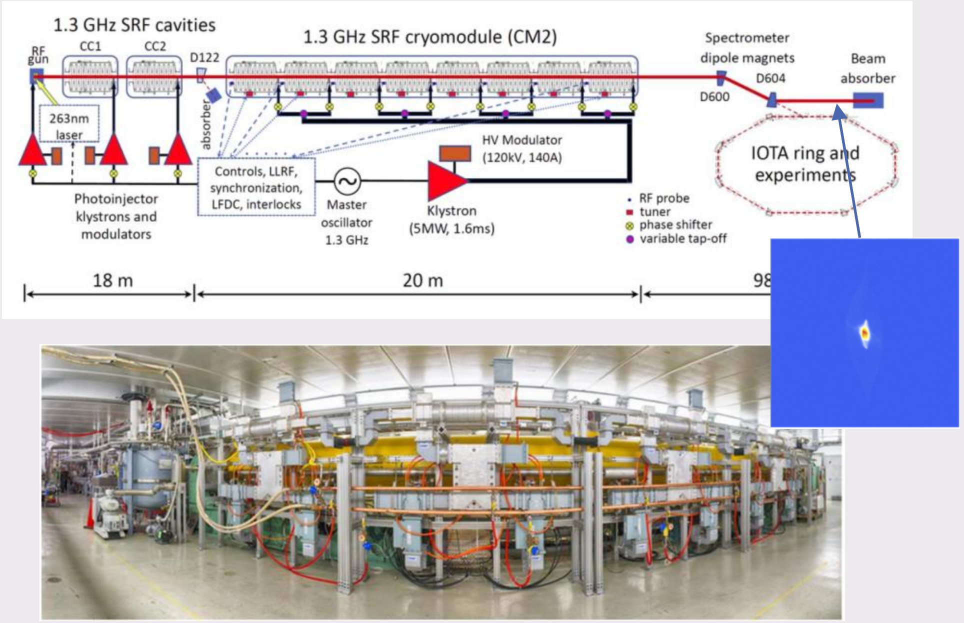
: ~ 1/10 scale to ILC-ML

After Re-treatment:

E-usable: 29.8 ± 5.1 [MV/m]

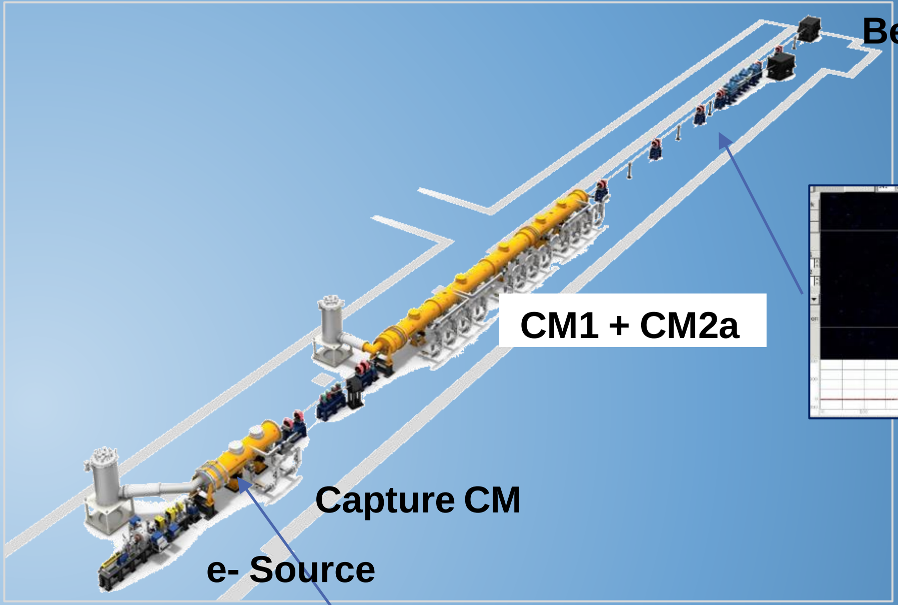
>10 % (47/420, RI) cavities exceeding 40 MV/m

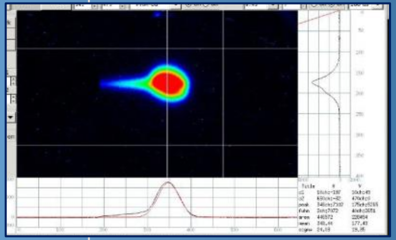
Fermilab, KEK achieving ILC Gradient Goal ≥ 31.5 MV/m with beam



Beam Acc. : 260 MeV by 8 Cavities,
<G> = 32.3 MV/m

Fermilab-FAST Progress, 2017



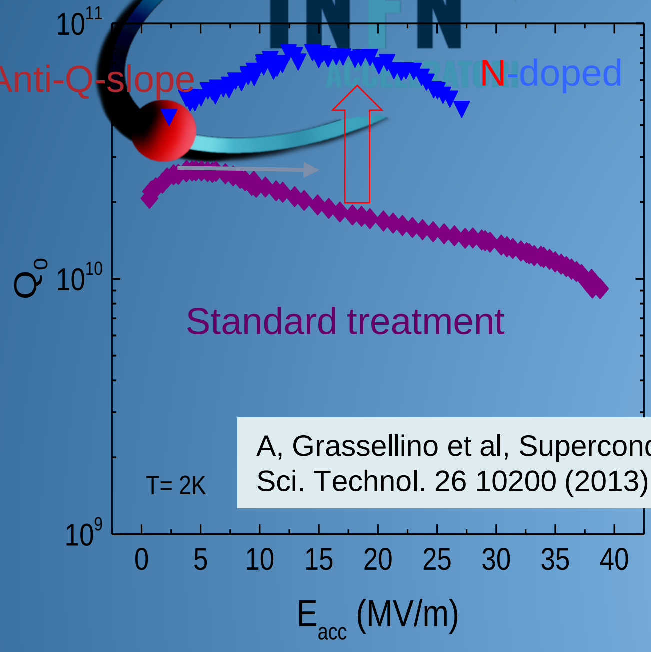


Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

KEK-STF2 Progress, 2019

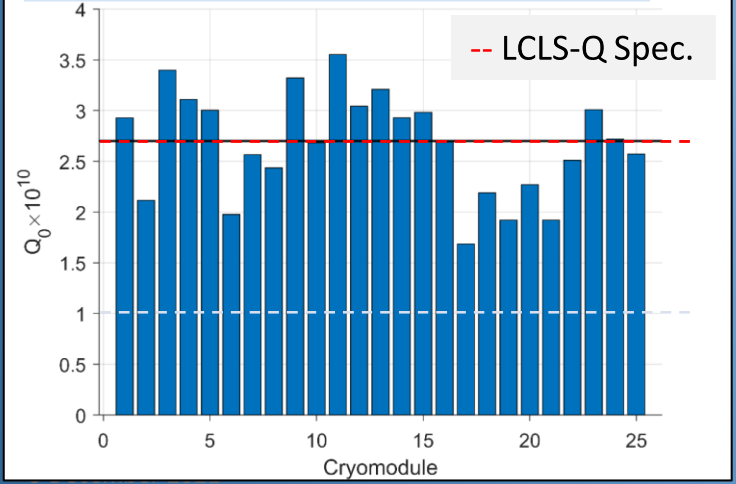
Courtesy, M. Ross

LCLS-II SRF Linac (SLAC/Fermilab/JLab Collaboration)



A, Grassellino et al, Supercond. Sci. Technol. 26 10200 (2013)

LCLS-II CM production in progress



1 km SCRF-CW Linac

- > x 2 **Q** achieved,
- N-doping at 800C,discovered by A. Grasellino et al.

