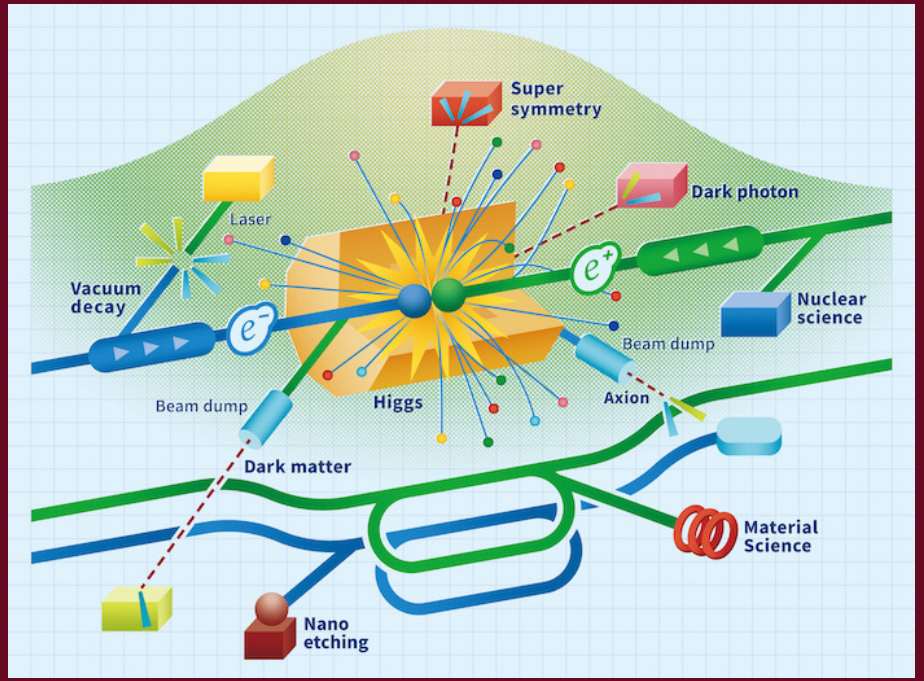
ILC industry capabilities in Europe with focus on SRF

Benno List, DESY

ILCX2021 ILC Workshop on Potential Experiments

Industry Forum

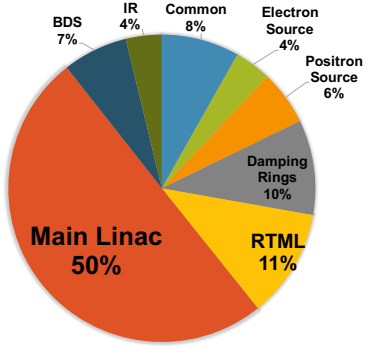
26.10.2021



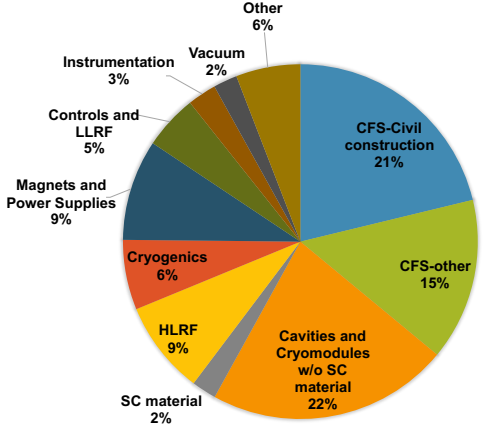
SRF: Key Technology for ILC

- **SRF Technology for Main Linac is ILC's main cost driver:**
  - Cavities & cryomodules (w/o material) 22%
  - SC material 2%
  - High-Level RF 9%
  - Cryogenics 6%
  - -> **overall 39%**
- **Industrial production is critical to**
  - Achieve target performance
  - Stay in budget and schedule
- **Mass production and industrialisation of SRF components has been in focus from beginning**
- **Availability of SRF components from industry is a main strength of ILC**
- **SRF technology is important basis for large number of accelerator projects in HEP and outside**

ACCELERATOR SYSTEMS
250GEV, 35MV/M



TECHNICAL SYSTEMS
250 GEV, 35MV/M



arXiv:1903.01629

IDT

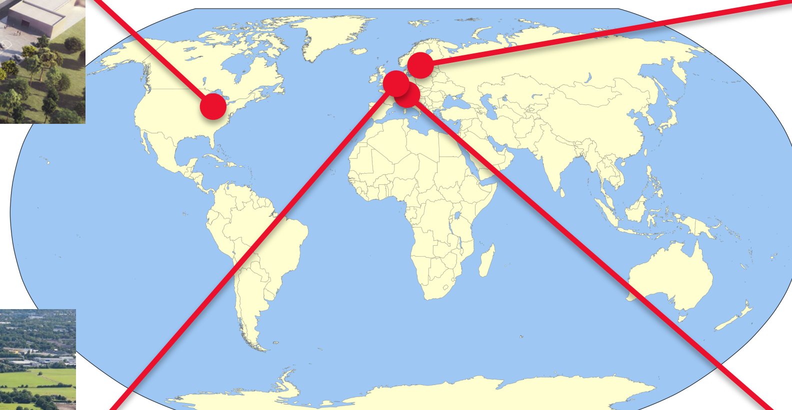
European participation in SRF accelerator projects

PIP-II Linac

Image: Fermilab https://news.fnal.gov/wp-content/uploads/2019/03/pip-ii-rendering-19-0025-01.jpg

ESS

https://europeanspallationsource.se/sites/default/files/styles/custom/public/images/media/2017-09/ESS_CLOSE_VIEW.jpg



Map: public domain https://commons.wikimedia.org/wiki/File:Blank_map_of_the_world_(Robinson_projection)_(10E).svg

European XFEL

XFEL GmbH

Crab Cavities for HL-LHC

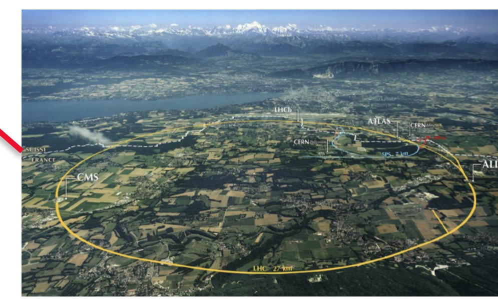
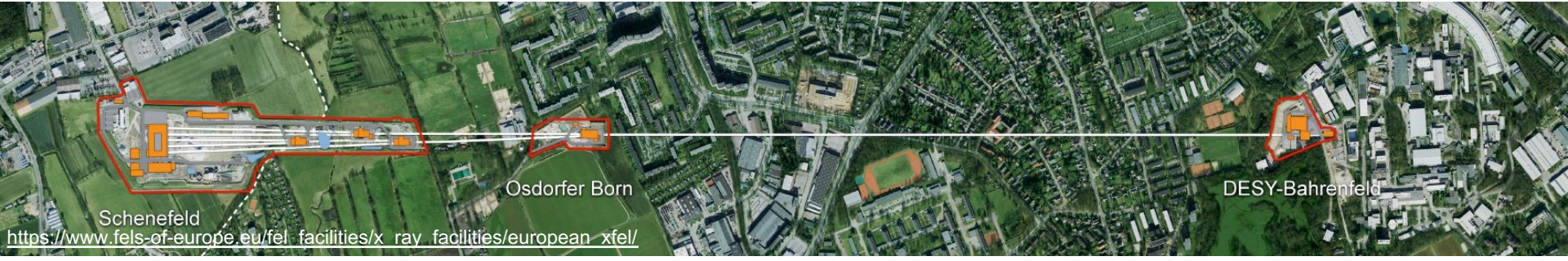


Image: CERN

… and many more

The European XFEL at DESY (Hamburg)



X-Ray Free Electron Laser Facility
Superconducting Electron Linac
drives 5 SASE beamlines

