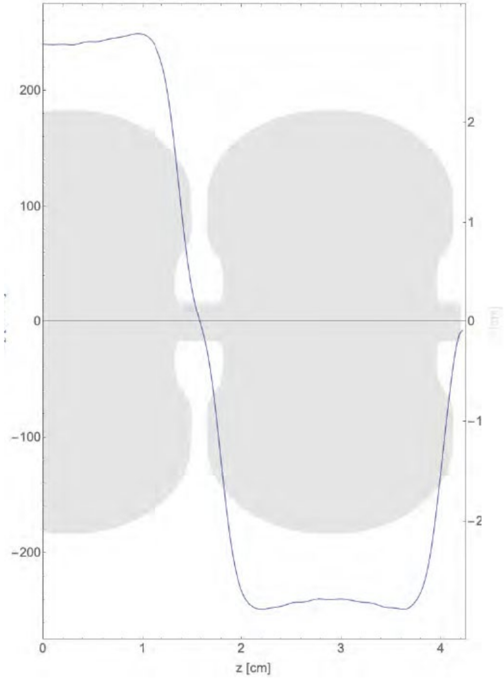
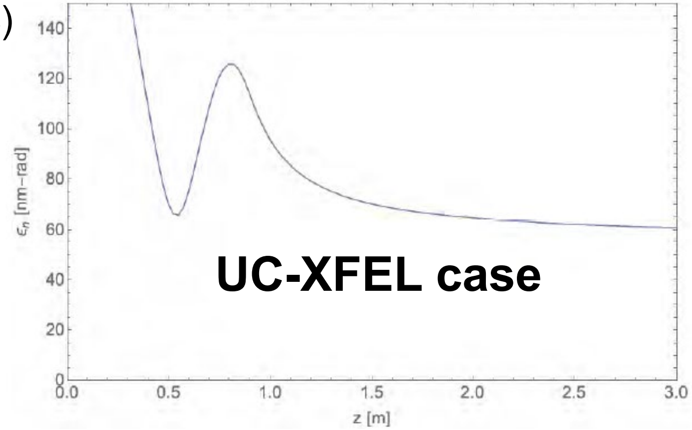
Ultra-high brightness cryo-photoinjector

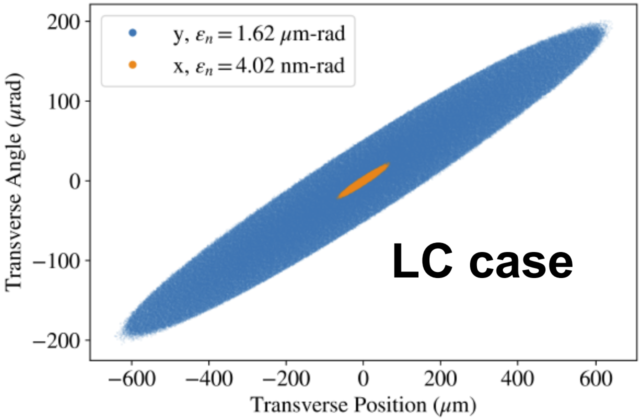
Fields: gun E_0=240 MV/m, solenoid B_0=6 kG

Optimized RF design (as in linac)
High spatial harmonic content





UC-XFEL case



LC case

Emittance: **<55 nm**
(400 nm in LCLS inj.)
Peak current 20 A.
Enabling element
of ultra-compact XFEL
J. Rosenzweig et al., *New Journal of Physics* (Oct. 2020)

Magnetized cathode case after skew-quad removal of angular momentum; split ε for linear collider (GARD)

Timothy Barklow

X-ray FEL-based γγ Collider Higgs Factory

XFEL γγ Colliders Provide a Unique Physics Environment

- 1 keV X-ray lasers, rather than optical lasers, provide a unique opportunity for a γγ Higgs factory. A year long scan generating 15K Higgs could detect a total Higgs width as small as 40 MeV.

