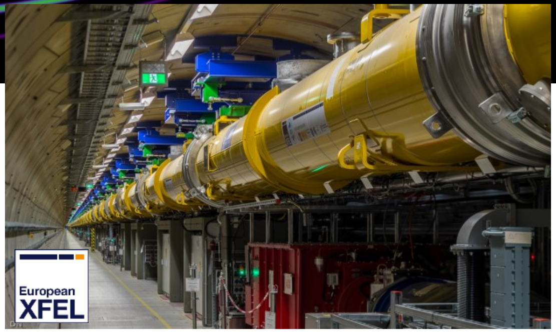
Overview on Future Continuous Wave X-Ray Free Electron Lasers



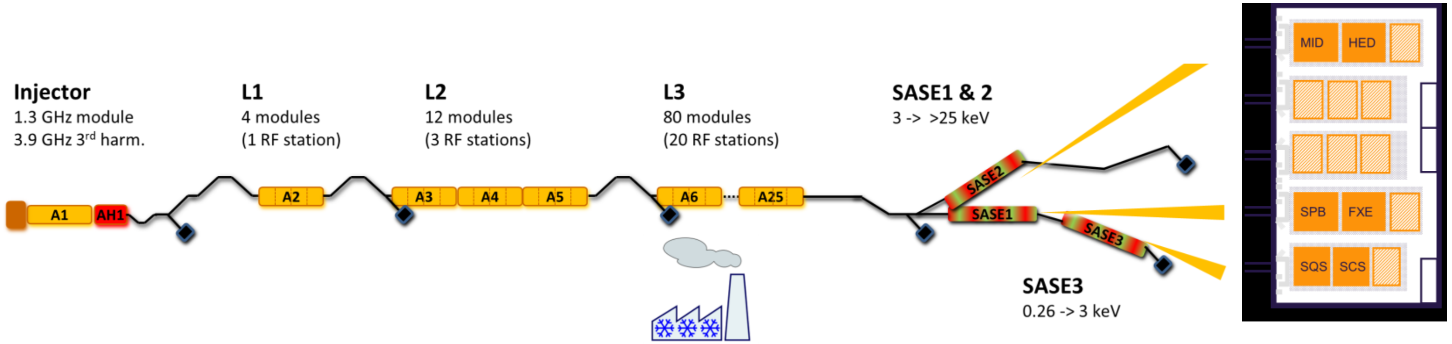
Hans Weise DESY. HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

FOR all the many enthusiastic SRF accelerator experts offering brightest FEL beams

MOB02

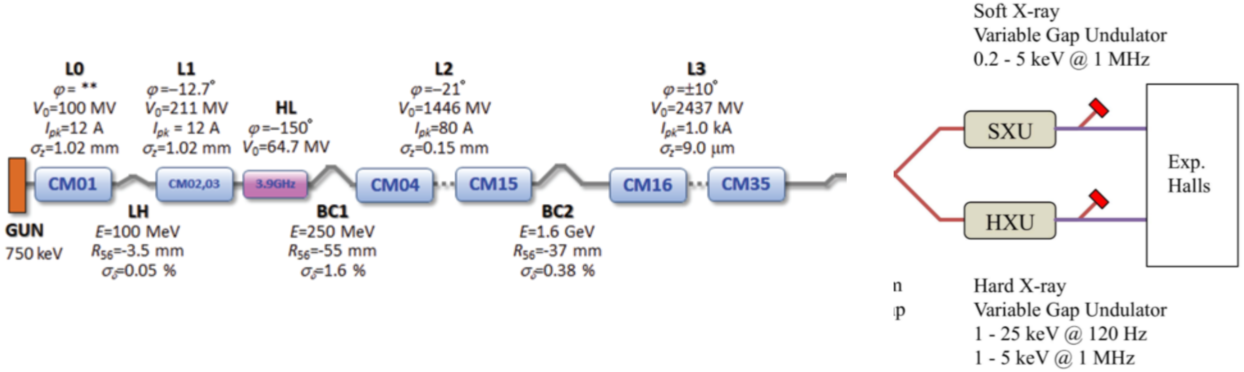
Three Large Facilities

We are going to see three large scale SRF based facilities worldwide



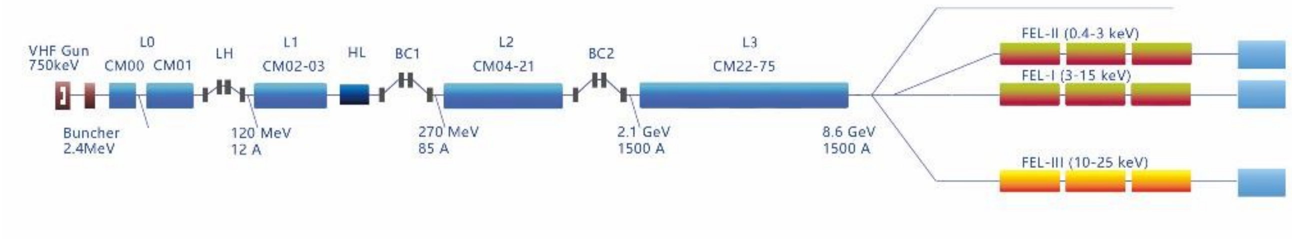
European XFEL

construction during 2009 – 2016
in operation since 2017
cw upgrade after 2025 (?, tbc)



LCLS-II

under construction since 2014
first lasing expected in 2021
HE 8 GeV upgrade until 2026



SHINE SARI

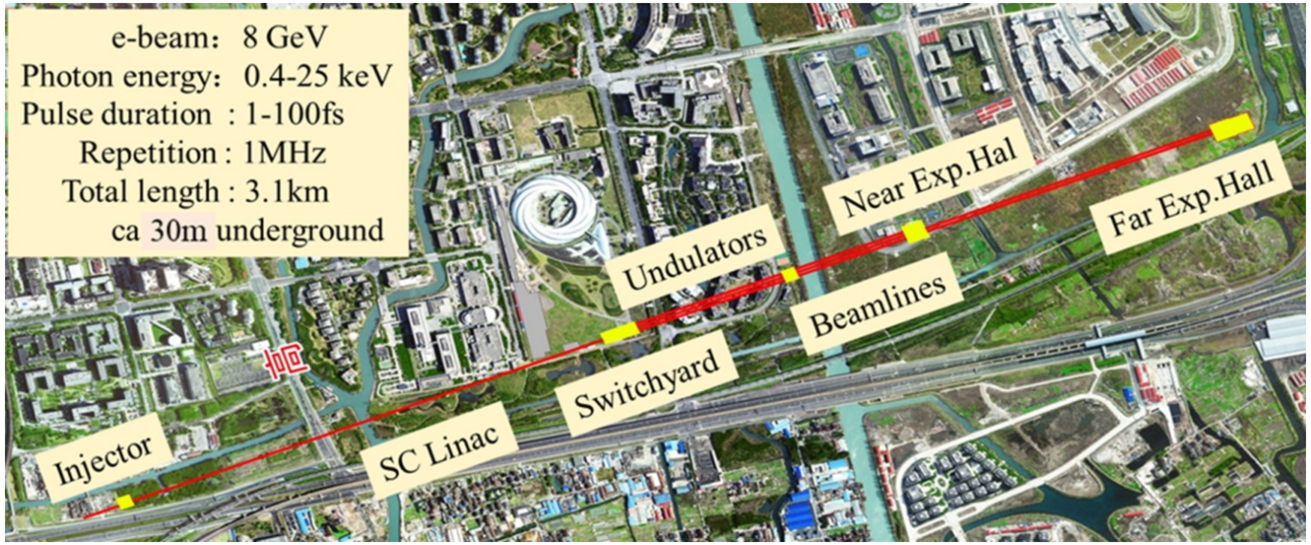
under construction since 2018
to be commissioned in 2025
goal: cw and 8 GeV