SRF e-Linac Parameters

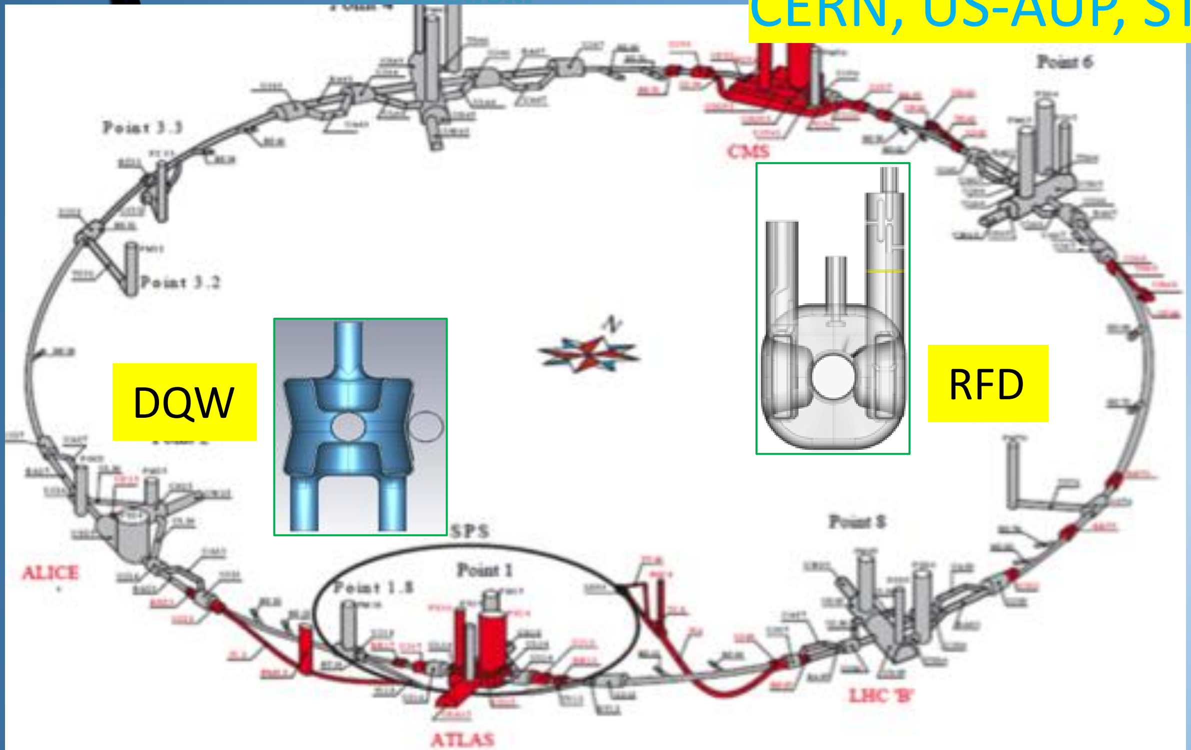
Beam: 4 (+ 4) GeV, up to 0.3 mA
SRF cavity:
- Frequency : 1.3 GHz, CW
- G: 18 ~21 MV/m
- Q: > 2.7 e10 (av.)
- # cavity = 280 (+160)
- # CM 35 (+20)

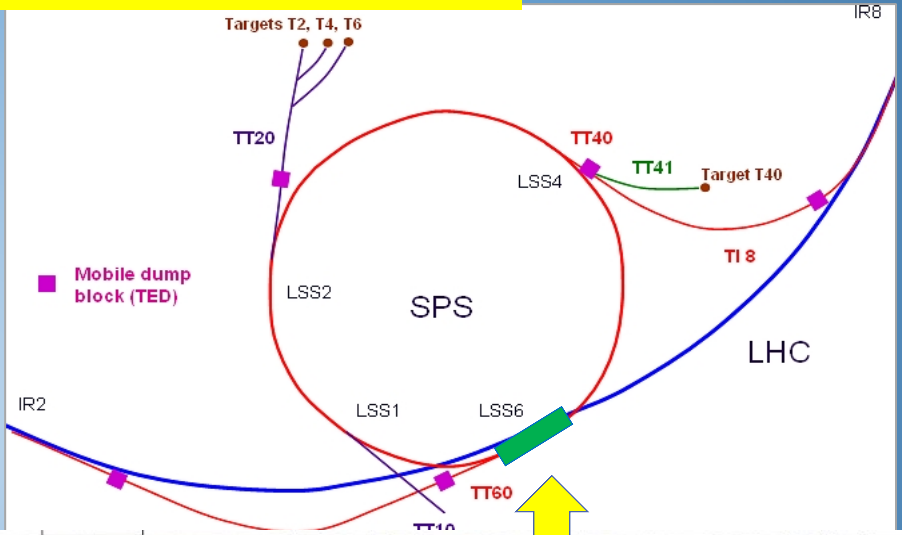
To be completed in 2020 (~2026)