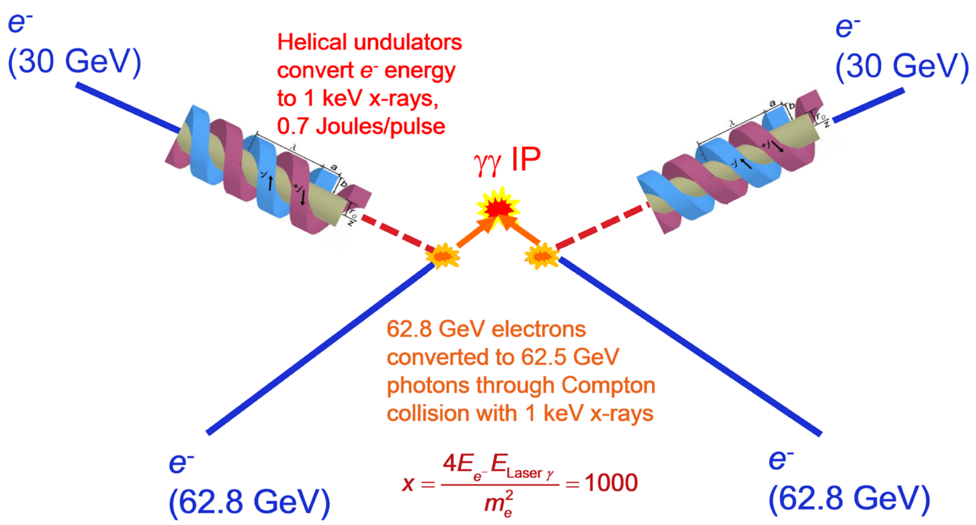
  n.b. Γ_{tot} @ $\gamma\gamma \equiv \sigma(ZH)$ @ e^+e^-

- This γγ Higgs factory would produce Higgs at the same rate as the ILC even though the γγ luminosity is 10x smaller.

- γγ backgrounds are much better than an optical laser collider (see figures). $e^-\gamma$ and e^-e^- backgrounds must also be considered since the $e^-\gamma$ (e^-e^-) lumi is 4x (2x) larger than the γγ lumi.

- Low energy electrons and γ's following multiple Compton scatters are a concern, and will be studied with CAIN.

$\sqrt{s_{\gamma\gamma}} = 125$ GeV   30,000 Higgs/year



e^- (30 GeV)

e^- (30 GeV)

Helical undulators convert e^- energy to 1 keV x-rays, 0.7 Joules/pulse

γγ IP

62.8 GeV electrons converted to 62.5 GeV photons through Compton collision with 1 keV x-rays

e^- (62.8 GeV)

$$x = \frac{4E_{e^-}E_{\text{Laser}\,\gamma}}{m_e^2} = 1000$$

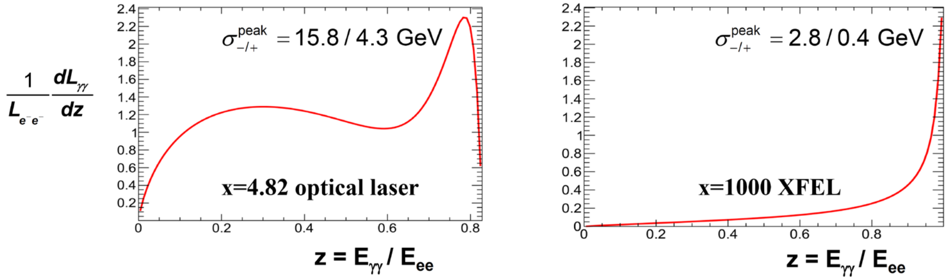
e^- (62.8 GeV)

Low emittance RF gun ⇒ no damping ring

Non-linear QED $\xi^2 = 0.16$

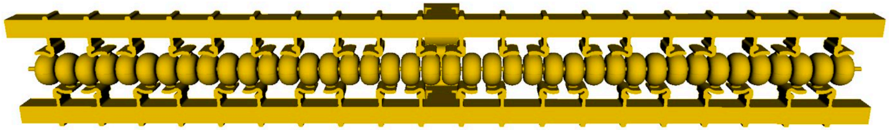
Due to e^- & laser polarization, Compton IP $\gamma\gamma \to e^+e^-$ negligible

Compton IP $e^-\gamma \to e^-e^+e^-$ scattering scales $E_{\gamma\gamma}$ peak by 70%.