Satellite Pictures Show the Size of Facilities

Even red-eyed flight passengers may see it before landing

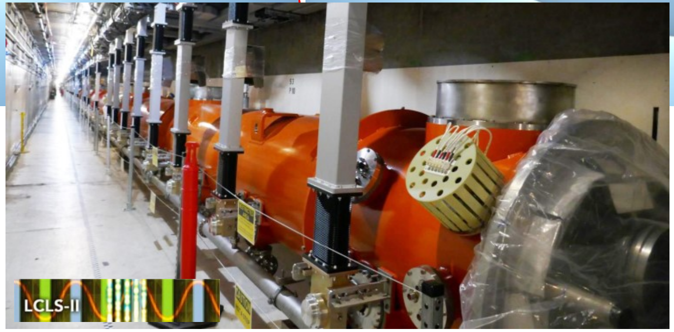
All three facilities

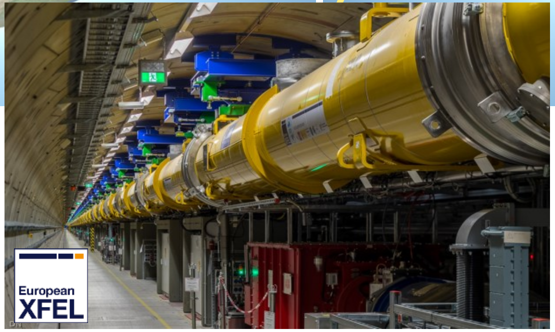
- have a total length of approx. 3 km
- are (being) built in a long tunnel
- SHINE has enormous similarities with E-XFEL
- LCSL-II will be the first cw X-ray FEL and can profit from the existing klystron gallery
- Experiments halls at E-XFEL and SHINE are of soccer field size



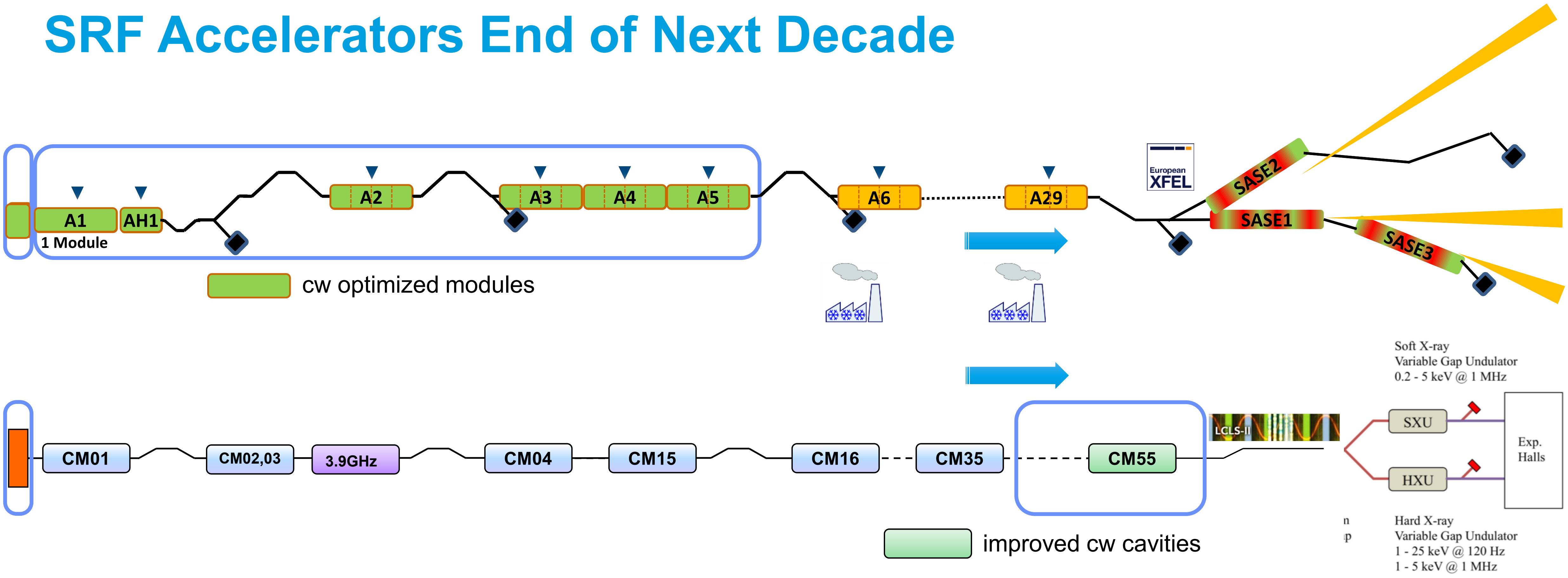
Typical Flight Distance of 12 Hours

SHINE – LCLS-II – XFEL – SHINE – ....





SRF Accelerators End of Next Decade



With the end of the next decade we expect approx. **250 SRF accelerator modules of one family** housing **2,000 superconducting cavities (1.3 GHz, 9-cell).**

- European XFEL and FLASH at DESY 120 modules (Discl.: the European XFEL upgrade is not yet a project)
- LCSL-II at SLAC 55 modules
- SHINE at SINAP 75 modules

The total installed cw electron beam energy will be almost 25 GeV.

History of SRF Accelerator Driven FELs

An absolutely non - exhaustive list of things to remember…

Free Electron Lasers and **SRF accelerators** were connected right from the beginning: The **HEPL SCA** complex was to be used for J. Madey's first experiments (see L. Elias, FEL2017).

One of the first SRF linac proposals came from P.B. Wilson H.A. Schwettman and W.M. Fairbank, 1963 HEAC, Dubna p.694 (1963).

Based on discussions with Schwettman, the **S-DALINAC** at Darmstadt Univ. **was extended by a near IR FEL** (early 90ies).

The successful **CEBAF** construction with SRF knowledge and people transfer from **Cornell Univ.** and elsewhere led to great expertise at JLAB. In consequence, FEL plans were developed and realized.

In the early 90ies the plans for **ELBE at Dresden, Germany**, were developed; here the successful work at Darmstadt and DESY Hamburg had quite some impact.

The **TESLA R&D** was pushed by many experts worldwide. **DESY** emphasized core team activities, started building the TTF facility and almost immediately added FEL plans. The success of the **FLASH facility** is known.

Until the late 90ies we worldwide designed several and built some **cw FELs** with

- low electron beam energy (affordable cryo load)
- recirculating beams, and based on ERL concepts

Today most of the SRF key players take responsibility for substantial contributions to SRF accelerators driving FELs. Almost all TESLA Collaboration members have their visible share.

The Family of X-ray SRF Accelerator Modules

Development started in the early 90ies

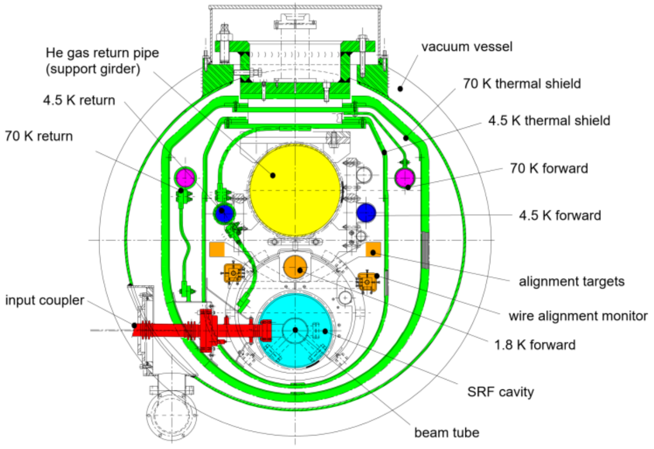
The first 8 cavity TESLA module was designed in collaboration between early TESLA Collab. members, with INFN (C. Pagani) in the lead, with FNAL contributions.

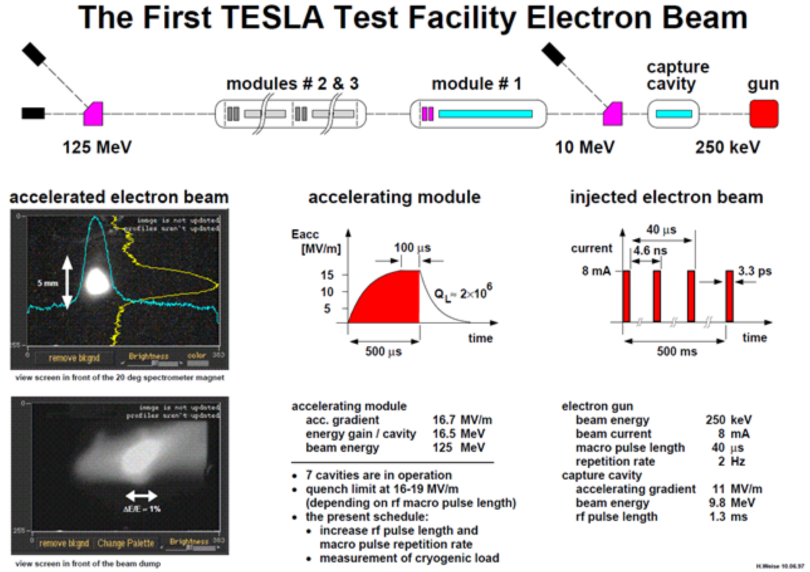
First electron beam was accelerated in 1997. The used cavities were coming from DESY, CEA, and soon from INFN.