- **Total length 3km**
- **100 ILC type cryomodules in main linac**
- **Design gradient 23.6MV/m**
- **25 RF stations with 10MW klystrons**
- **First beam Dec 2015**

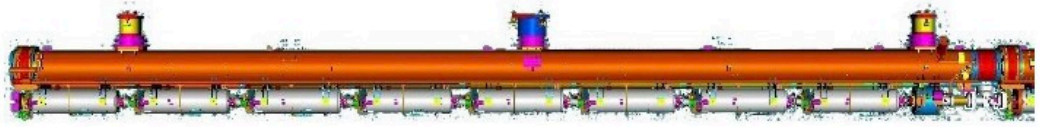
“A 10% prototype of the ILC’s ML”

Beam energy	17.5GeV
Pulse rate	10Hz
Pulse duration	0.6ms
Bunch charge	0.02 – 1nC
Bunches/pulse	2700

European XFEL

Contributors to the XFEL Accelerator

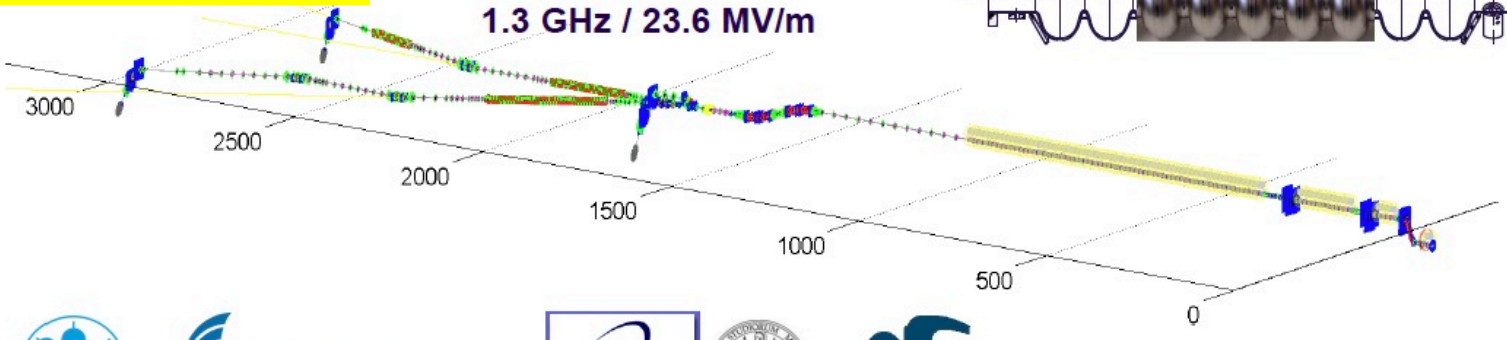
100 accelerator modules



A European In-Kind Contribution project

800 accelerating cavities

1.3 GHz / 23.6 MV/m

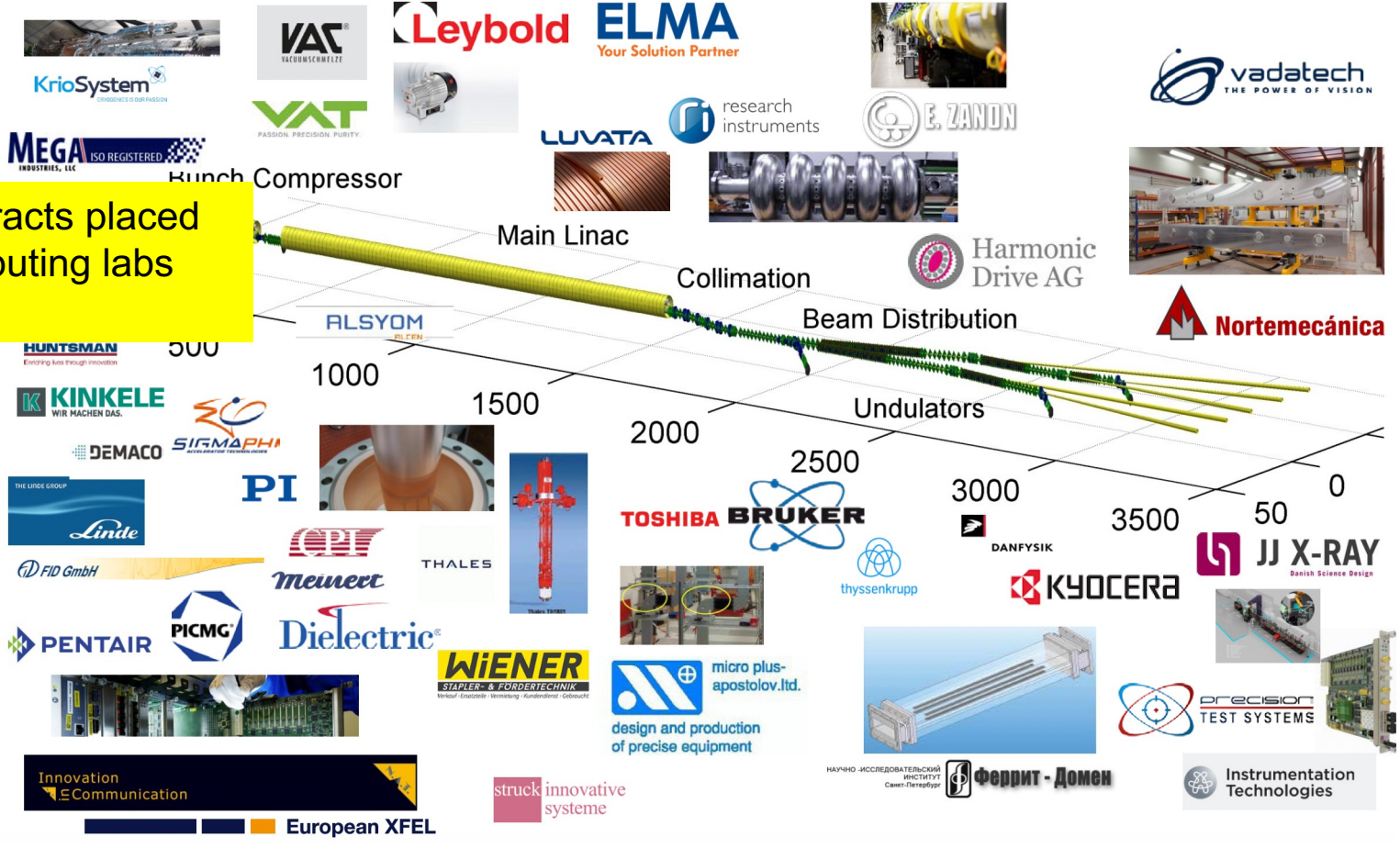


DESY · HELMHOLTZ ASSOCIATION · INFN · irfu · cea · saclay · cnrs · In2p3 · MINISTERIO DE EDUCACIÓN Y CIENCIA · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas · Wrocław University of Technology · IHEP ИФВЭ · UPPSALA UNIVERSITET · PAUL SCHERRER INSTITUT PSI

H. Weise, IPAC 2014,
https://accelconf.web.cern.ch/IPAC2014/talks/weib03_talk.pdf

Companies contributing in-kind to the construction

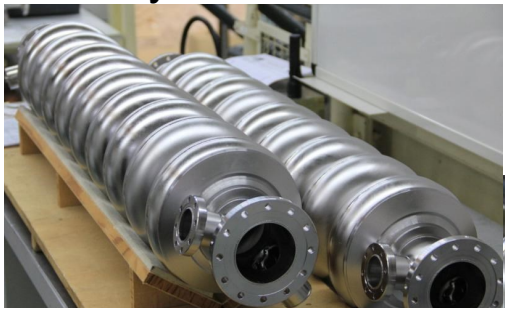
Industrial contracts placed through contributing labs and centrally