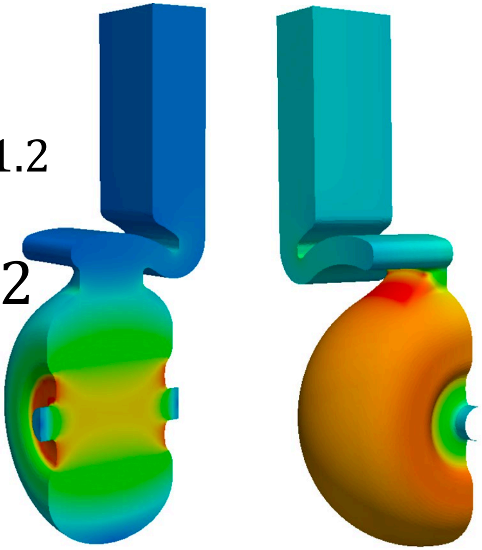
First Meter Scale Prototype in Development at C-band

One meter (40-cell) C-band design with reduce peak E and H-field



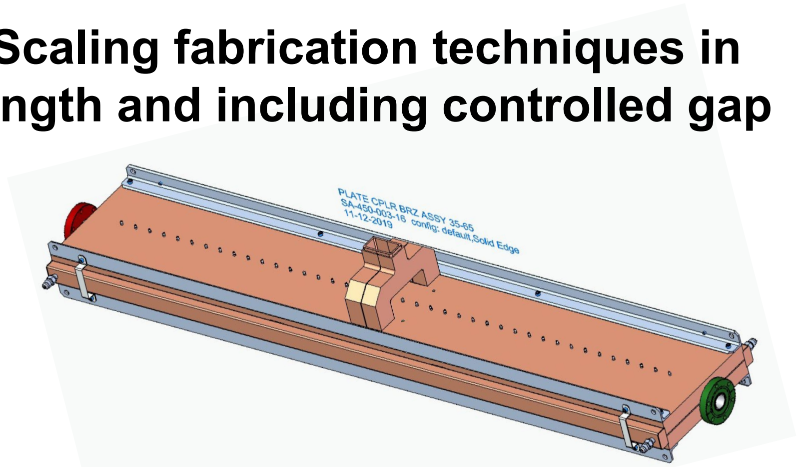
$$\frac{H_{peak}}{H_{unperturbed}} = 1.2$$