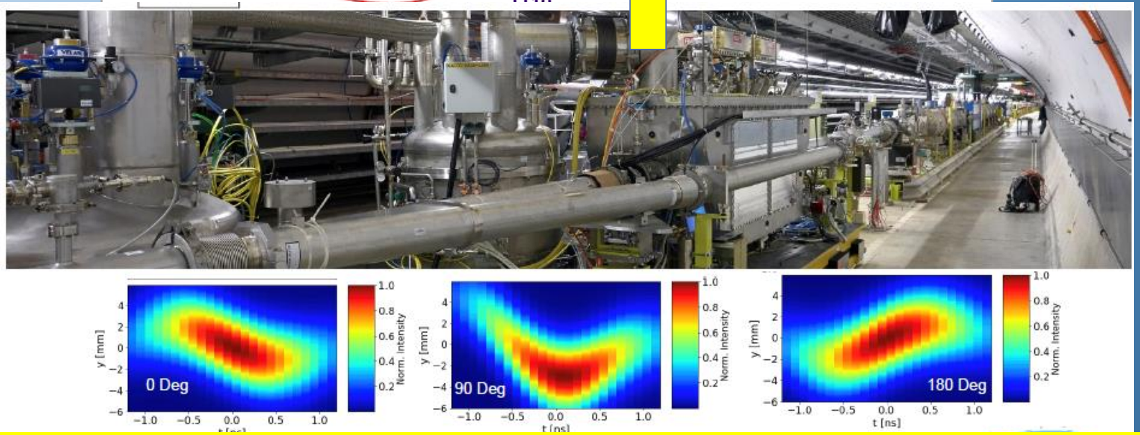
Nb SRF Crab Cavities for HL-LHC

CERN, US-AUP, STFC, TRIUMF Collaboration

Courtesy,
R. Calaga, O. Capatina,
A. Ratti, L. Ristori



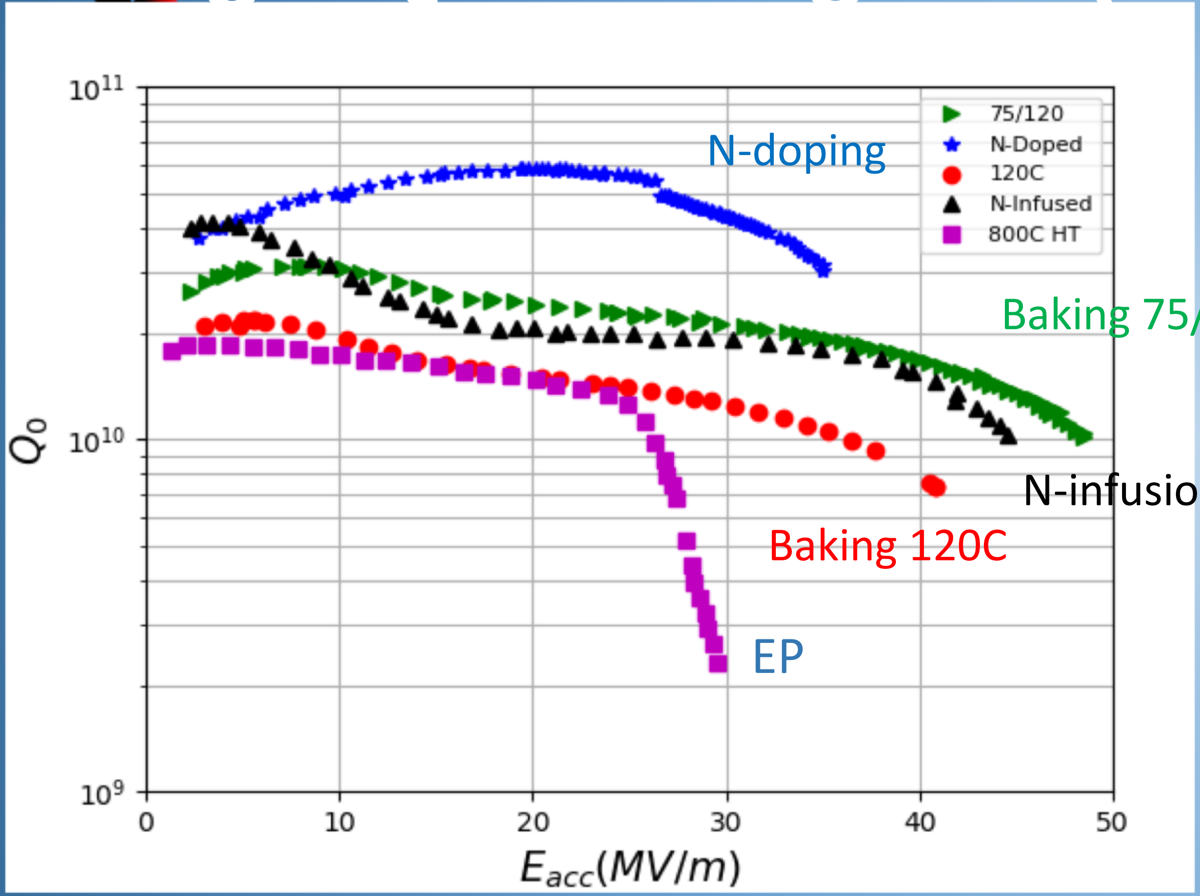




Crabbing p beam demonstrated at SPS, 2018
New successful test in 2021

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

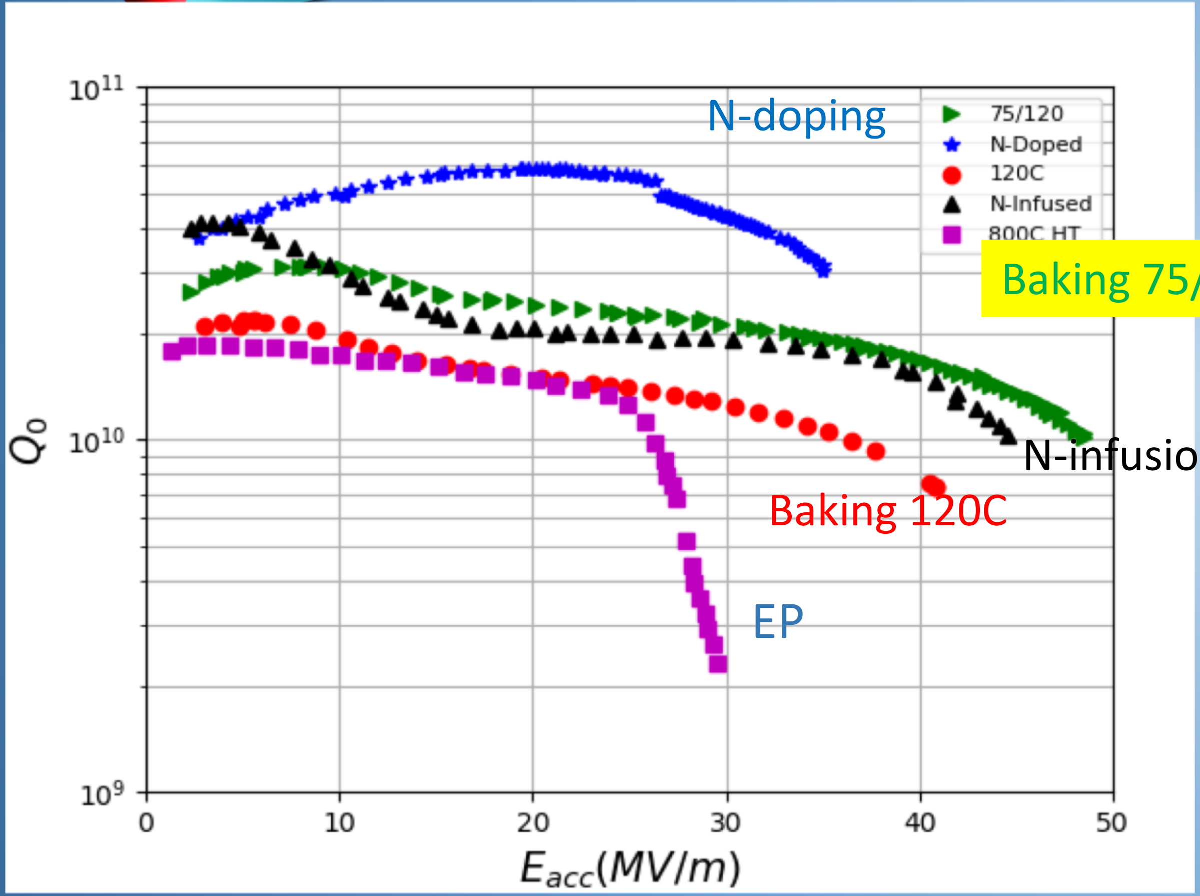
Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019