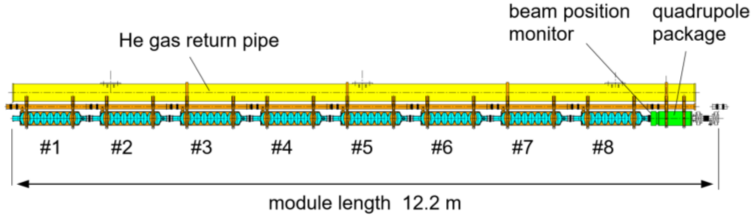
Extensive cavity R&D brought the usable gradient towards 25 MV/m with quality factors high enough to support 800 µs / 10 Hz electron beam operation.

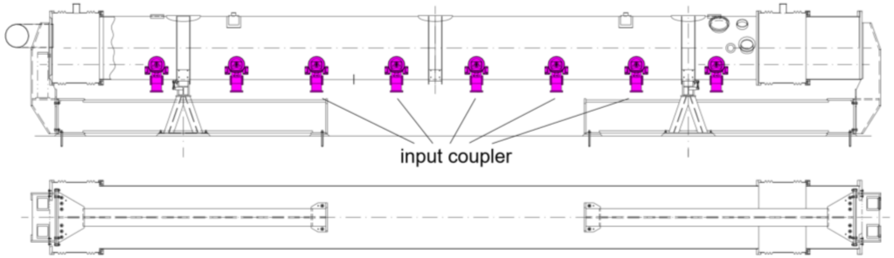
Module sub-systems were developed by TTC; RF power coupler (DESY & FNAL), sc magnet (CIEMAT), freq.tuner (CEA & INFN).

Injector R&D developed from thermionic sources to nc RF guns (typ. 5 MeV, long pulse train, > 5MW, low emittance, Cs2Te).









European XFEL Cryomodule

Improved TTF design; still in operation at FLASH

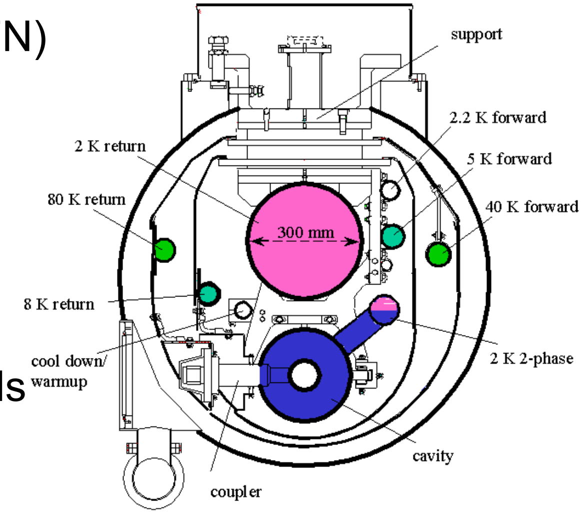
The **next cryomodule generation** (again INFN) addressed

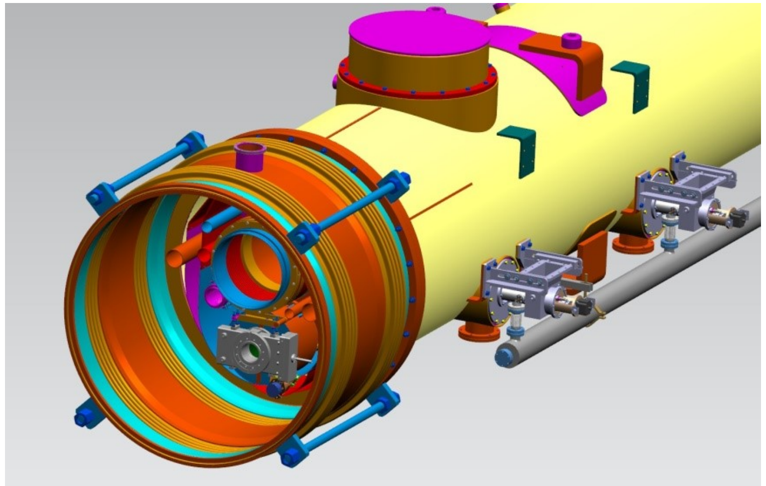
- new concept accommodating longitudinal shrinkage during cool down; adjusted alignment tolerances
- reduced diameter and costs
- redesign of thermal shields incl. finger welds
- so-called TTF-III RF power coupler

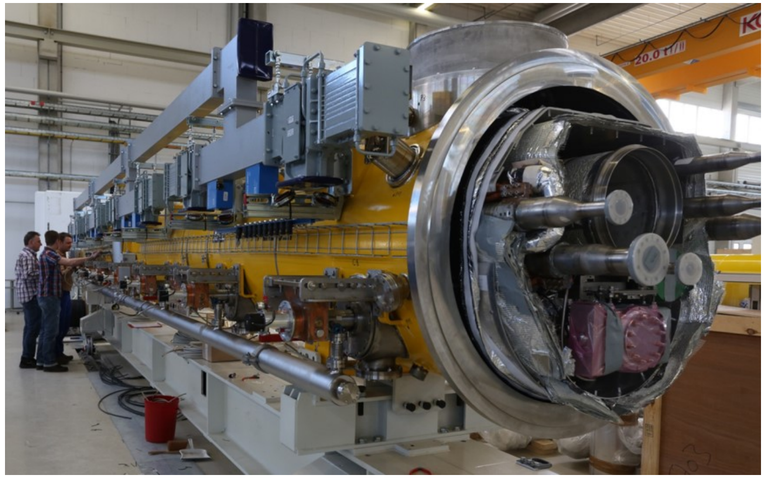
The **final iteration** (DESY and INFN) prepared **for large scale XFEL production**:

- identification of qualified vendors
- optimized assembly
- transport issues

In parallel: INFN work on 3.9 GHz module, based on standard module and FNAL39.







European XFEL Cavities, RF Couplers and Modules

Industrialization (factor 30) was made – 8 cavities & couplers i.e. 1 module every week!

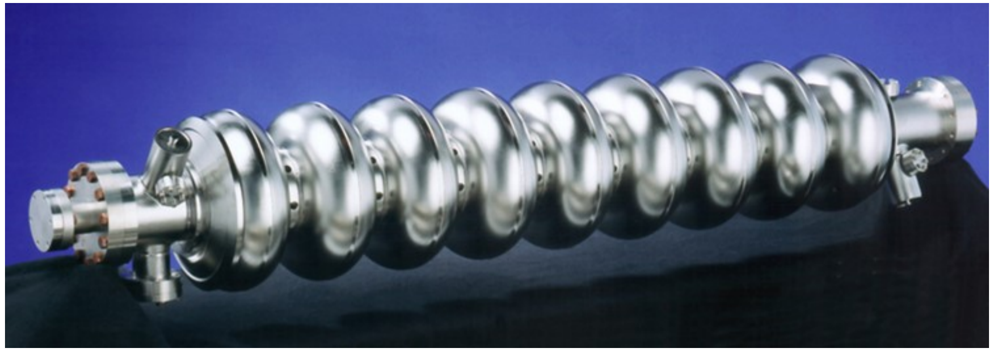
For the first time

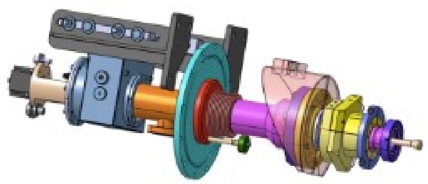
- **800 cavities for 100 modules in two years**
- large scale industrial production
- **DESY coordinated activity with major (!) contributions from in-kind partners**
- almost all previous R&D partners on-board, either in-kind or at least consulting