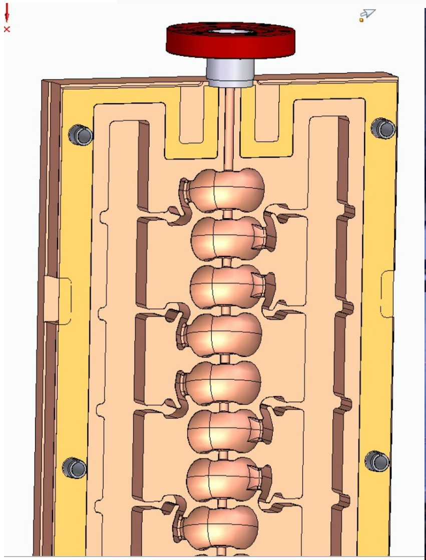
$$\frac{E_{peak}}{E_{acc}} = 2.22$$

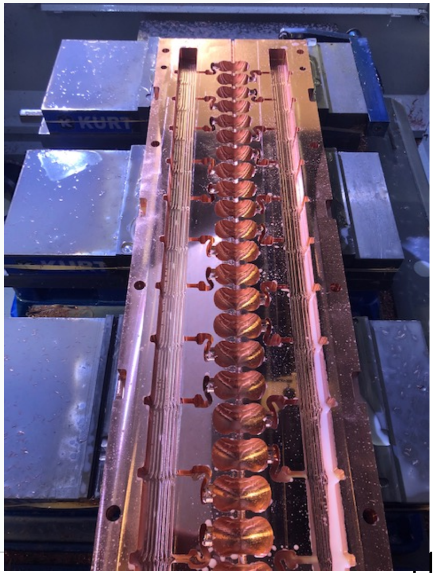


S. Tantawi, and Z. Li

Scaling fabrication techniques in length and including controlled gap



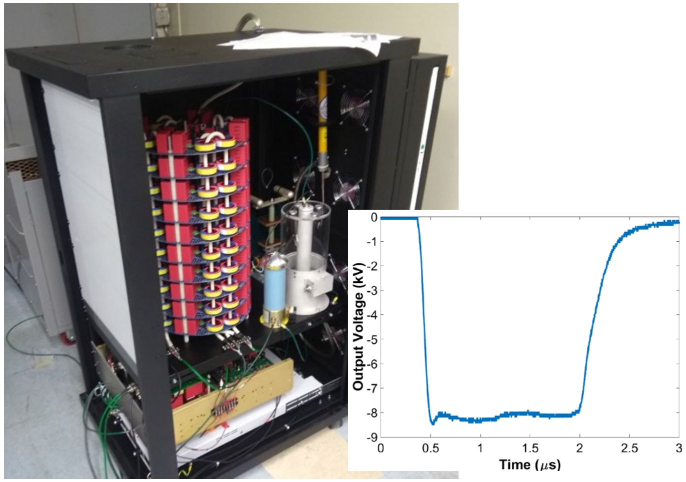


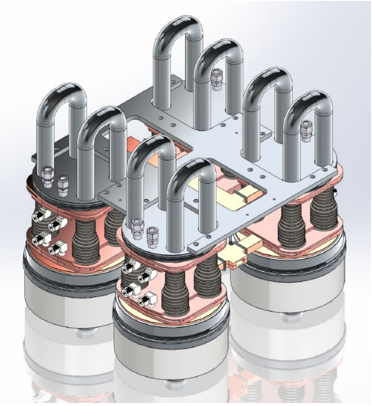


RF Source Development for Accelerator Technology Requires Large Commercial Scale Applications

- Multiple active programs for compact high-flux x-ray sources for security and medicine: NNSA, DHS, Stanford Medical
- DHS: Cost is a key driver - full screening at ports of entry requires km-scale production
- All aspects of RF accelerator transitioning to industry

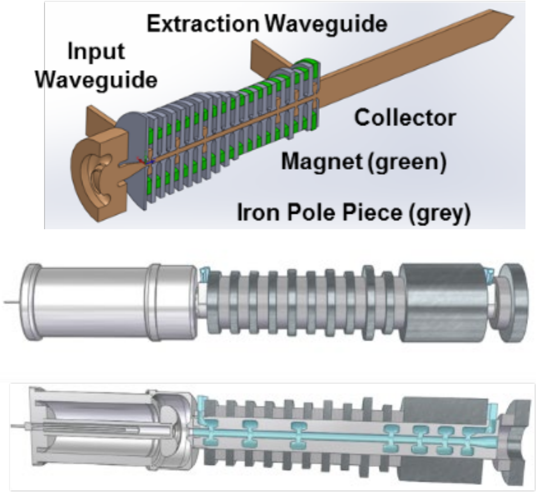
Low-cost “Digikey Catalog” Marx Modulator





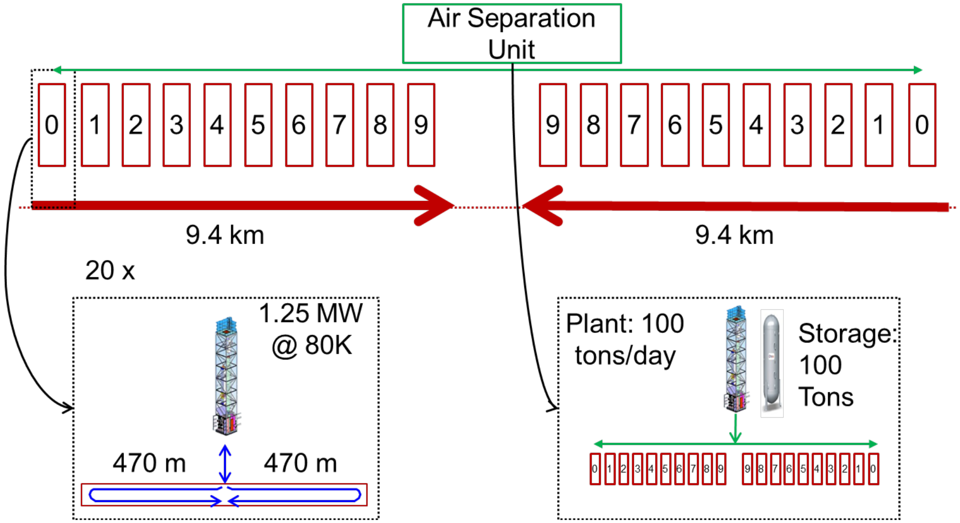
Modular Klystron Array operating at extremely low voltages