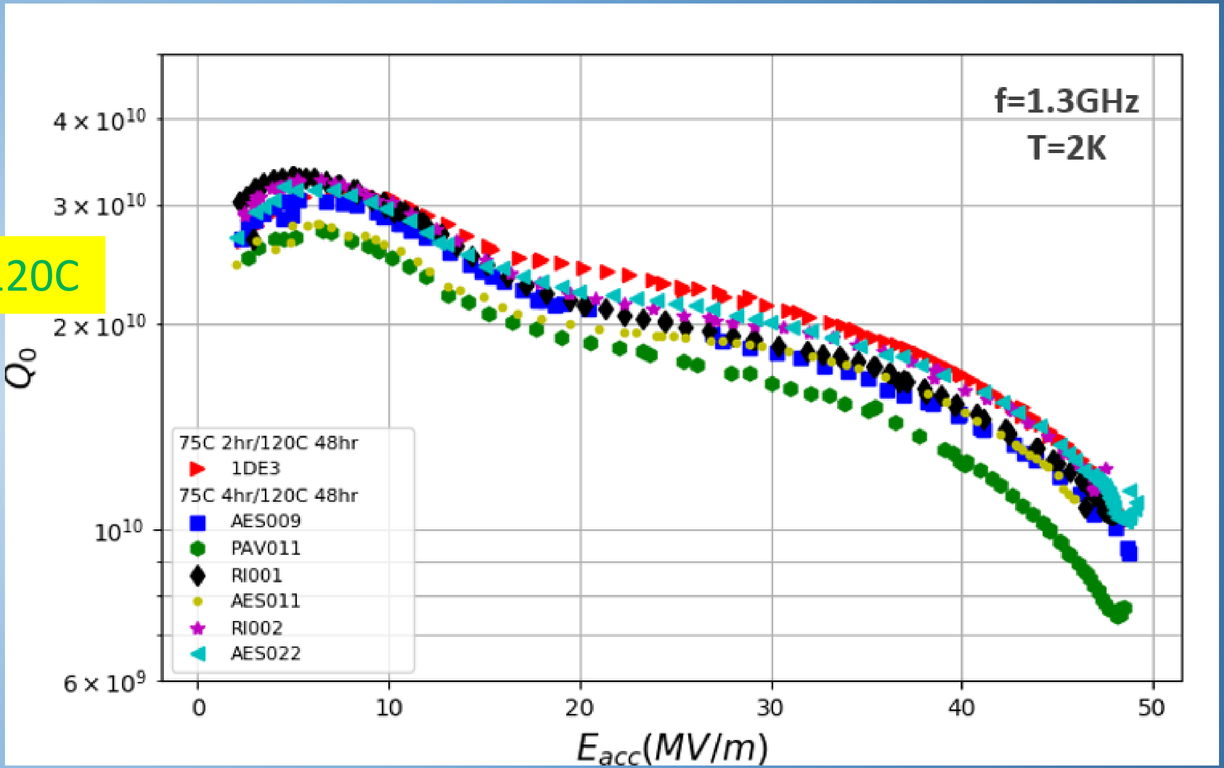


- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

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

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





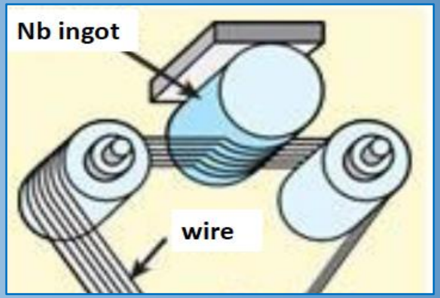
Repeated on second cavity TE1AES009 (fine grain, AES, WC)

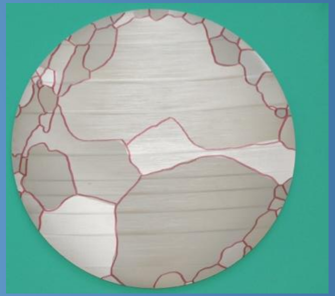
https://arxiv.org/abs/1806.09824

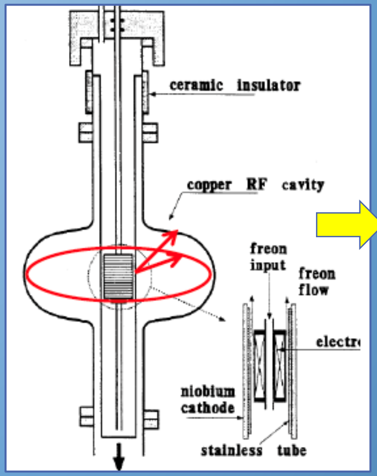
- Performance at **Fermilab** confirmed by **Cornell**, **DESY**, and **JLab.**

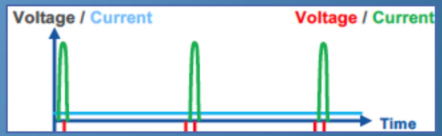
Challenges in SRF Cavity Technology

- **Bulk-Nb:**
  - **High-G and -Q optimization**
    - Low-T treatment w/ or w/o N-infusion.
  - **Large-Grain (LG) directly sliced from ingot**
    - For possible less contamination and cost-reduction
- **Thin-film Coating**
  - **Nb thin-film** coating on **Cu**-base cavity structure
    - Important for lower frequency and/or low-beta application.
    - A New approach to realize flatter Q-slope (higher-Q)
    - **H**igh **P**ower **I**mpulse **M**agnetron **S**puttering (HiPIMS) , instead of
    - **DC** **M**agnetron **S**puttering (DCMS)
  - Nb_3Sn / MgB_2 film coating on **Nb** or **Cu**
    - To reach much higher G, with higher B_c (B_{sh})





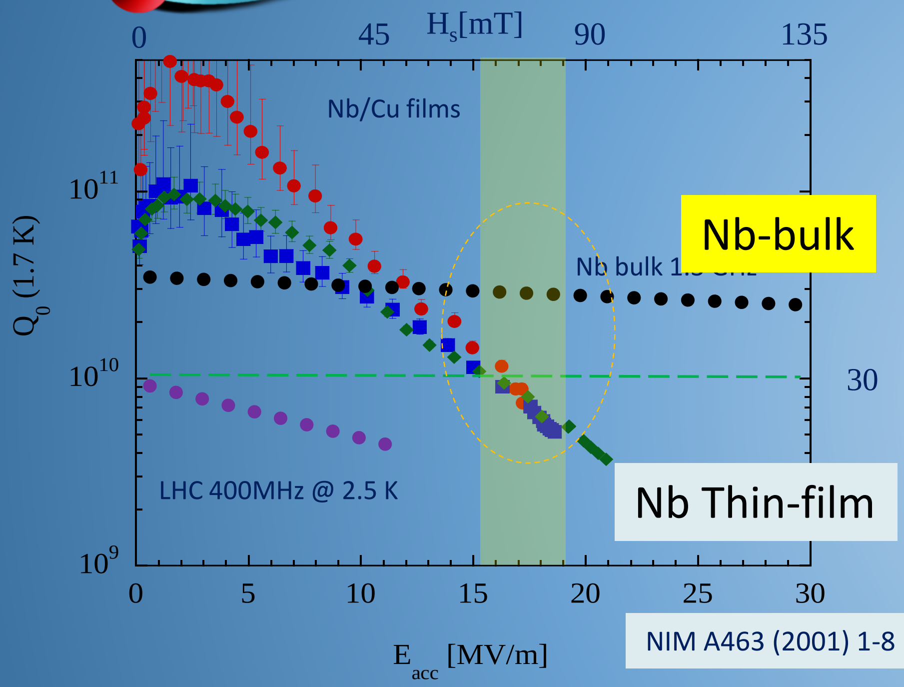




Courtesy: S. Calatroni

DC Magnetron Sputtered Nb/Cu Films

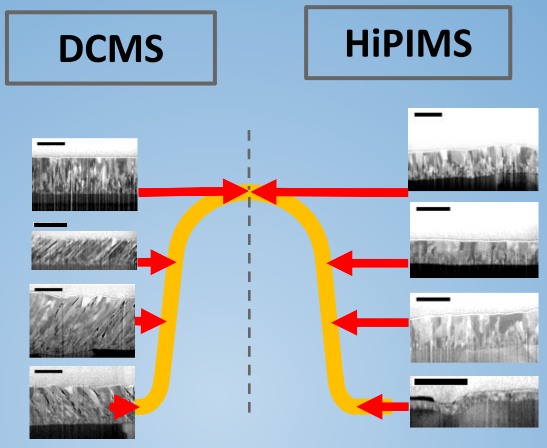
1.5 GHz Nb/Cu cavities, sputtered with Kr @ 1.7 K (Q_0=295/R_s)