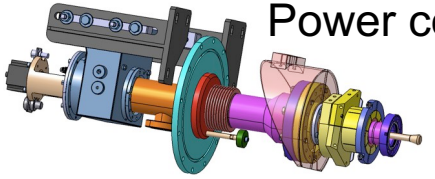
A. Bonucci https://agenda.infn.it/event/17822/contributions/88679/

European XFEL – Key Components

Cavitiy



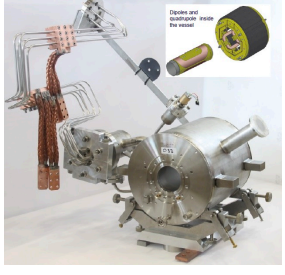
Power coupler



Cryostat and cold mass

Cryomodule

SC Quad



Waveguide distribution

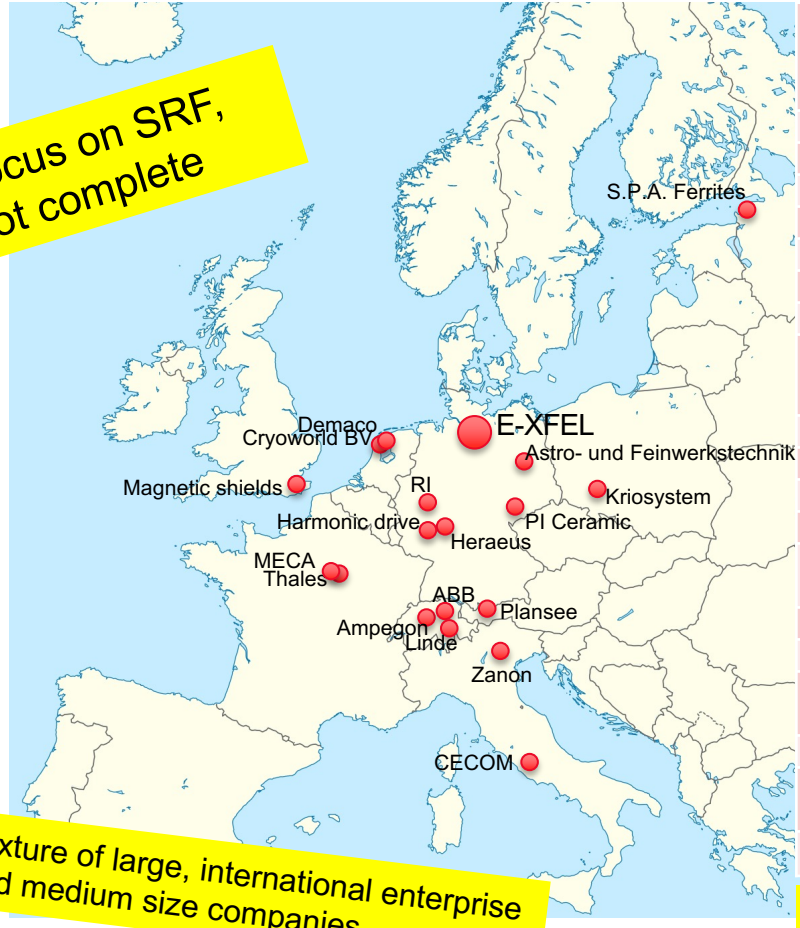
Klystrons

Cryo plant

Pictures from H. Weise, https://accelconf.web.cern.ch/IPAC2014/talks/weib03_talk.pdf

European XFEL: Industrial Partners

Focus on SRF, not complete



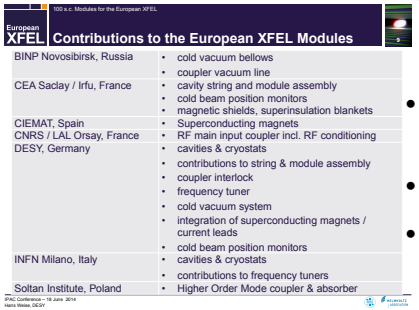
Niobium Sheets	Heraeus (*), Tokyo Denkai, Ningxia OTIC, PLANSEE (*)	DE, JP, CN, AT
SRF Cavities	Zanon, RI	IT, DE
Magnetic shield	MECA, Magnetic shields	FR, UK
Couplers	Thales/RI, CPI	FR/DE, US
QUAD/BPM Package	CECOM	IT
Tuners		
Piezos	PI Ceramic	DE
Motors	Harmonic drive	DE
Mechanics	Astro- und Feinwerktechnik Adlershof	DE
Cryomodule ass.	Alsyom	FR
Cold Mass	Zanon, IHEP/CX Wuxi	IT, CN
Phase shifters	Microplus	US
Waveguides	Mega industries	US
Circulators, RF Loads, Directional coupler	S.P.A. Ferrite Ltd	RU
Klystrons	Thales,Toshiba, CPI	FR, JP, US
Modulators	Ampegon	CH
Pulse cables	Dielectric Sc, Silec cable (General cable)	US
Pulse transformer	ABB	CH
Cryo transfer lines	Demaco, Kriosystem Sp. Budker BNP, Cryoworld BV	NL, PL, RU, NL
Cryo plant	Linde Kryotechnik AG	CG

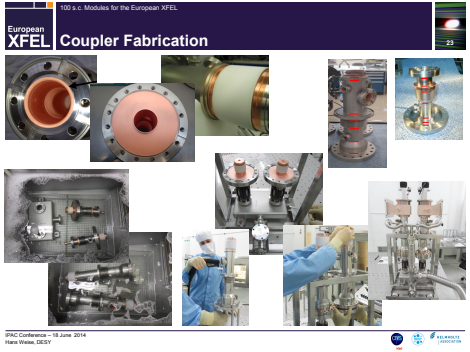
Mixture of large, international enterprise and medium size companies

(*) given up the business

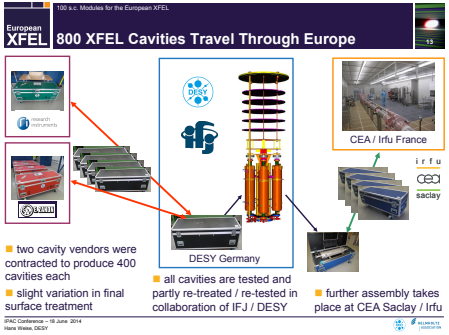
Data by Hans Weise

European XFEL: Successful partnership with industry

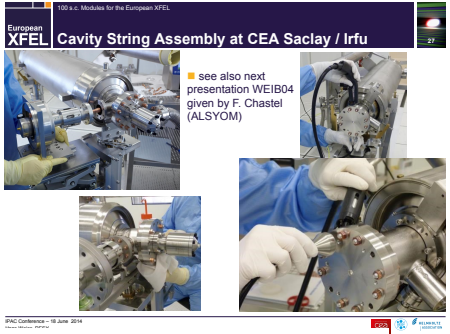


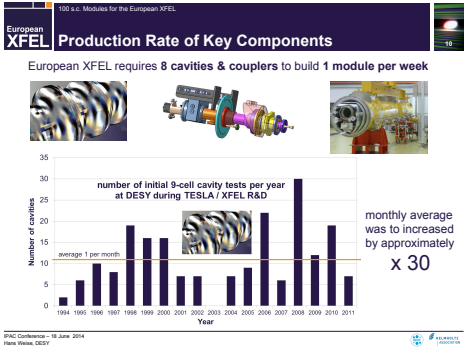


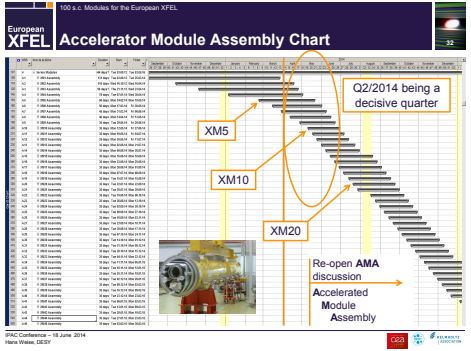
- **Procurement of components from industry by in-kind contributors and centrally**
- **Test and quality control in laboratories**
- **Cryomodule assembly line at CEA Saclay / IRFU, with industry personnel**
- **Final rate: 1.25 cryomodules / week: one module every 4 working days -> ~sufficient for one ILC production center!**