THE specification was developed for components as well as procedures

- DESY and INFN for cavities & modules
- DESY and CEA for module assembly
- DESY and IN2P3 for RF power couplers
- …

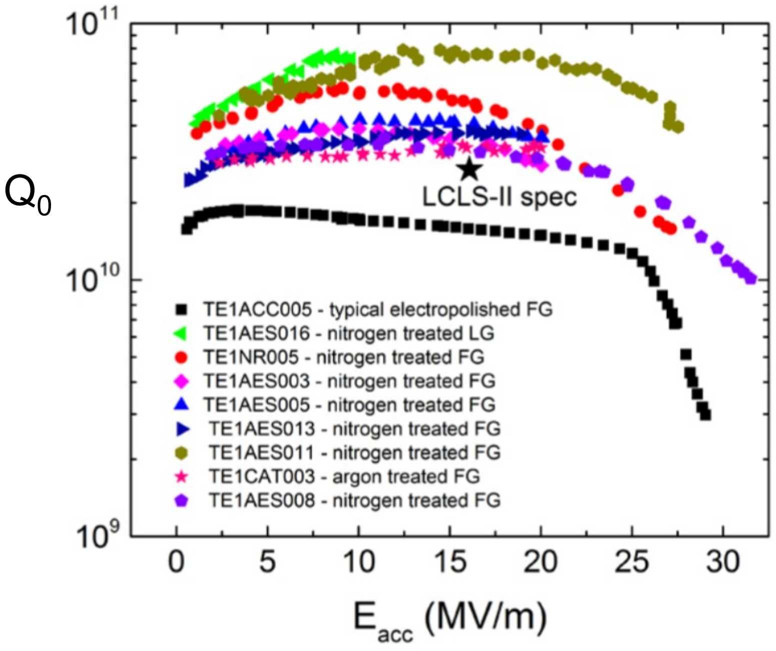
R&D work came to an end, **status frozen for the next 7 years of construction**.





LCLS-II Construction Based on N-doping

Early Fermilab exploration defined the starting point



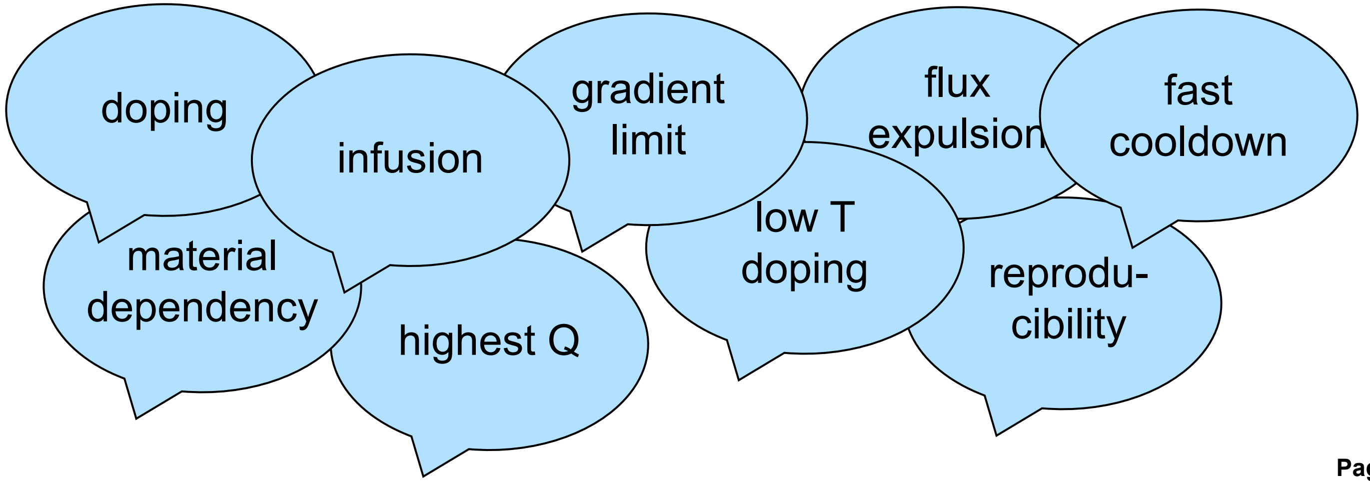
SRF accelerators can be operated continuous wave, assuming acceptable cryogenic load.

Fermilab and JLAB established and further developed so-called **N-doping recipes** to drastically reduce this cryo load. **The challenging LCLS-II specs can be met.**

For detailed R&D issues and discussion see e.g. presentations of scientific work at **TTC meetings (https: tesla.desy.de). Great results!**

The industrial production of improved cavities had initial challenges; many things to learn…

The SRF community profits a lot from FNAL, Cornell, JLAB, …



LCLS-II Module Incorporates Improvements

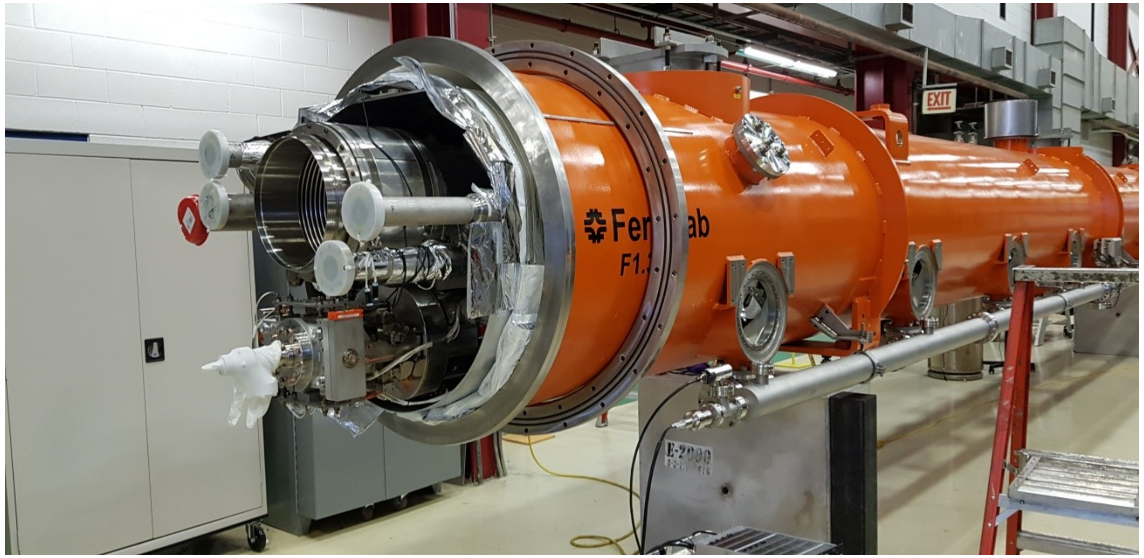
The first cw optimized 'kid in the family'

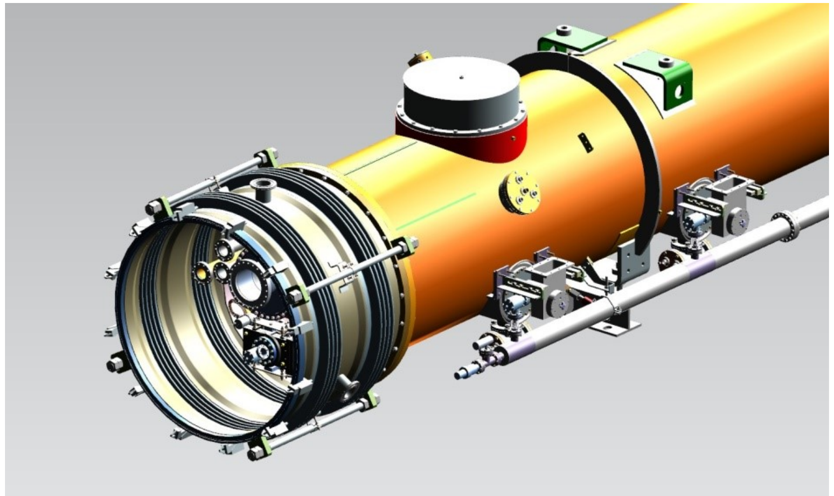
LCLS-II modules incorporate

- XFEL module design
- FNAL R&D results (ILC)
- **improvements** in order to put into effect the achieved cavity performance
  - fast cool-down
  - better magnetic shielding
  - optimized thermal loads in cw operation
  - accessibility of frequency tuners

RF power couplers got thicker copper plating of stainless steel surface; otherwise unchanged.