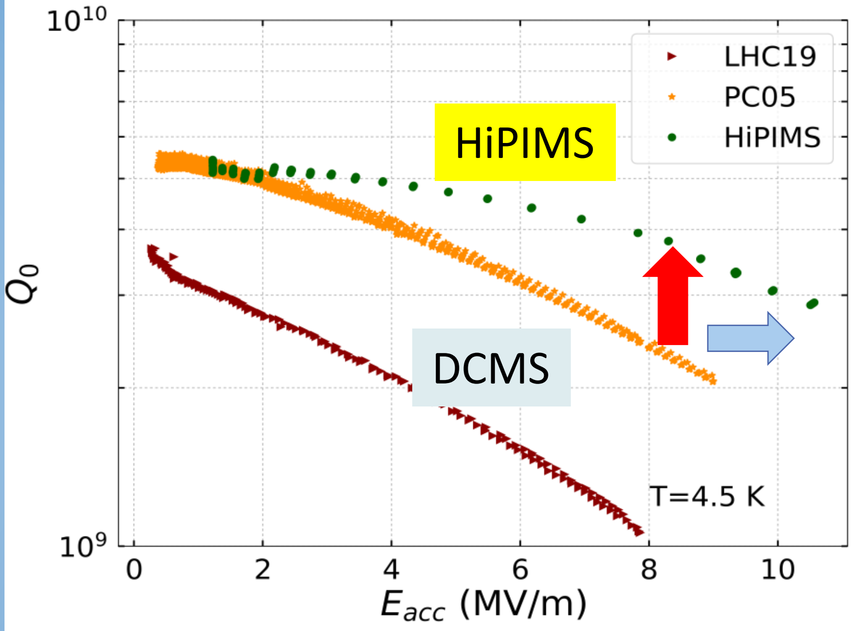
NIM A463 (2001) 1-8

HiPIMS coatings – QPR Sample

To be important challenge for < 600 MHz (FCC)



700 MHz β=0.65 Single Cell Cavity profile



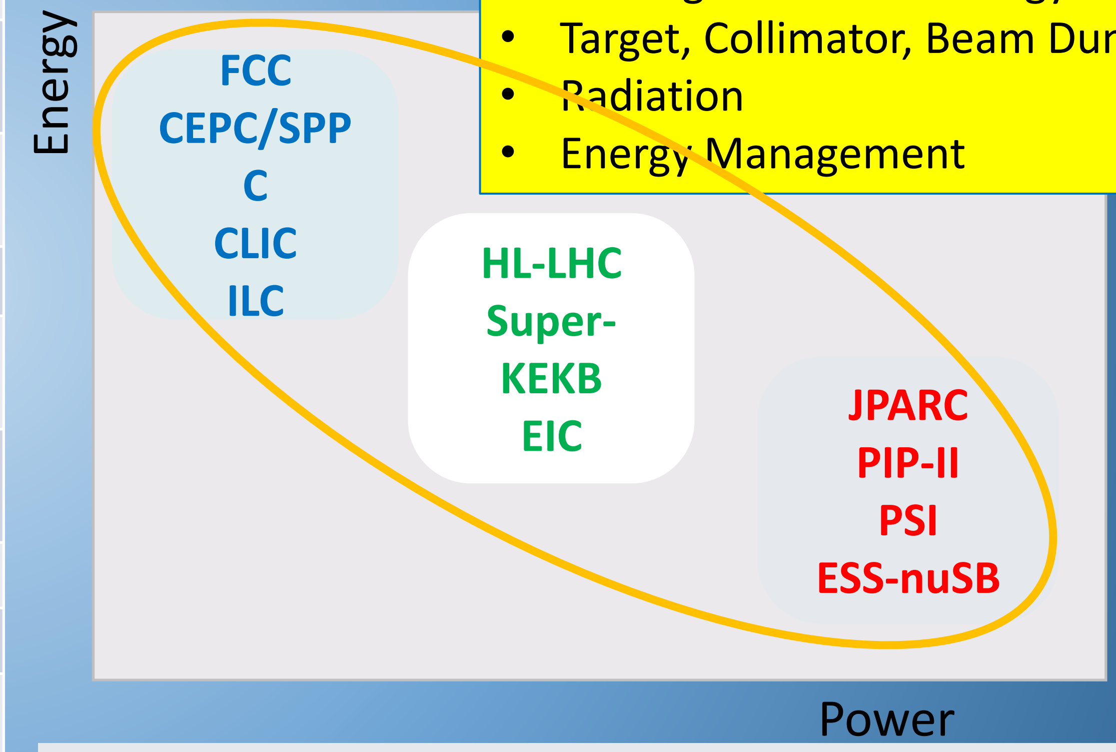
- Q = 1×10^{10} @ 15 MV/m, for thin-film cavities:
  - competitive option in several future projects.
- R&D focused on:
  - improving the “slope”

- HiPIMS Nb/Cu to be comparable to bulk Nb on quadrupole resonator sample at 400, 800 and 1,300 MHz.
  - To be discussed more by M. Benedikt (in Acc. Session).
- Q-slope seems to be flatter
  --> High-Q, resulting **Power Saving**,
- Projected performance > 2x better than LHC specifications

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

Intensity frontier vs. Energy Frontier

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



Common Issues:

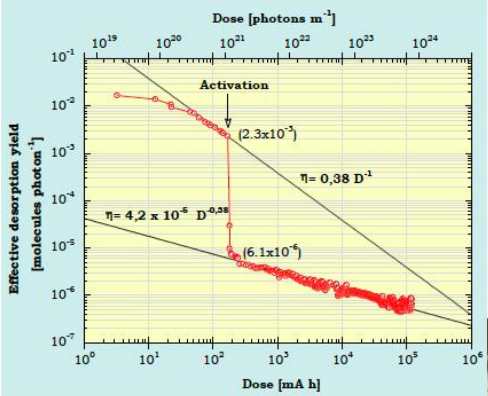
- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management

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

Courtesy: F. Bordry

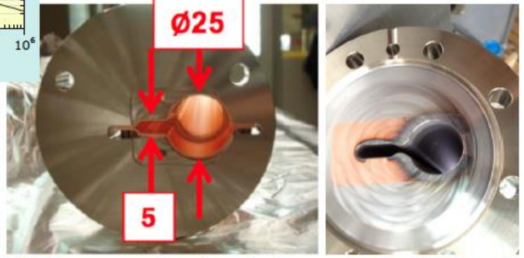
Vacuum

Extinction of gas sources



- **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.

Reduction of synchrotron-radiation desorption yield after NEG activation



MAX IV vacuum chamber: before and after NEG coating

Advanced Technology for particle accelerators
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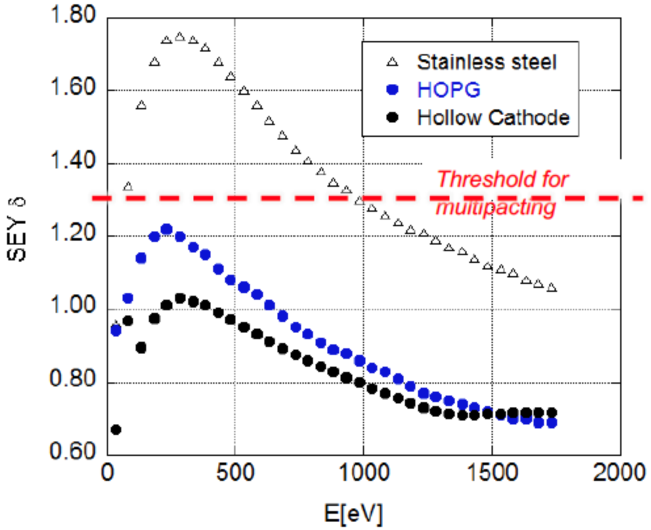
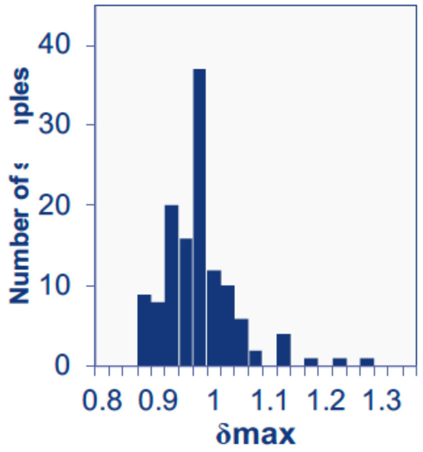
ICFA 2014 – IHEP – Beijing - 29th October 2014