- **Established a strong industrial base for SRF equipment**
- **Caveat: European Niobium suppliers (Heraeus, Plansee) not available anymore**







Benno List

Slides: H. Weise, How to produce 100 superconducting modules for the European XFEL in collaboration and with industry, https://accelconf.web.cern.ch/IPAC2014/talks/weib03_talk.pdf

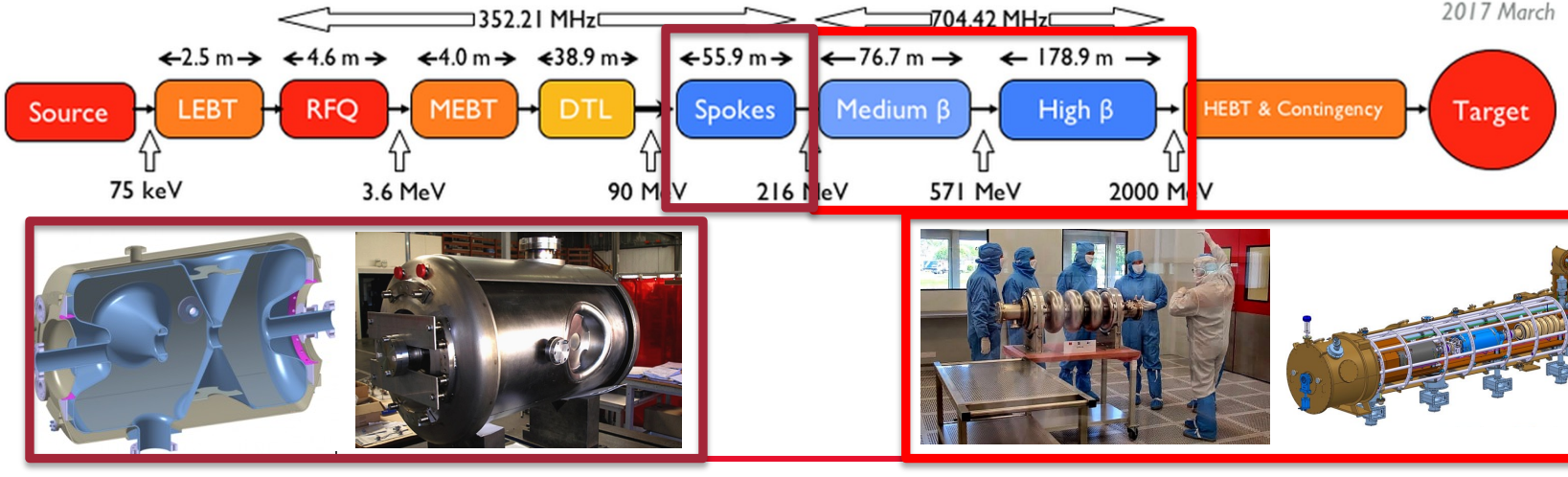
European Spallation Source

European Spallation Source ESS
Under construction in Lund (Sweden)
Operational in 2026

Superconducting Proton Linac

Spoke and elliptical cavities

Beam power	5MW
Beam energy	2GeV
Pulse rate	14Hz
Pulse duration	2.86ms
Pulse current	62.5mA



R. Garoby, Status and plans of the ESS neutron source (2021), doi:10.7566/JPSCP.33.011003

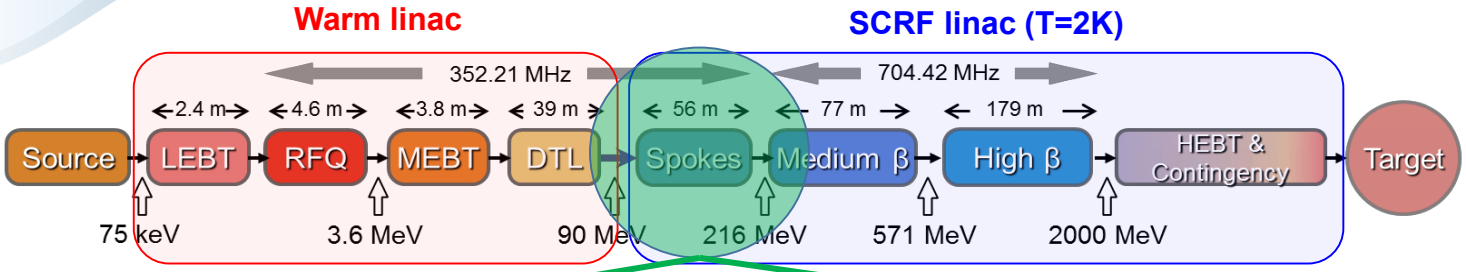
https://europeanspallationsource.se/accelerator/linac

ESS LINAC Work Matrix

	EU	Germany	France		Italy		Poland	Spain	Sweden	UK
	ESS-Lund	DESY	CEA	CNRS	Elettra	INFN	IFJ-PAN	ESS-Bilbao	Uppsala	STFC
Linac Components										
RF systems	✓				✓			✓		
LLRF									✓	
Cryomodules			✓	✓						
SRF cavities			✓	✓		✓				✓
Powers Couplers			✓	✓						
Frequency Tuners			✓	✓						
Cold vacuum	✓		✓	✓						
Module Assembly			✓	✓						
Test Infrastructures										
RF cavities/ couplers		✓	✓	✓						✓
RF cryomodules	✓		✓	✓			✓		✓	

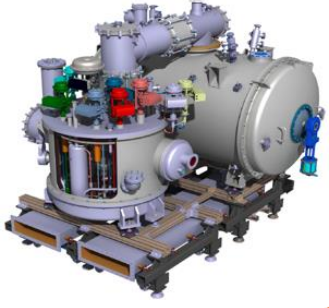
O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

ESS In-Kind Contributions



Delivery of 13 Spoke cryomodules (90 – 216 MeV)

Cryogenic destribution of the Spoke section (13 Valve boxes + Cryo distribution lines + « end box »)



O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

SRF Cavities Testing

ESS Double-spoke, 352 MHz

- Prototype cavity
  - test **without** and **with** power coupler
  - RF conditioning
  - Q_0, gradient, fill time,
  - Lorentz force detuning, microphonics
  - test LLRF, SEL,
  - tuner operation
  - nominal gradient

H. Li et al, NIM A927 (2019) 63

- **HL-LHC Crab, 400 MHz**
  - prototype cavity, w/o He jacket
  - double quarter wave (DQW)
  - first cavity test in vertical cryostat
    - successfully completed 8-Oct!