Unfortunately some lessons were to be learned wrt. long distance module transport.





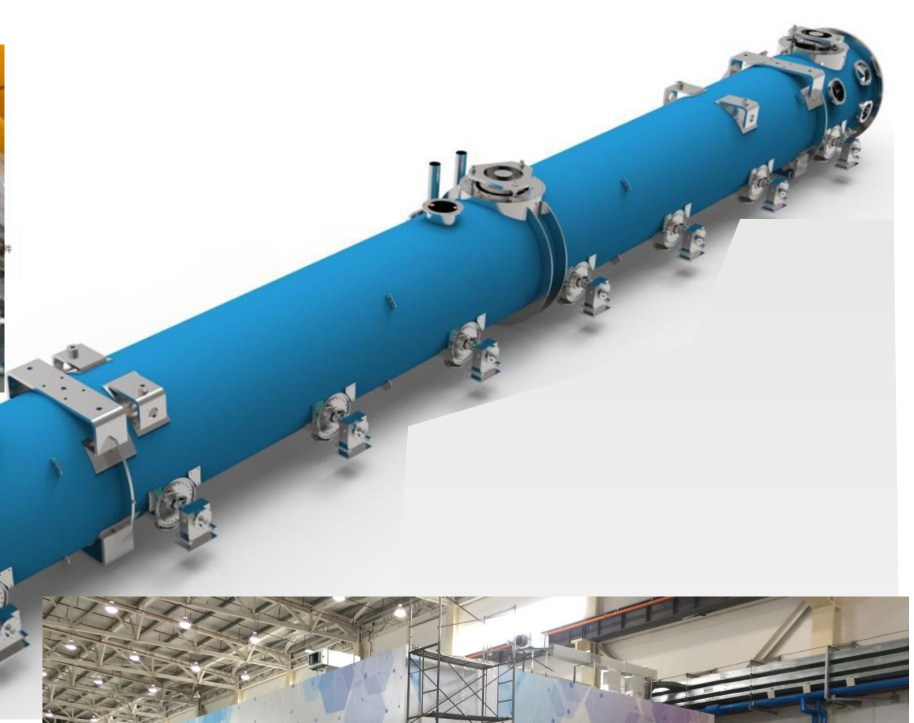
And Now Comes SHINE

Chinese institutes are well known TESLA partners

SHINE activities profit from

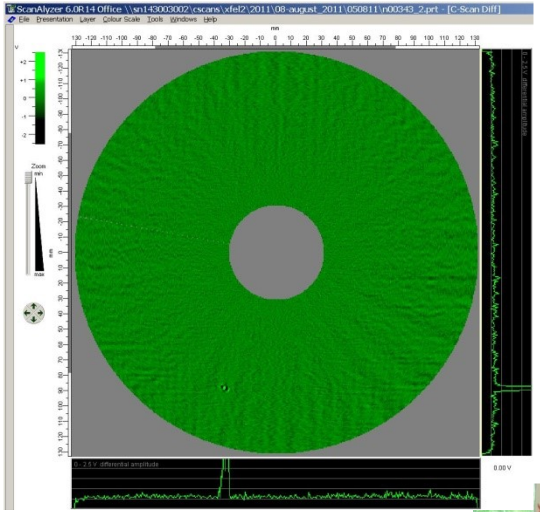
- Published XFEL and LCLS-II R&D results
- Published TESLA / ILC R&D results
- Longtime TTC membership of several Chinese institutes (**IHEP, PKU, Tsinghua, IMP**)
- **IHEP Beijing** qualified a vendor (CX / WUXI) by building an XFEL prototype cryomodule
- IHEP was contracted to build 58 of the 103 **European XFEL cryostats**, with execution at WUXI
- Meanwhile WUXI activities include fabrication of all **LCLS-II cryomodules**, and also **FRIB cryostats and transfer lines**.
- Last BUT NOT LEAST: a large fraction of the Nb sheets used are coming from **OTIC Ningxia**.

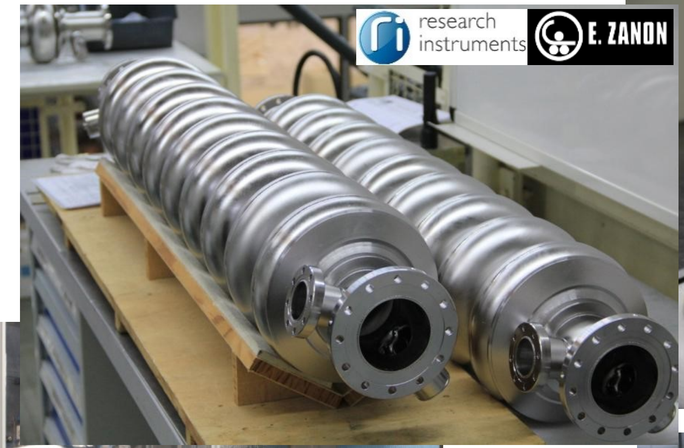
More about several years of industrialization at Chinese vendors see e.g. J. Gao, ICHEP2018.

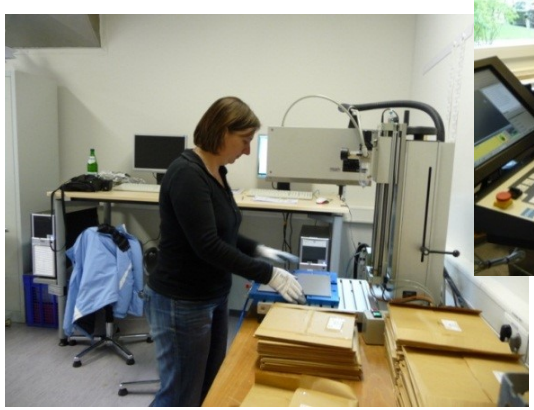


Construction of Large XFELs Requires Industrialization

Industrialization, logistics AND quality management is a must







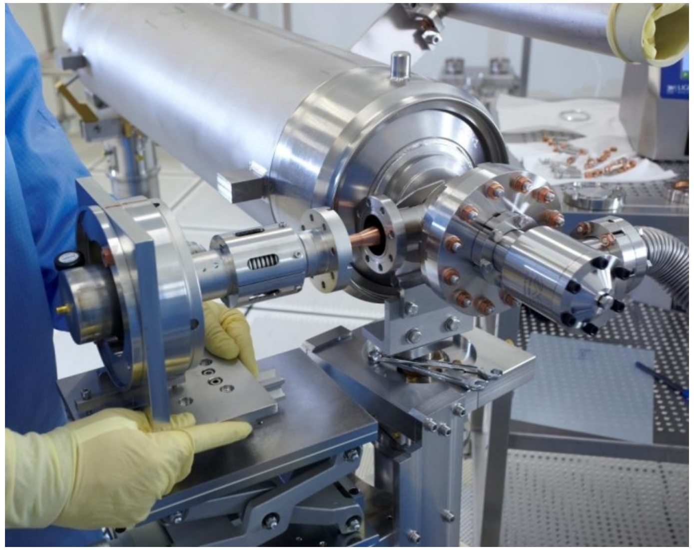
QS of Niobium sheets
(developed for E-XFEL, now done at DESY for all SRF based (large) scale facilities)