Courtesy Paolo Chiggiato 41

Eradication of eclouds: carbon coatings





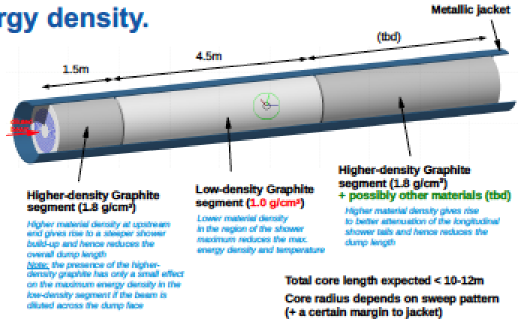
Courtesy: S. Gilardoni

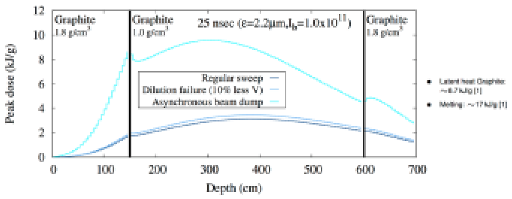
Beam Dump & Collimators for FCC-hh

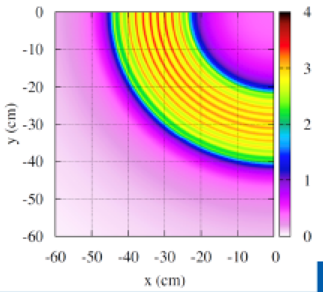
More in Anton's presentation

FCC-hh dump concept (LHC-like Graphite dump)

- **Beam sweeping à-la LHC to reduce energy density.**
- ANSYS calculations progressing on this conceptual design.
- Failure scenarios under consideration like sweep change due to dilution kicker failure or asynchronous beam dump







Material development:

- Working together with companies to investigate low density graphite thermomechanical properties
- Exploring alternatives for less traditional material

Collimator: future proposals

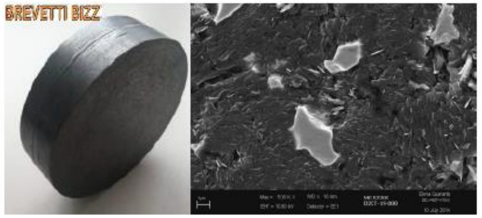
- Higher diffusing absorber material, to enhance the cooling transfer to the Cu-Ni circuit
  - Use of ceramic-graphite composites, such as Molybdenum-Graphite or Titanium-Graphite
- Lighter absorber
  - Minimise the energy density on the jaw (low density carbon foams)
- More rigid housing and stiffener
- Higher water flow in the cooling pipes
- Jaws Monitoring/possibly deformation-correcting, systems.
  - project launched CERN/University of Huddersfield

Courtesy: F. Bordry

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.



MoGr Key Properties	
Density [g/cm³]	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 completemented by advanced tests in dedicated facilities

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Courtesy Stefano Redaelli

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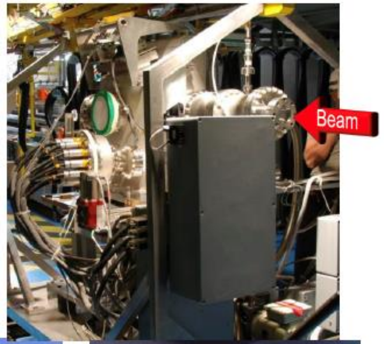
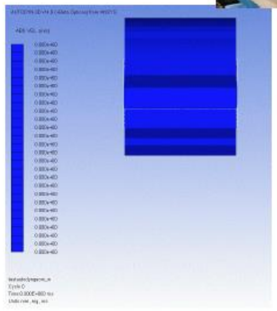
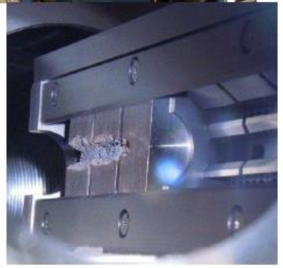
e.g. HiRadMat Experiments

- 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

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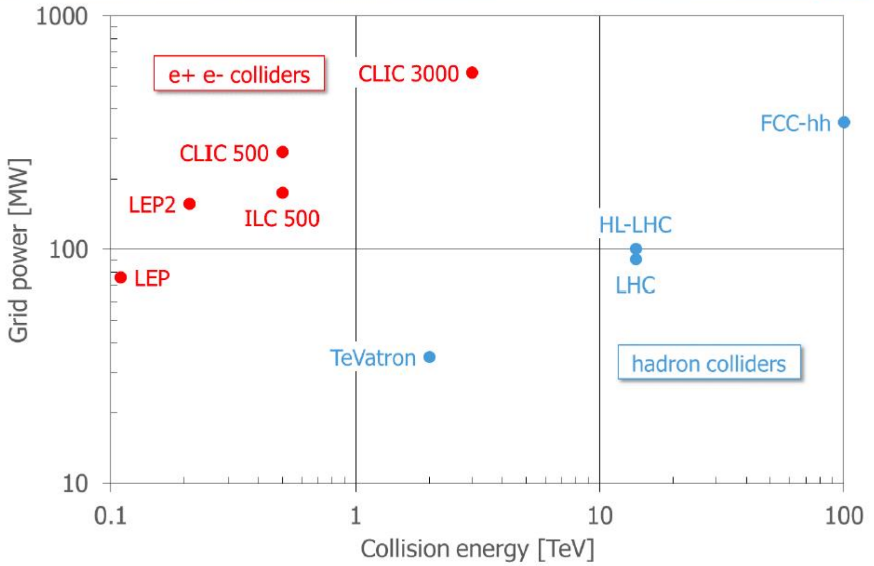
Courtesy: Ph. Lebrun

Energy Efficiency and Management in Accelerators

Power consumption of high-energy particle colliders

4th Workshop Energy for Sustainable Science at Research Infrastructures



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

Ph. Lebrun 4th W Energy for Sustainable Science 3

Beam power, particle energy, intensity

Linear accelerators

4th Workshop Energy for Sustainable Science at Research Infrastructures

- Average beam power

Beam current, Particle energy

$$P_{beam} = \delta I \frac{E}{e} = f_{rep} N_{pulse} E$$

Duty factor, Repetition frequency, Particles per pulse

- Example: ESS proton linac
  - $E = 2$ GeV
  - $I = 62.5$ mA
  - $\delta = 4$ %
  - $P_{beam} = 5$ MW average