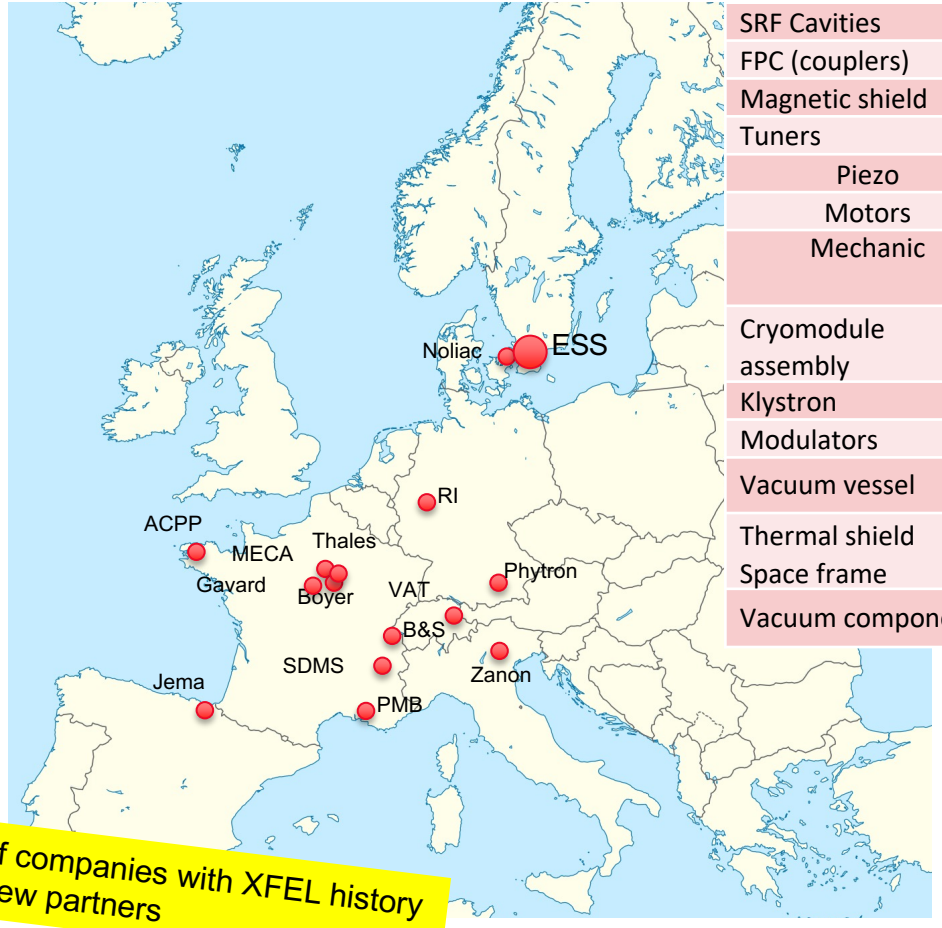
ESS Elliptical, 704 MHz

- RF stations
  - acceptance test of HV modulator for ESS local test stand
  - test RF distribution (circulator, load)
- Prototype high beta elliptical
  - with power coupler and tuner
  - RF conditioning
  - Q_0, gradient, fill time, heat load
  - Lorentz force detuning, microphonics
  - test LLRF, SEL, tuner operation

H. Li et al, LINAC 2018, THOP066

O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

ESS: Some SRF Industrial Partners



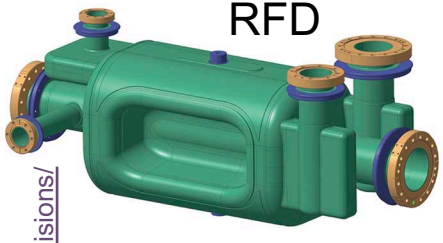
SRF Cavities	Zanon and RI	IT DE
FPC (couplers)	PMB	FR
Magnetic shield	Meca magnetic	FR
Tuners		
Piezo	Noliac	DK
Motors	Phytron	DE
Mechanic	Yvon Boyer and Gavard	FR, FR
Cryomodule assembly	B&S	CH
Klystron	THALES, CPI	FR, US
Modulators	Jema	ES
Vacuum vessel	ACPP	FR
Thermal shield Space frame	SDMS	FR
Vacuum components	VAT	CH

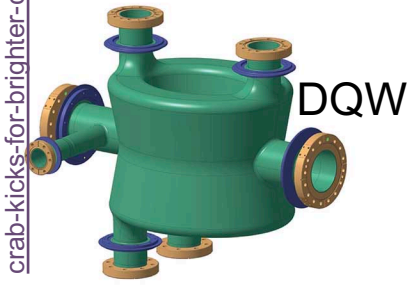
Mix of companies with XFEL history and new partners

Data by Enrico Cenni

High-Luminosity LHC at CERN, Geneva

© CERN https://cds.cern.ch/images/CERN-PHOTO-201708-196-10





https://cerncourier.com/a/crab-kicks-for-brighter-collisions/

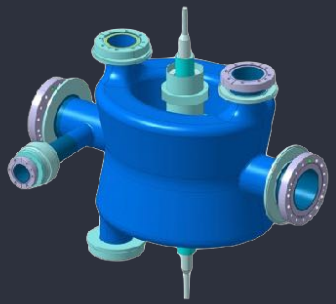
High-Luminosity upgrade of LHC accelerator

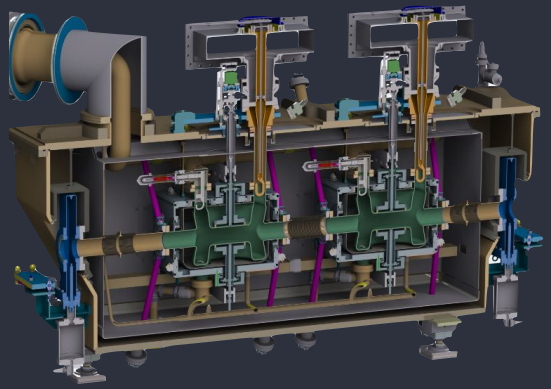
- Installation 2025-27
- 16 sc crab cavities around CMS and ATLAS IPs

https://hilumilhc.web.cern.ch

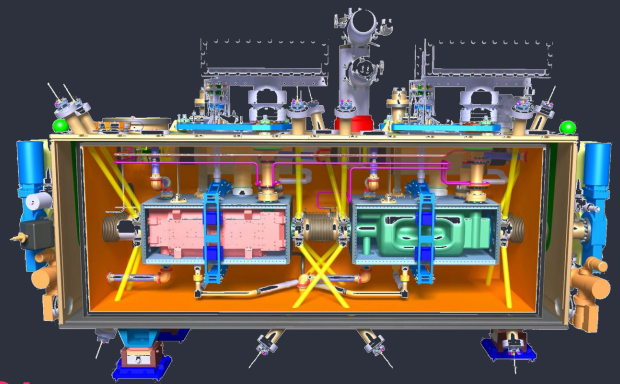
2 types of Crab cavities

Double Quarter Wave
- Vertical crossing for Atlas
- SPS test in 2018





RF Dipole
- Horizontal crossing for CMS
- first vertical test in Feb. 2020
- SPS test in 2021



Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power (SPS)	40 kW

➡ 2 cavities/beam/IP side
➡ for ATLAS and CMS
➡ 16 cavities/8 CMs in total

see M. Garlasche, Wed. 15:30, WG4
J. Mitchell, today, 16:18, WG2

courtesy R. Calaga/O. Capatina

F. Gerigk, Superconducting RF at CERN, https://indico.cern.ch/event/817780/contributions/3632119/

HL-LHC-Crab/EU Work Matrix

DQW cryomodules (5)	RFD cryomodules (5)	Solid State RF Systems (20)
Cavities + processing + helium vessels by Research Instruments (DE) under CERN	Bare cavities by Zanon (IT) under US-AUP	High power solid state amplifiers by BINP-Russia collaboration
Cold magnetic shields: UK	Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by US-AUP	First step, one amplifier prototype for qualification of SSPA technology
HOM couplers + antennas: MEPHI-Russia & CERN		
4 CM: UK (STFC) & 1 CM: CERN, with some components by CERN	5 CM by TRIUMF-Canada with some components by CERN	
All cavities & CM cold validation tests at CERN (and a few at Uppsala-Sweden)	CM cold validation tests at CERN	