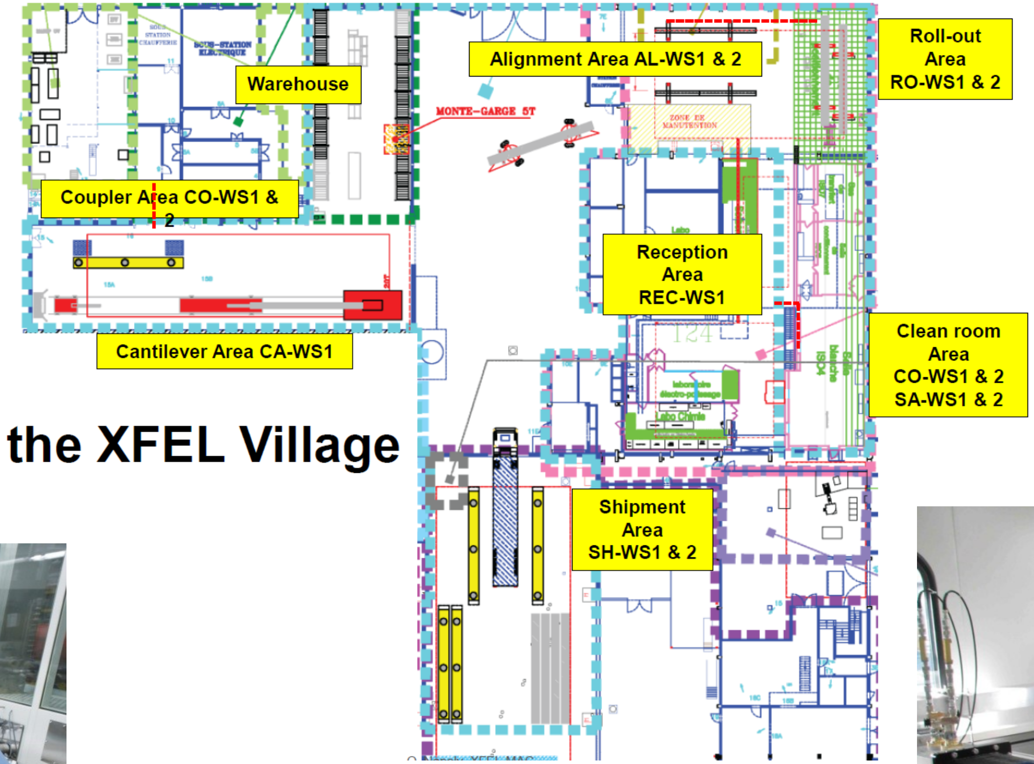
Tools for **successful cavity fabrication in industry** were developed and handed over, but are still maintained by DESY.

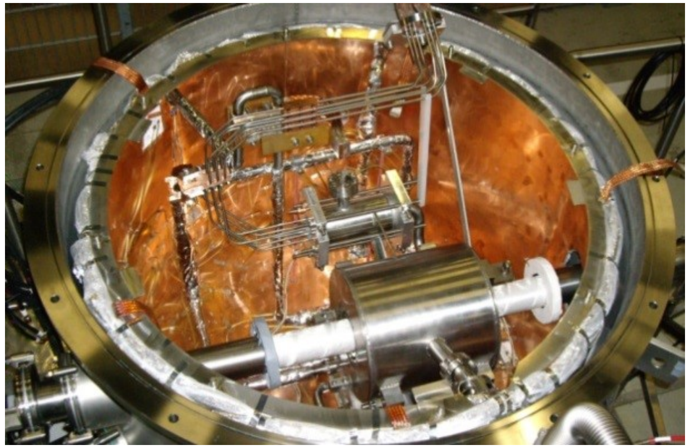
Cavity tuning machine
(developed (w/ FNAL support) and handed over, and still maintained by DESY)

Several Laboratories Operated European XFEL Infrastructure

Infrastructure at DESY, IRFU / CEA Saclay, and LAL Orsay



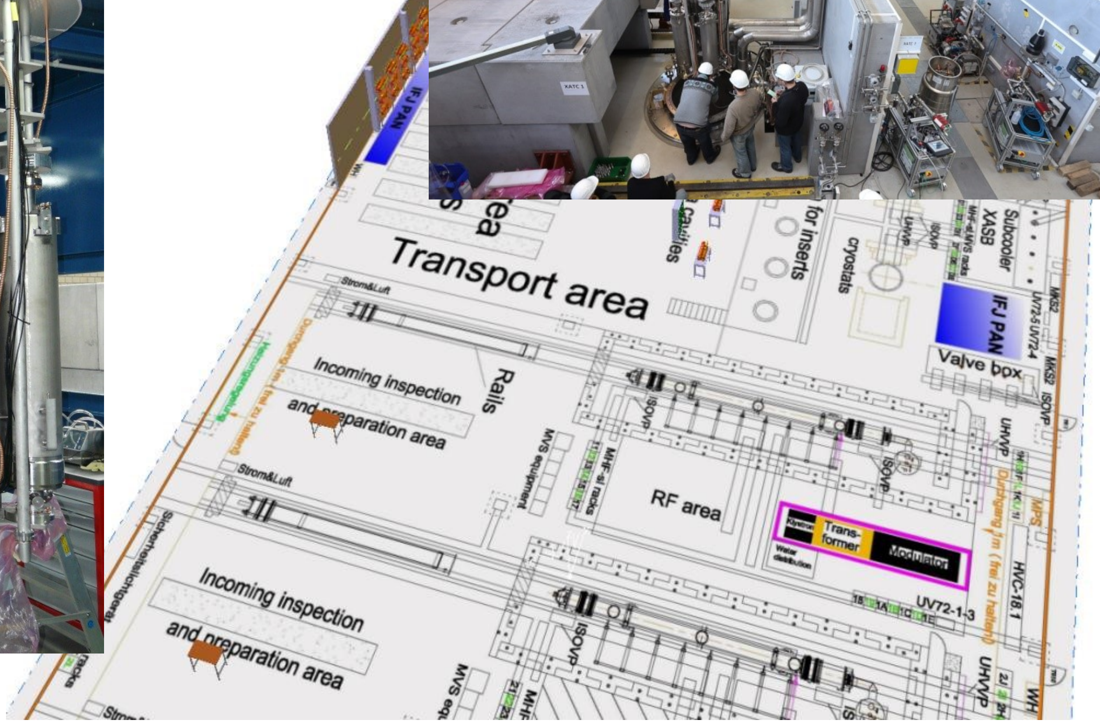




Remarkable SRF infrastructure was set-up by several partners of the Accelerator Consortium.

Component Testing and Quality Assurance for E-XFEL

The Accelerator Module Test Facility (AMTF) Facility at DESY



Test stands (cavity & module) were designed, built and operated, with the help of major in-kind contributions.