Ph. Lebrun 4th W Energy for Sustainable Science 11

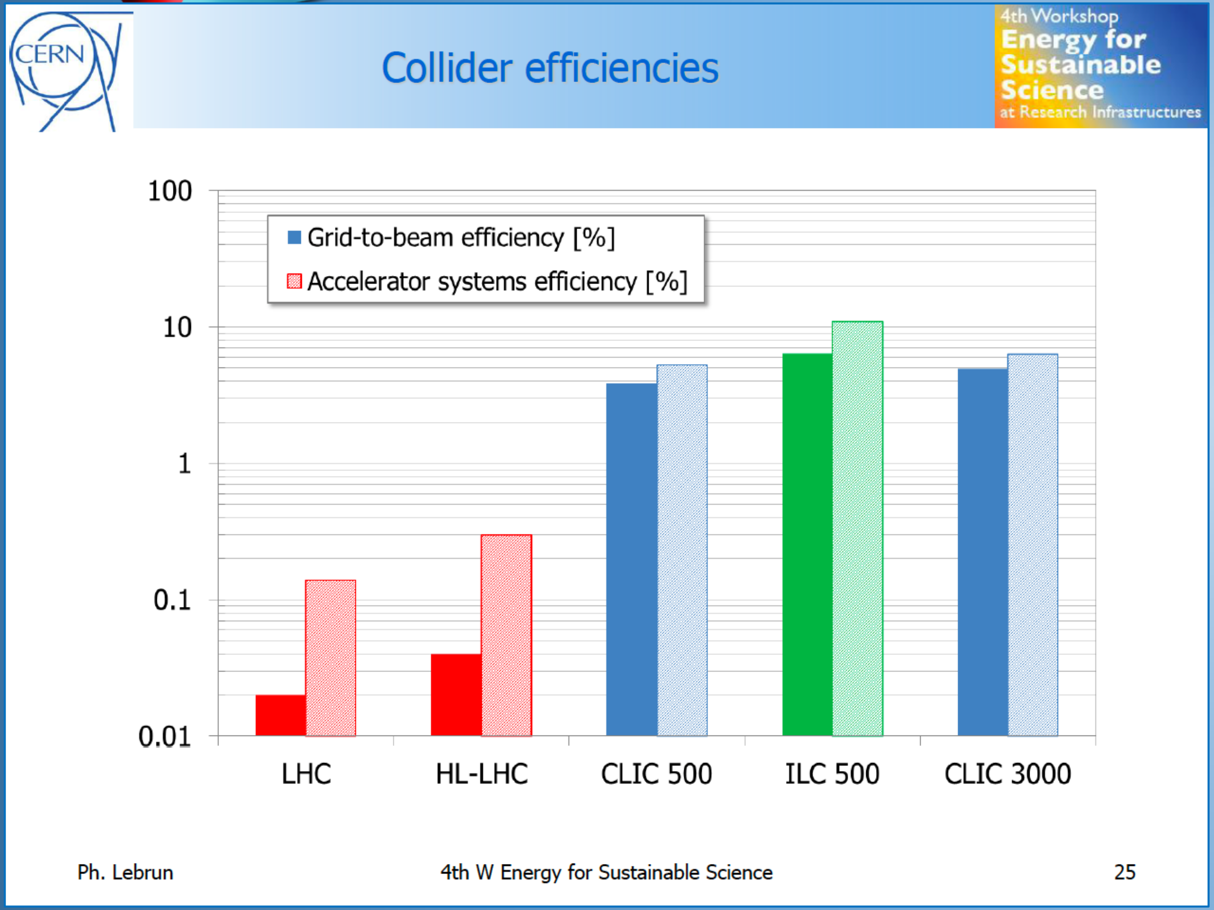
Key Issues in Energy Management

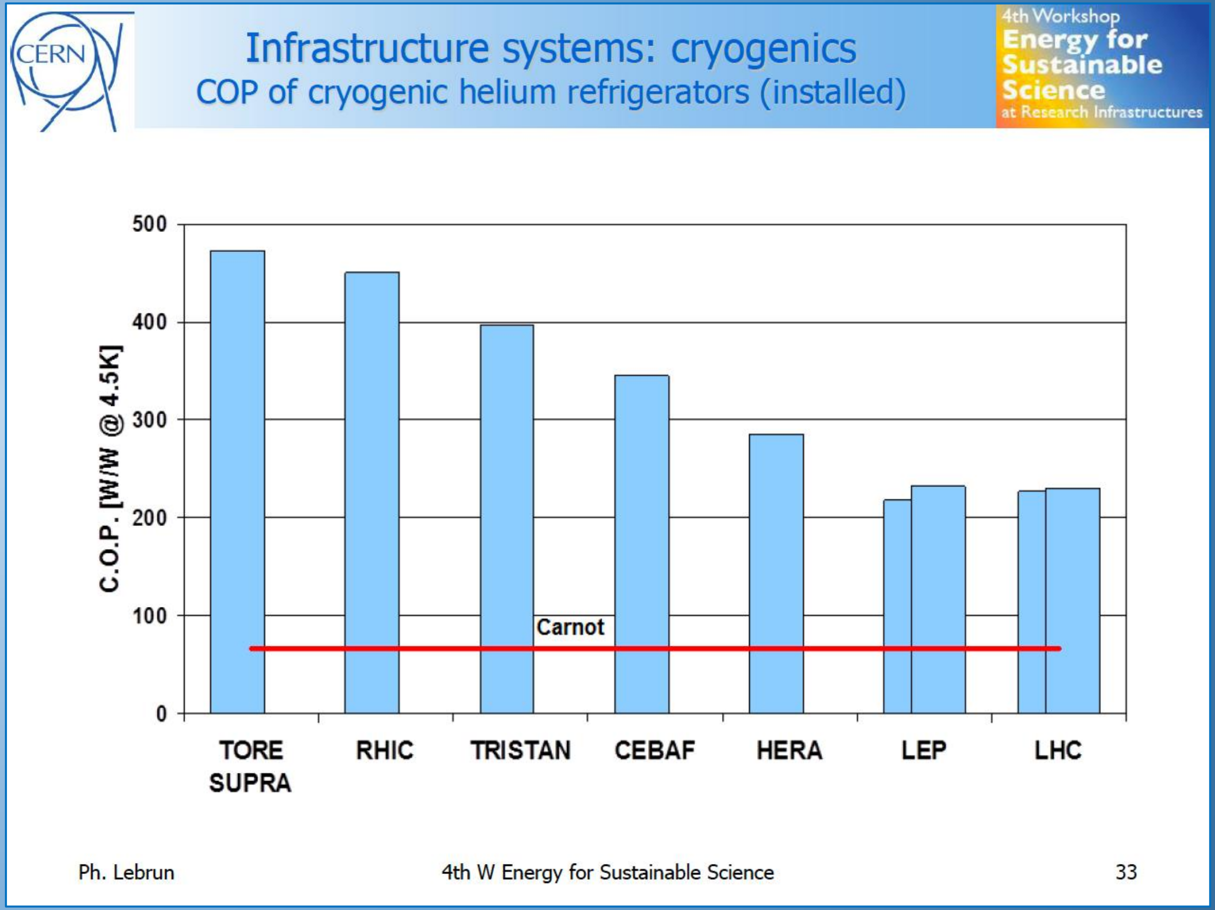
in both Energy- and Intensity-frontier Accelerators

- **Energy Saving**
  - Superconducting technology
- **System Efficiency Improvement**
  - Power system efficiency
  - RF modulator and Klystron,
    - Two beam acceleration
  - Cryogenics system efficiency
    - Depending on operational temperature (such as SR heat removal by Ne=He cycle)
  - Efficient beam dynamics
  - Novel, accelerator scheme
- **Dynamic Energy Balance**
  - **Power** (W) to **Energy** (W-hour) efficiency
  - Dynamic operation in best optimized season/day/time.
  - Re-use/Recycling energy in cooperation with wider community