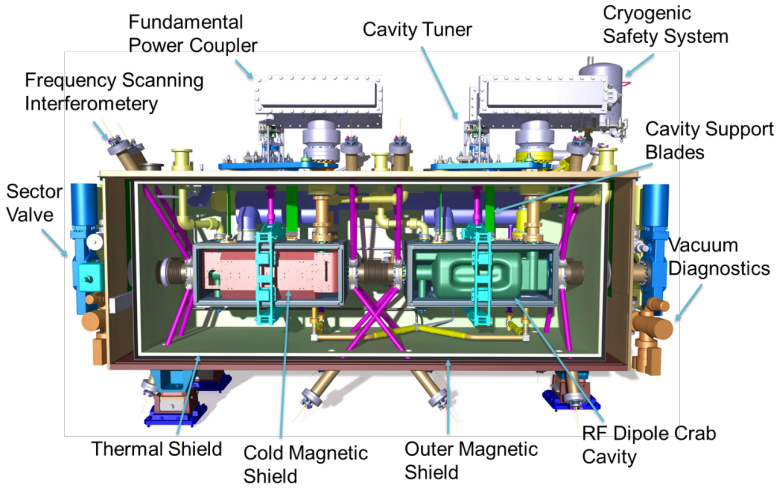
O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

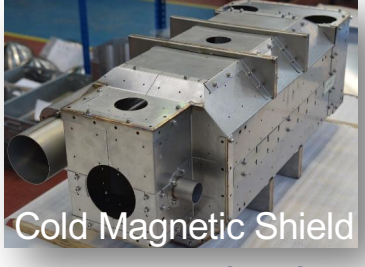
SRF Cryomodule Activities – HL-LHC Cryomodule (2010 - 25)

- First prototype cryomodule tests completed on SPS in mid 2018.
- **First ever evaluation of crab cavities with a proton beam!**

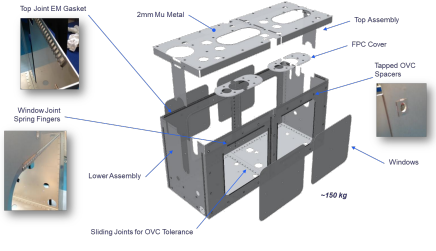
STFC, Lancaster, CERN, BNL, FNAL, Jlab, ODU & SLAC

- A 2-cavity pre-series (RFD) cryomodule design being developed and manufactured at Daresbury (2021).
- UK also providing 4 production (DQW) cryomodules for installation during LHC LS3 (2024-25).

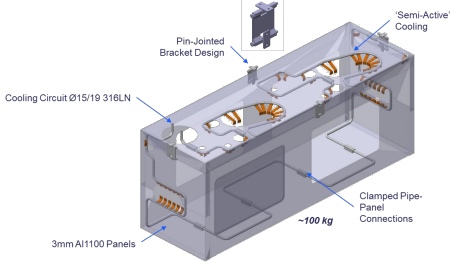




Warm Magnetic Shield



Thermal Shield

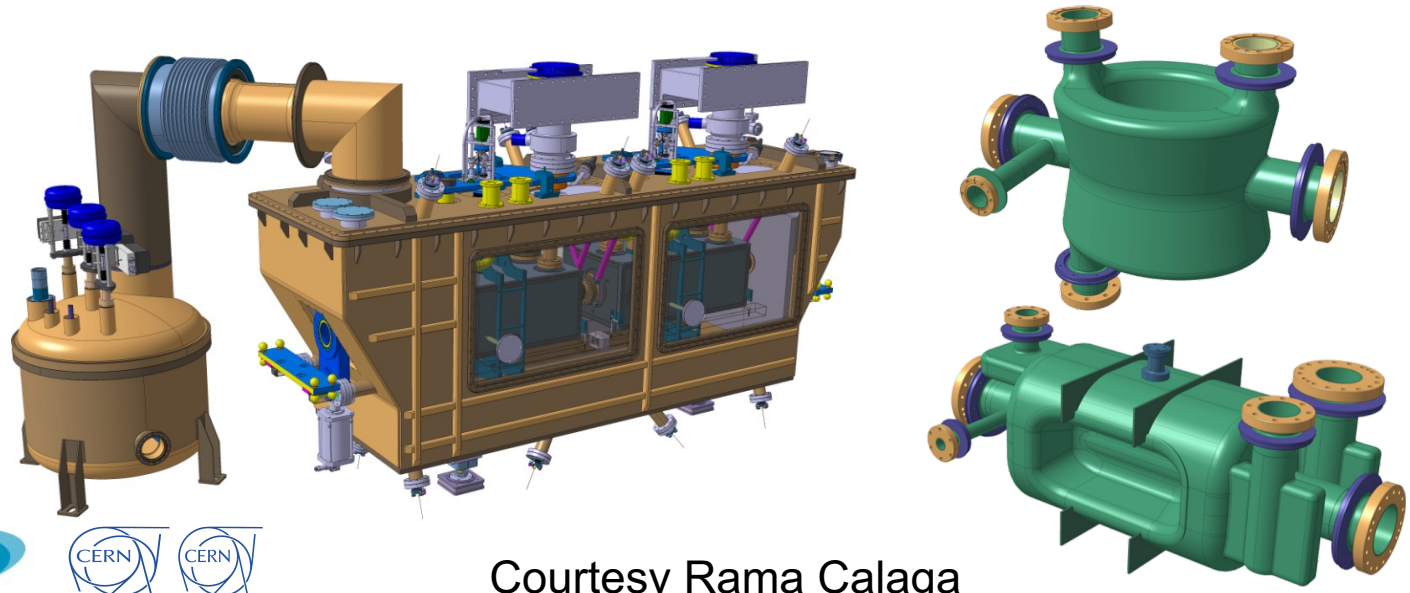


Science and Technology Facilities Council

P. Macintosh, LCUK Community planning meeting 2020
https://indico.cern.ch/event/943948/contributions/3965938/

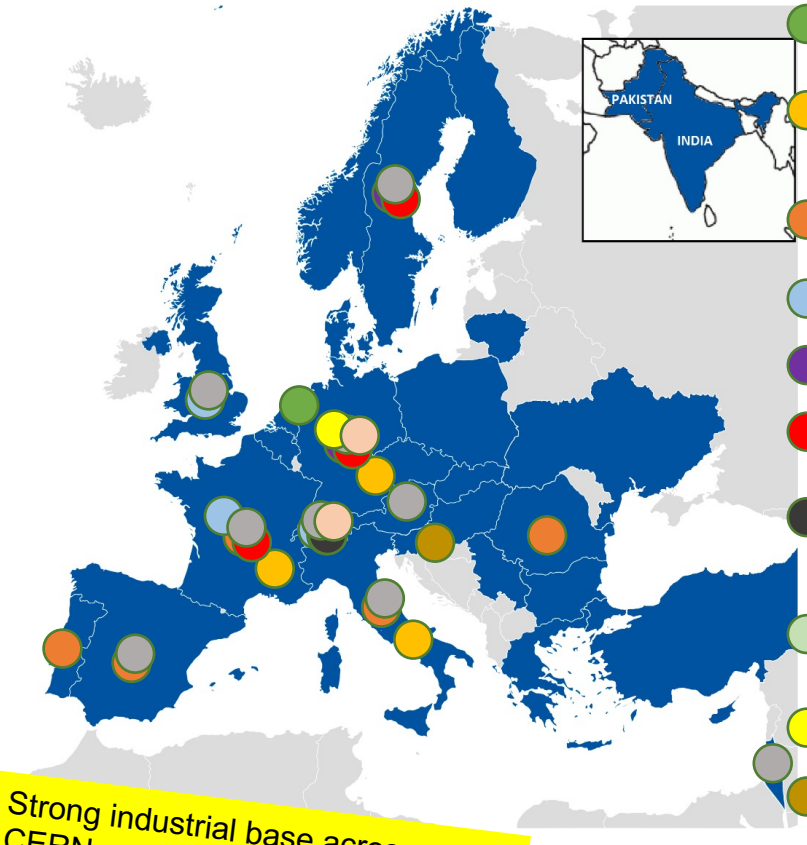
WP4 – Crab Cavities & RF

HL-LHC DOMAINS OF ACTIVITY	
Electrical equipment, electronics and instrumentation for accelerators	
Cryostats and subcomponents for cryogenic equipment	
High precision Assembling and manufacturing technologies	
Raw Materials	