Installation Can Be Challenging

Strong expert teams (engineering, installation, logistics) are required

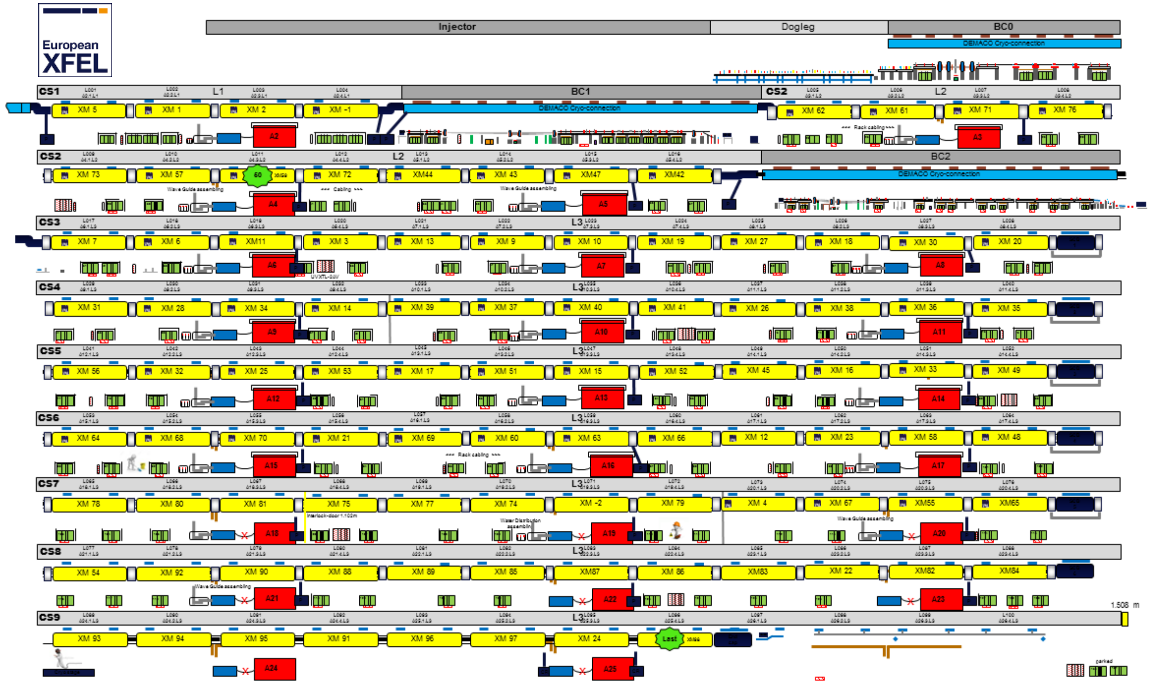










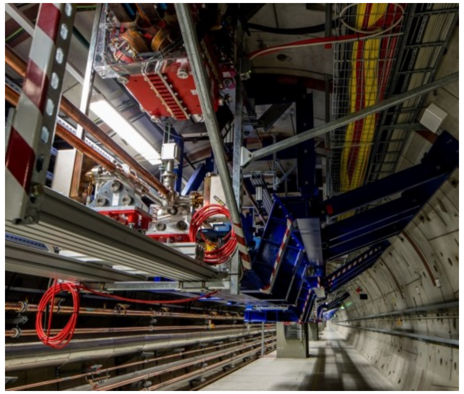
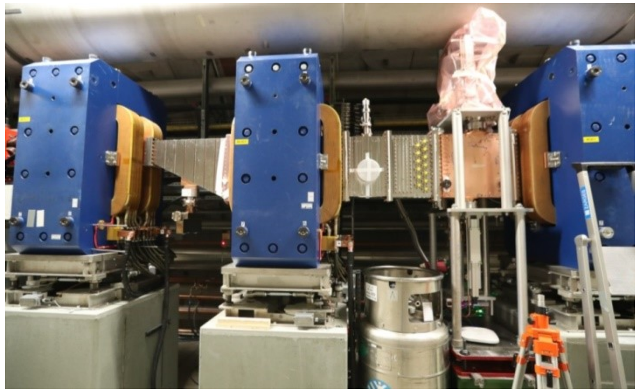



Ramp up as a common effort

The supply chain included many sub-systems, and had critical dependencies. From the parts procurement until the final installation.

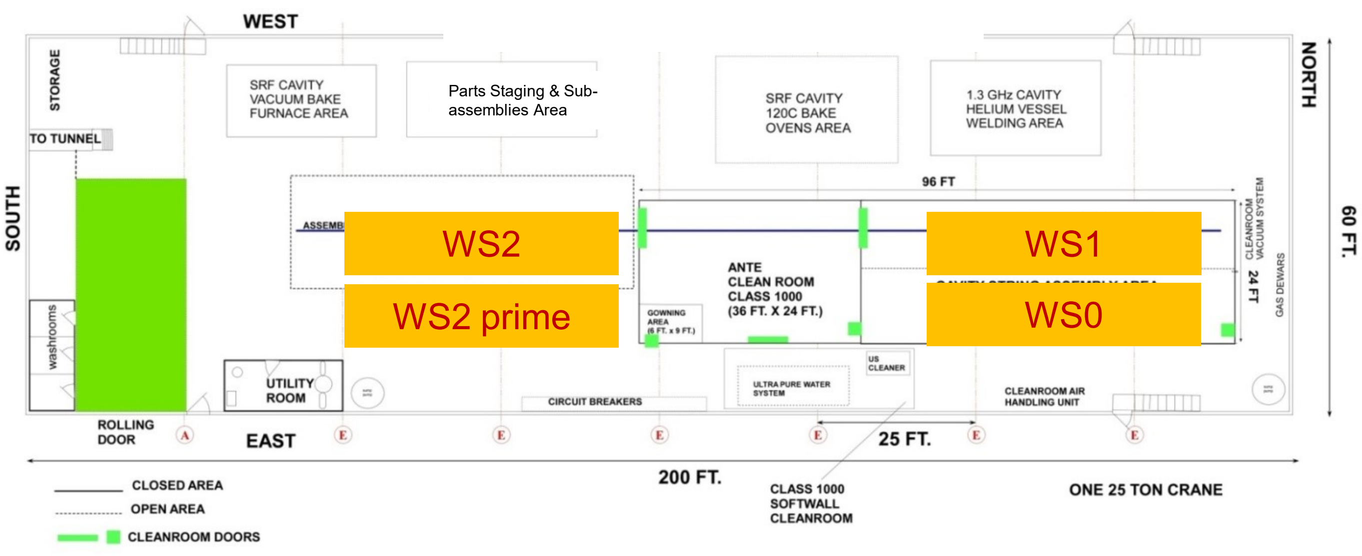
IMPORTANT DISCLAIMER

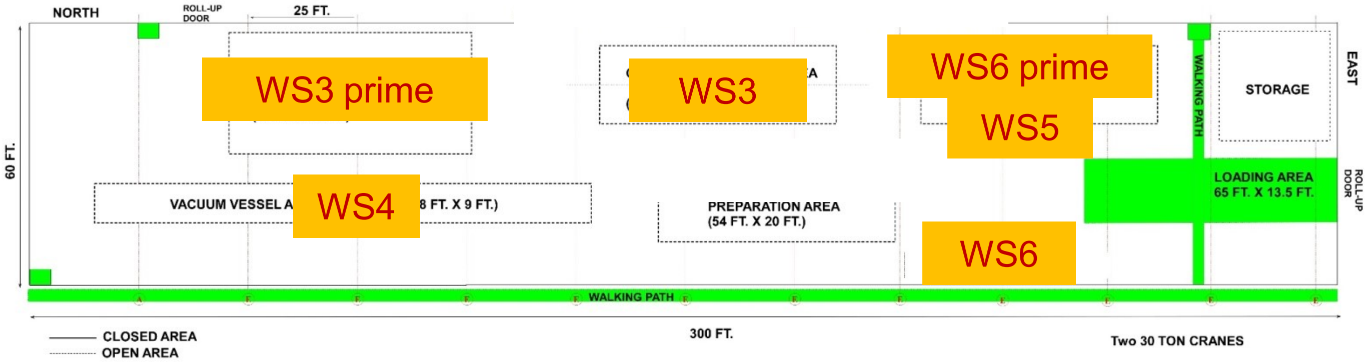
Building an X-ray FEL requires much more than only SRF Modules. This presentation highlights SRF but esteems all other contributions and sub-systems (often identical w/ nc facilities).

Fermilab and JLAB are Strong LCLS-II Partners

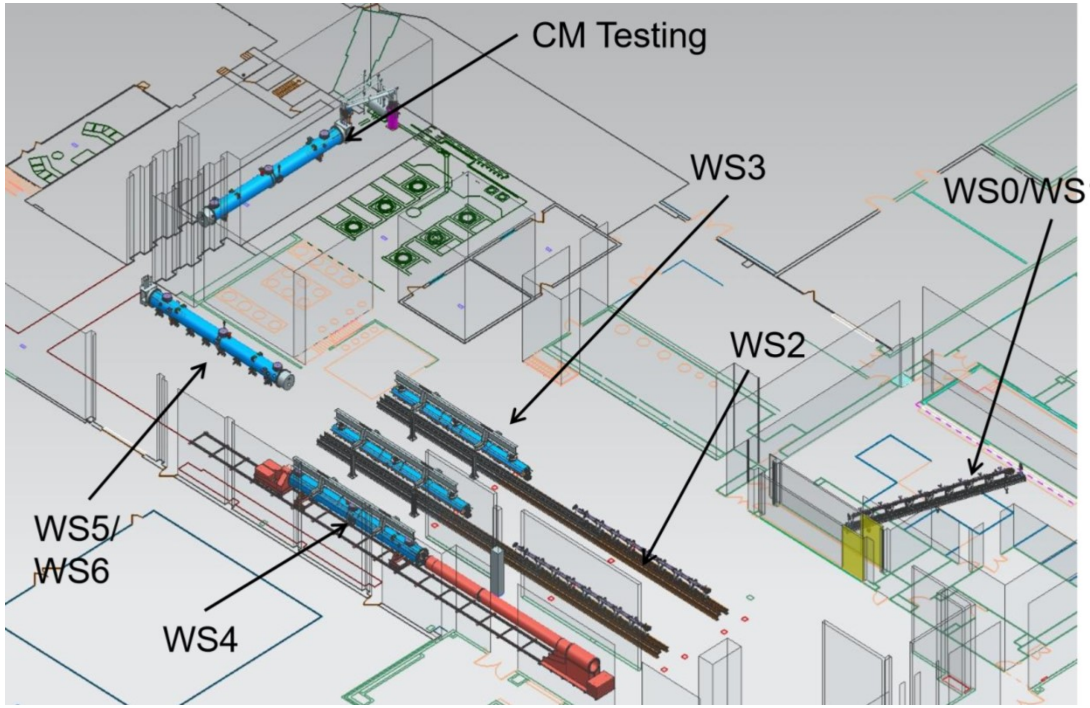
Infrastructure at Fermilab has strong similarity with CEA and DESY set-ups