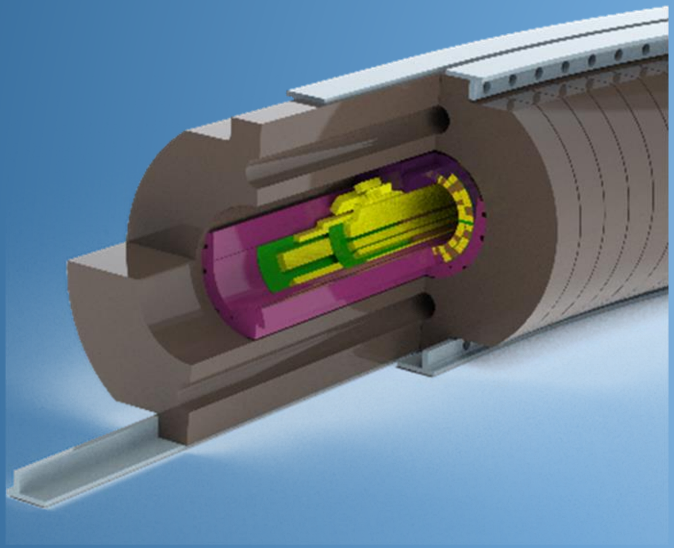
Courtesy: Ph. Lebrun

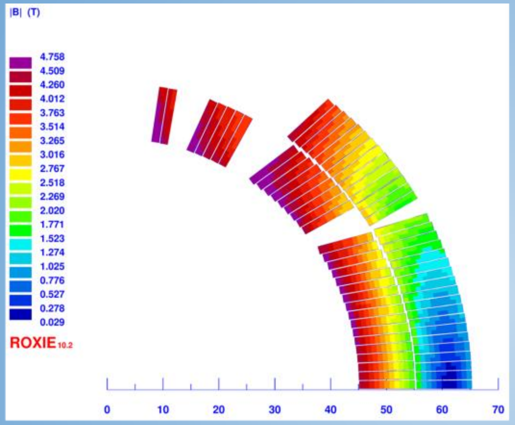
Energy Efficiency and Management in Accelerators

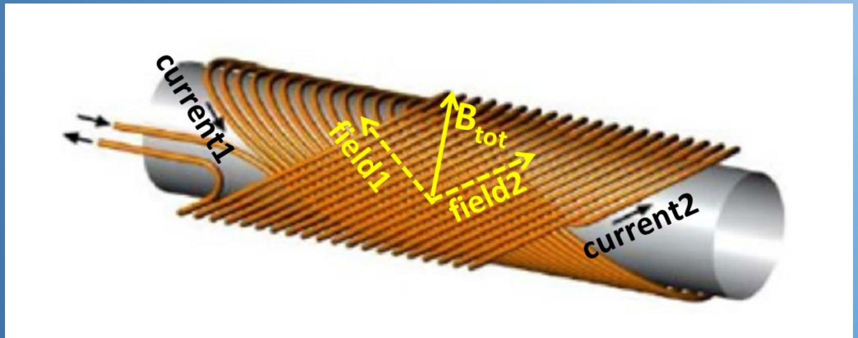


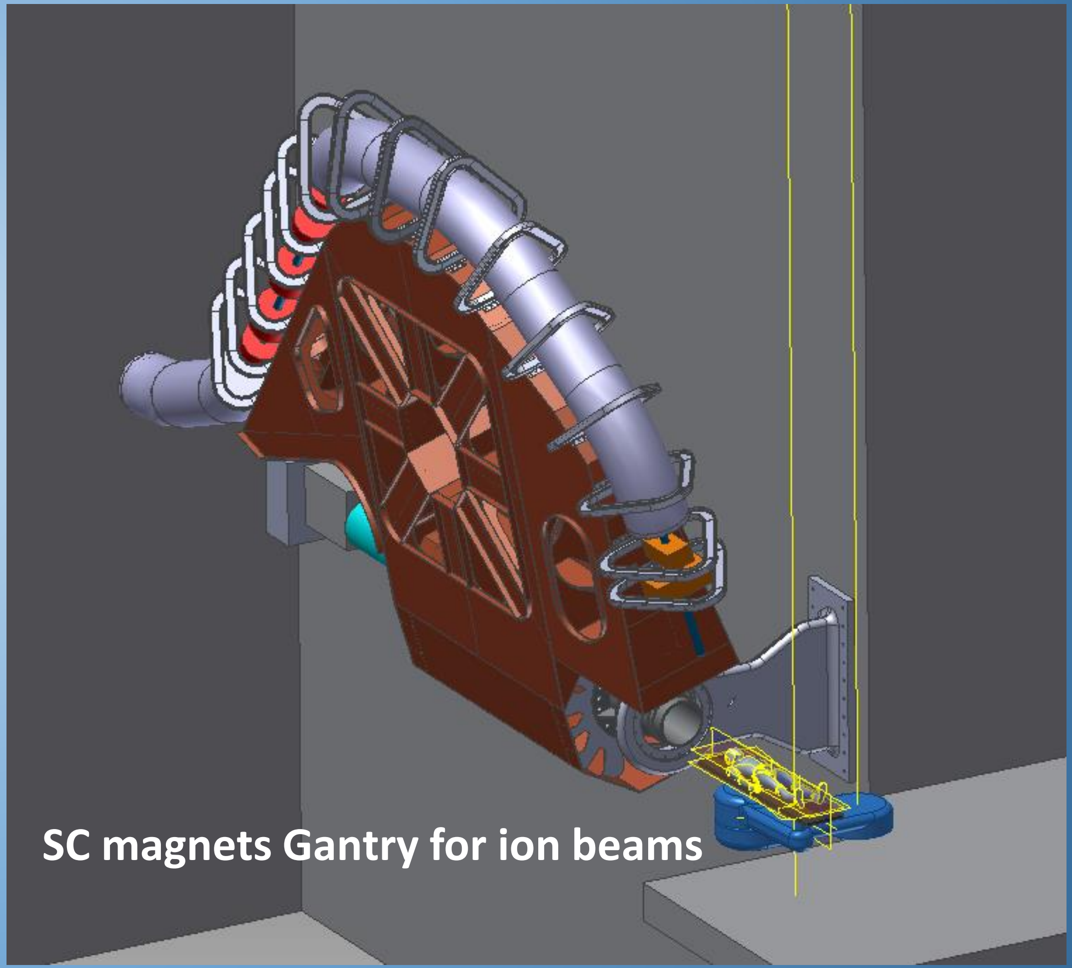


Goal: not only "new" technology turn collider technology for society



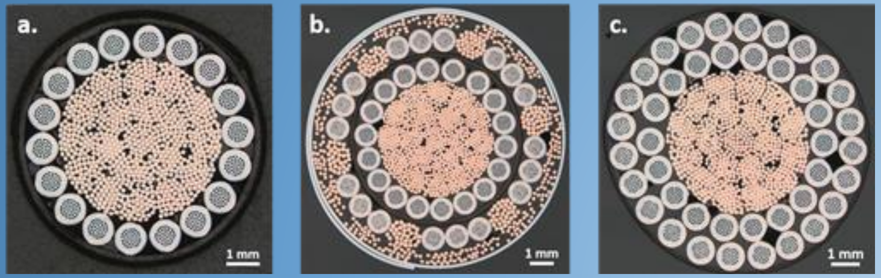


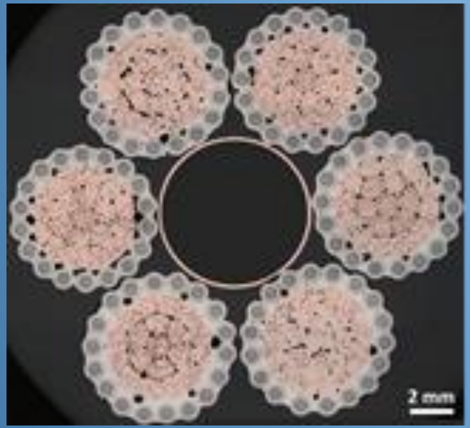




SC magnets Gantry for ion beams

SC links @ Hilumi LHC
100 kA – 3 kV





(relatively) low cost MgB_2

100 kA-20 kV
→ 1-2 GW
→ 20 K!!

Zero emission: CO_2 - e.m.radiation)
No impact on landscape

Thanks for the attention!