Courtesy Rama Calaga

Presently identified as potential suppliers



Domain	Firms	State
Niobium and NbTi	Tokyo Denkai, Ningxia	JP; CN
Nb & Nb-Ti: Forming & Machining techniques	Research Instruments, BMAX, SDMS, ZANON, 3D Metal Forming	DE; FR; IT; NL
Electron Beam Welding of Nb and NbTi	Research Instruments; SDMS, Bodycote, CNIM; E. Zanon	DE; FR; IT
Cryostats and components	Raff+Grund, NTG; Cadinox, Nortemecanica; SDMS, Allia; E. Zanon, Criotec, ALCA; Arsopi; Metal Techniks	DE; ES; FR; IT; PT; RO
Low temperature magnetic shields	Vacuumschmelze; Meca Magnetic; Magnetic Shields	DE; FR; UK
Precision alignment for SRF	Etalon AG; Hexagon Metrology	DE; SE
Precision Tuning System Components	Rollvis; Harmonic drive; Schaeffler; SKF	CH; DE; FR; SE
Vacuum Valves for RF application	VAT	CH
RF Power system at 400 MHz	AFT; Ampegon, IBA; Beko, Cryoelectra, R&S, Spinner; TTI, Indra, Btesa, MIER; Thales, SigmaPhi; Elbit; DB science, Neera, Itelco-Electrosys; Exir; Microwave Amplifiers	AT; CH; DE; ES; FR; IL; IT; SE; UK
RF Coupler	Wesgo	DE
RF Controls: Digital I/Q Demodulators & DSPs	AMS	AT
PLC Controls	ABB; Siemens	CH; DE

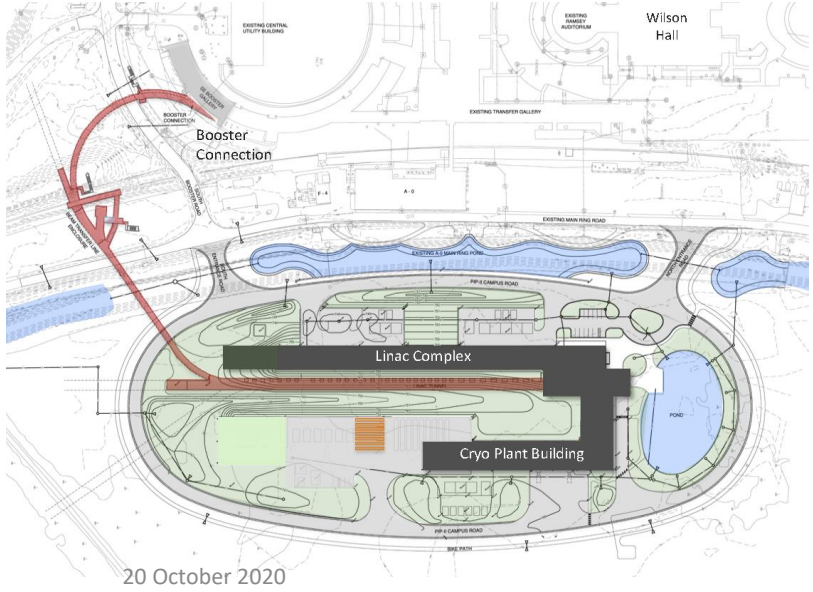
Strong industrial base across most CERN member states, except for raw material

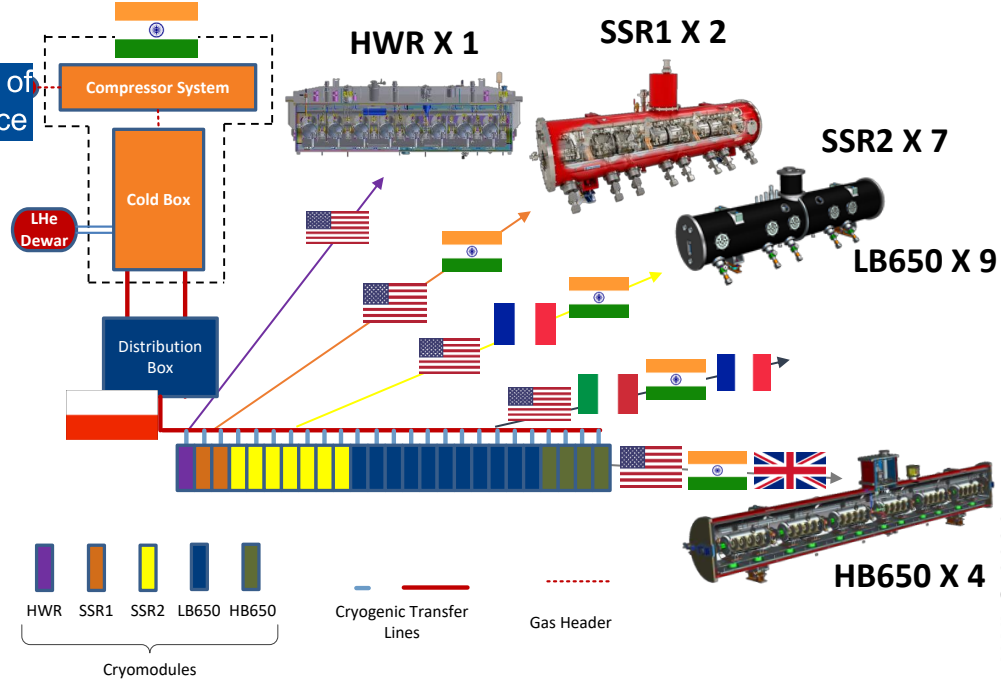
Data R. Calaga

PIP-II Linac

- Proton Improvement Plan is under construction in Fermilab, including a 800 MeV proton superconducting linac, operating in CW mode.
- Six countries are, so far, contributing to the cold linac construction.

Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science





O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

PIP-II LINAC Work Matrix / EU

Fermilab is leading and hosting the project, for LBNF/DUNE.

Four DAE (India) labs are major contributors for cavities, couplers, cryomodules, RF amplifiers, etc.

Legend:
- ✓ Prototypes
- ✓ Production Series

	France		Italy	Poland	UK
	CEA	CNRS	INFN	WUST	STFC
Linac Components					
Cryogenics				✓	
Cryomodules	✓				✓
SRF cavities		✓	✓		✓
Powers Couplers	✓	✓			
Frequency Tuners		✓			✓
Cold vacuum	✓				✓
Module Assembly	✓				✓
Test Infrastructures					
RF cavities/ couplers		✓			✓
RF cryomodules	✓				

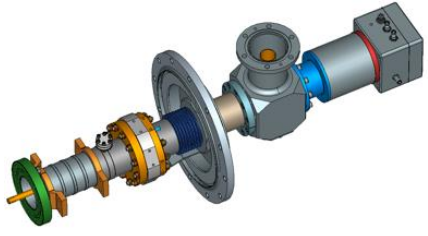
O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

In-Kind Contribution to PIP-II : Deliverables

State-of-the-art SRF treatments for low-beta cavities (Spoke, QWR).