Fermilab and JLab are Strong LCLS-II Partners

Infrastructure at JLAB mimics functionality of E-XFEL facilities



LCLS-II collaborative effort

- Jefferson Lab builds and tests 21 –1.3 GHz cryomodules
- Fermilab builds and tests 19 –1.3 GHz cryomodules and 3 – 3.9 GHz cryomodules
- SLAC receives, inspects and installs the cryomodules
- CM interconnect welding after DESY training
- RF connection etc. is long time SLAC expertise
- procurements were split ~ 50/50 between JLab and FNAL
- SLAC procured fundamental power coupler

New Infrastructure for SHINE under Construction in China

Infrastructure for SHINE is going to be commissioned

The new infrastructure at SINAP

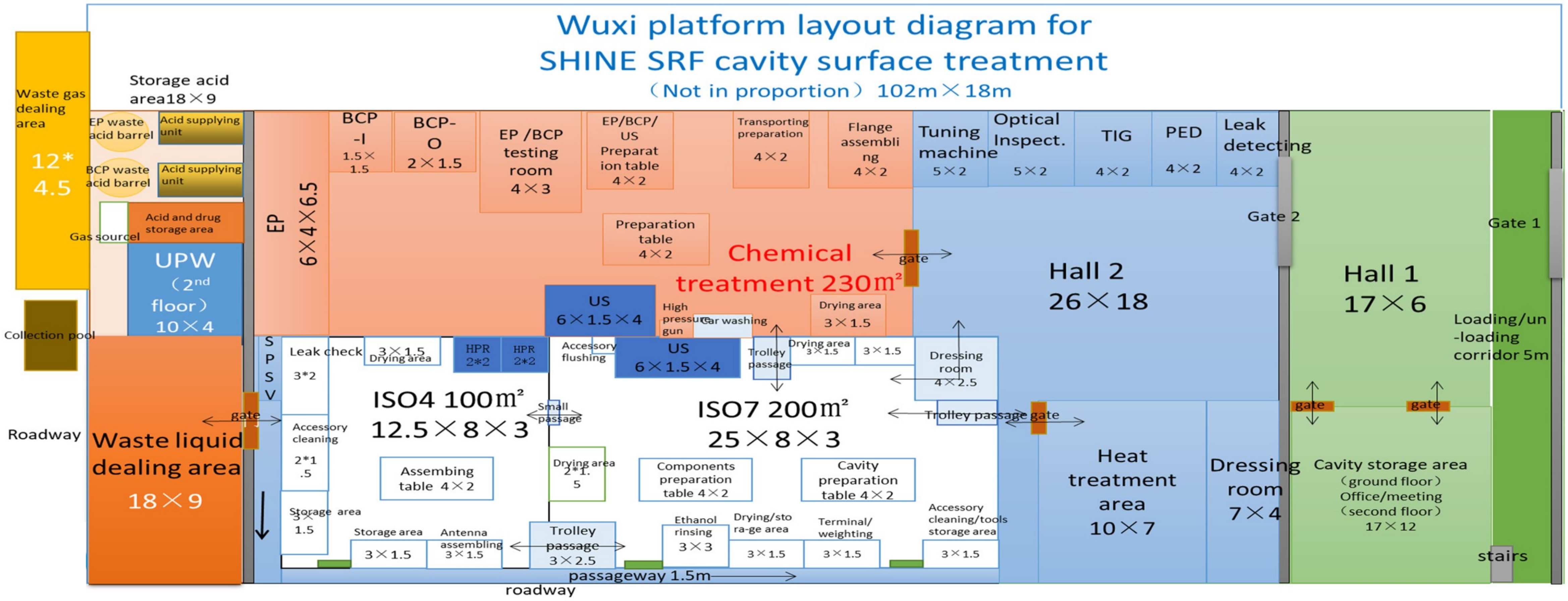
- ISO4 & 7 cleanrooms for assembly
- cryogenic test bench
- ultra pure water systems
- cryomodule assembly station

Similar infrastructure under commissioning at

- IHEP Beijing and CX / WUXI
- cavity fabrication at OTIC Ningxia

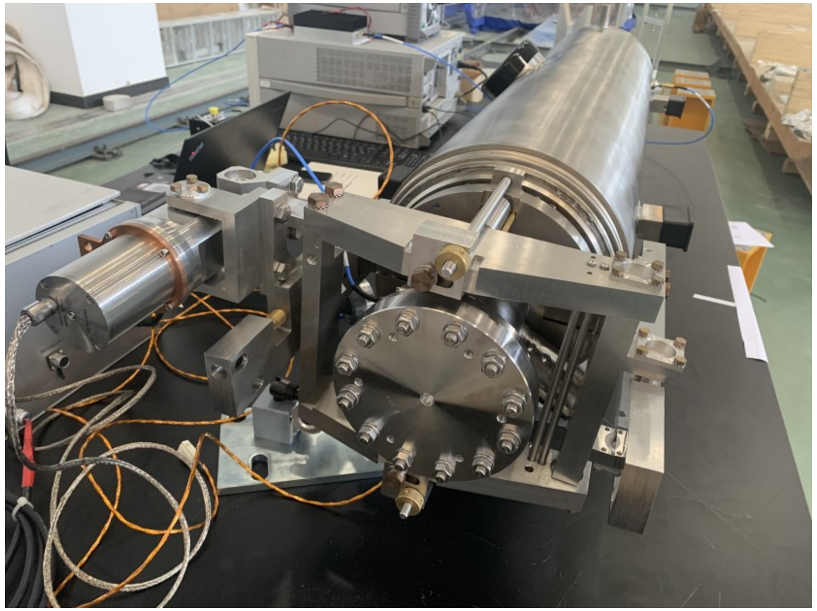
New Infrastructure for SHINE under Construction in China

The company CX Wuxi is located roughly 150 km west of Shanghai.



Prototype Components for SHINE

Infrastructure for SHINE is going to be commissioned



Prototype components

- 1.2 GHz cavity with auxiliaries
- Fundamental RF power coupler
- sc focusing magnet
- CW solid state amplifier

Cavity fabrication and vendor qualification at different places; backup for SHINE are European cavity vendors.

Collaboration with DESY on new materials and training.

LCLS-II Installation at SLAC

Roughly 50% of modules are in the tunnel

Civil Construction at SHINE Proceeds

SRF hall, cryogenic building and shaft#2 on the SARI campus

CW X-Ray FELs Call for R&D

Improved cavities and modules AND electron sources are required

Cavities

- worldwide activities on **N-doping and N-infusion** to find even better recipes
  FNAL, JLAB, Cornell
  DESY, KEK, China and others
- **large grain Nb** material including qualification according to pressure equipment directives
  DESY, KEK, China and others

Modules

- **operation of existing SRF modules** in cw mode, or at least long pulse
- cw operation of **RF power couplers**
- development and test of **cw RF power sources**

ALL cw X-ray labs and contributors

CW electron sources

- SRF gun would give highest flexibility
- LCLS-II solution (Berkeley APEX gun) requires next generation to support lasing at high electron beam energies

ALL cw X-ray labs and others (FZDR, BNL, DESY, KEK, …)

X-ray Facility Construction is a Worldwide Team Effort

Peaceful research allows for fruitful collaboration AND connects the world

European XFEL

SHINE

- good scientific practice
- collaboration
- common R&D
- peaceful research
- science diplomacy
- intellectual property
- dual use
- strategy
- world politics
- openness
- naivety
- copy with due respect
- ask before take
- caution
- hope & friendship

Many Thanks to all SRF Enthusiasts Working for X-ray FELs

We strongly collaborate… and face the need for competition only in some moments

Special thanks to Marc Ross / SLAC and Dong Wang / SINAP for providing material for this overview.

Additional material used from other published conference presentations, e.g. SRF2019 (Andrew Burrill and Hongtao Hou).