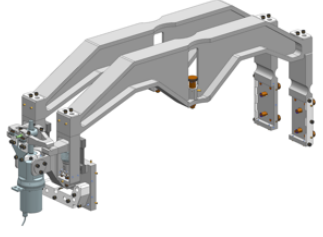
SSR2 SPOKE RESONATORS : Collaborative mechanical design

- **Pre-production phase : 4 cavities**
  - Fabrication follow-up
  - Optimization of surface treatment (R&D)
  - Validation in vertical cryostat of RF performances
  - Transportation to FNAL



TUNERS : Support to final design

- **Pre-production phase : 5 tuners**
  - Procurement
  - Fabrication follow-up
  - Validation in vertical cryostat
  - Transportation to FNAL



SSR POWER COUPLERS : Support to final design

- **Pre-production phase : 4 couplers**
  - Procurement
  - Fabrication follow-up
  - Support for RF conditioning

SURFACE TREATMENT AND VALIDATION OF SRF SPOKE CAVITIES THANKS TO THE UNIQUE CAPABILITIES OF SUPRATECH PLATFORM AT IJCLAB

O. Napoly, AWLC 2020, https://agenda.linearcollider.org/event/8622/contributions/46392/

UK Industry SRF Development (2019 – 22)

PIP-II – 650MHz high beta cavity

The Welding Institute (TWI)

- Demonstrate successful EBW of SRF cavities:
  - Demo-1: 2-cell 1.3 GHz and
  - Demo-2: PIP-II Demonstrator

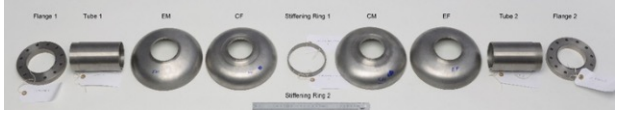
NAMRC

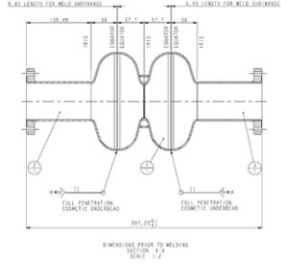
- All EBW tooling
- Demonstration of Nb - NbTi EBW processes.

Shakespeare Engineering

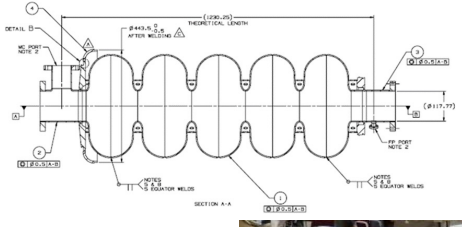
- Pressing, machining and manufacture of all cavity components.
- Tuning and dimensional verification of all components.

2-cell 1.3GHz test cavity





PIP-II 650MHz cavity demonstrator

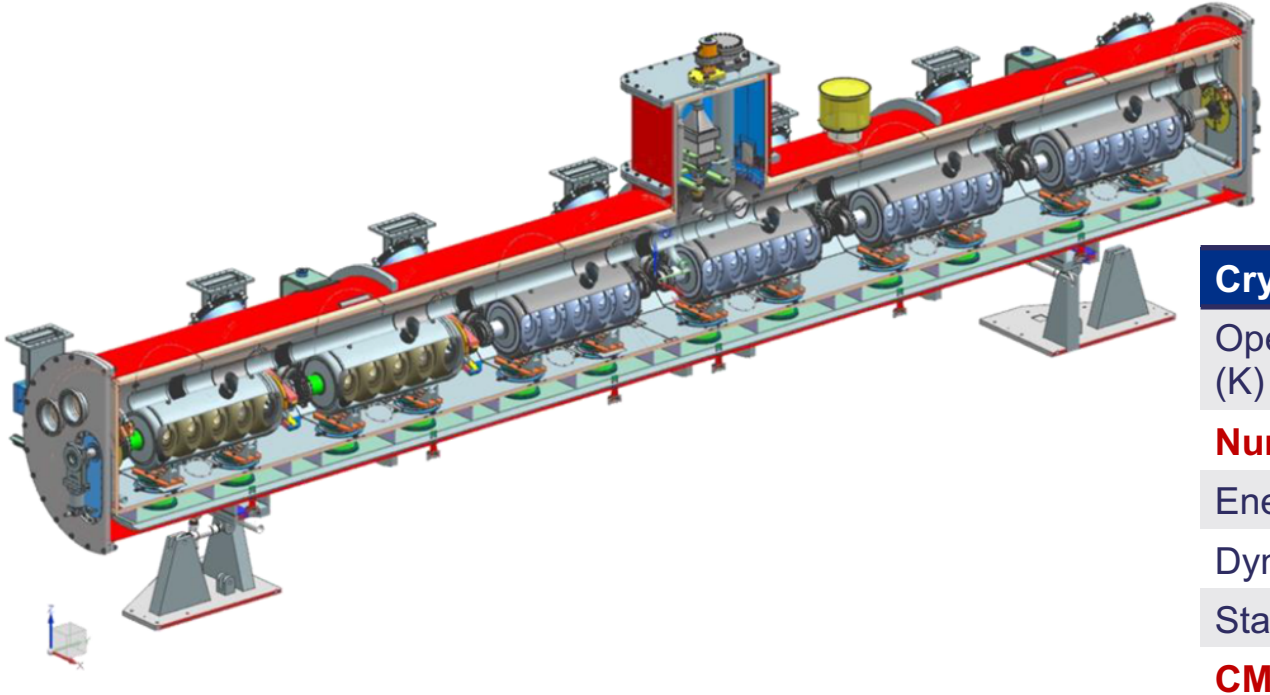


All manufacture, including EBW to be performed in UK!

Science and Technology Facilities Council

P. Macintosh, LCUK Community planning meeting 2020
https://indico.cern.ch/event/943948/contributions/3965938/

SRF Cryomodule Activities – PIP-II High Beta Cryomodule (2019 - 25)



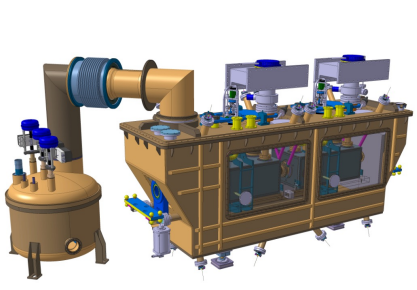
Cryomodule (CM)	PIP-II
Operating Temperature (K)	2
Number of Cavities	**6**
Energy Gain (MeV)	~110
Dynamic Load (W)	130
Static Load (W)	32
CM Length (m)	**9.8**
Number of Cryomodules	**3**

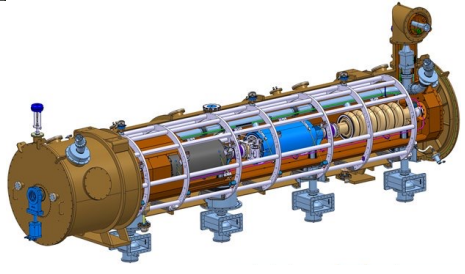
Science and Technology Facilities Council

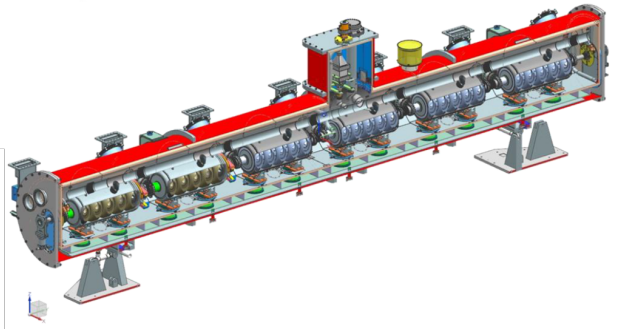
P. Macintosh, LCUK Community planning meeting 2020
https://indico.cern.ch/event/943948/contributions/3965938/

Summary and Conclusion

- **E-XFEL as a European in-kind project established a successful collaboration**
  - with partner labs across Europe
  - technical infrastructure for assembly and tests
  - a network of industrial partners in Europe and overseas
- **Laboratories with E-XFEL experience and new partners participate in new projects, e.g.**
  - ESS, PIP-II, HL-LHC
  - Further projects: R&D for ILC, E-XFEL CW upgrade
- **Infrastructure for assembly and tests remain valuable assets**
- **Extensive European industrial capabilities for SRF and all other accelerator related technologies**
- **European industry has much to offer and much to gain**







Thank you for your attention

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