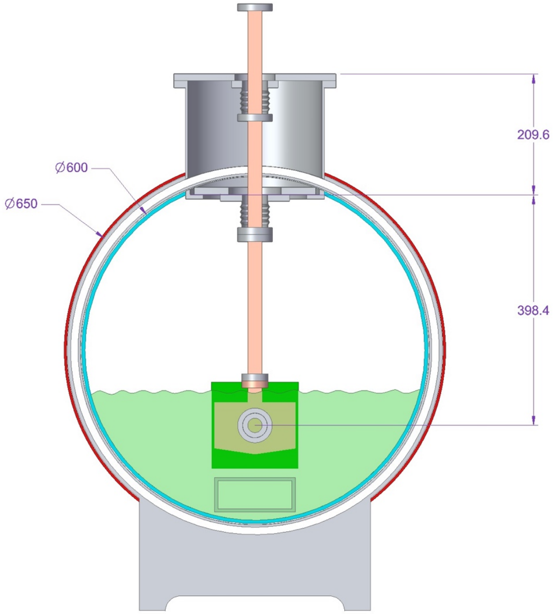
Integrated Pole Pieces/ Long Period Halback Arrays



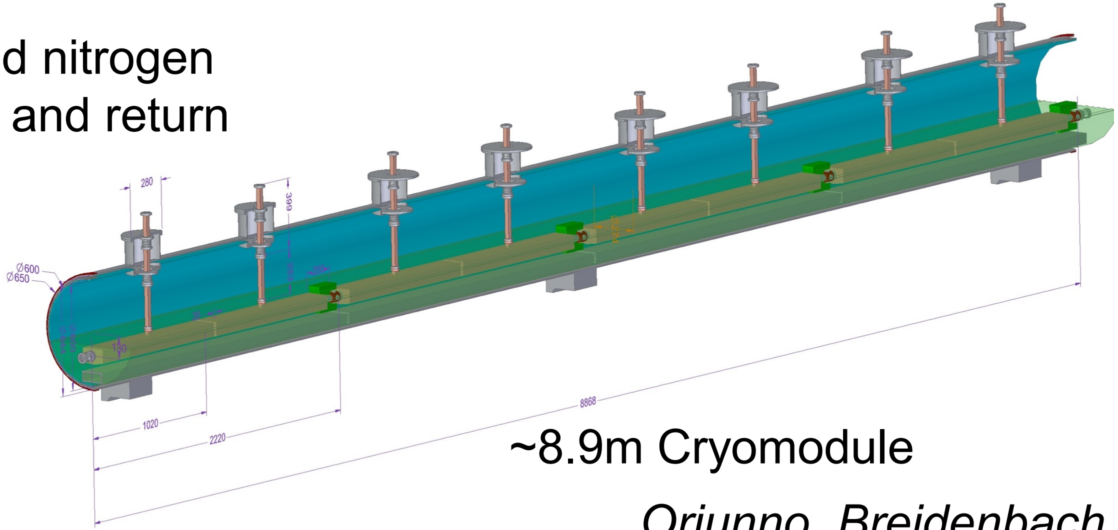
Preliminary ΔE = 1 GeV Cryomodule Design for High Average Power Implementation with ~90% Fill Factor

- X-band structure demonstrated full average power over short length (0.25 m)
- Cryomodule design developed for cryoplant layout to cool 24 MW/linac thermal load at 77K





Shared nitrogen supply and return



~8.9m Cryomodule

Oriunno, Breidenbach

C^3 Technical Maturity

- Overall Technical Maturity

  2 – Some R&D in a few key areas required (scaling modular units)
- Critical Technologies and TRL level
  - RF source cost reduction; commercial options available R&D to reduce cost – TRL 6
  - Wakefield detuning / damping – integrate quadrature damping into design – TRL 3
  - Cryogenic system and alignment systems – TRL 4
- Technically limited timeline
  - 2 yrs meter scale – with wakefield damping, cryogenics and dedicated rf source
  - 4 yrs to modular GeV units

CEPC Accelerator R&D Priority

1) CEPC 650MHz 800kW high efficiency klystron (80%) (No commercial products)

2) High precision booster dipole magnet (critical for booster operation)

3) CEPC 650MHz SC accelerator system, including SC cavities and cryomules

4) Collider dual aperture dipole magnets and dual aperture qudrupoles

5) Vacuum chamber system

6) SC magnets including cryostate

7) MDI mechanic system

8) Collimator

9) Linac components

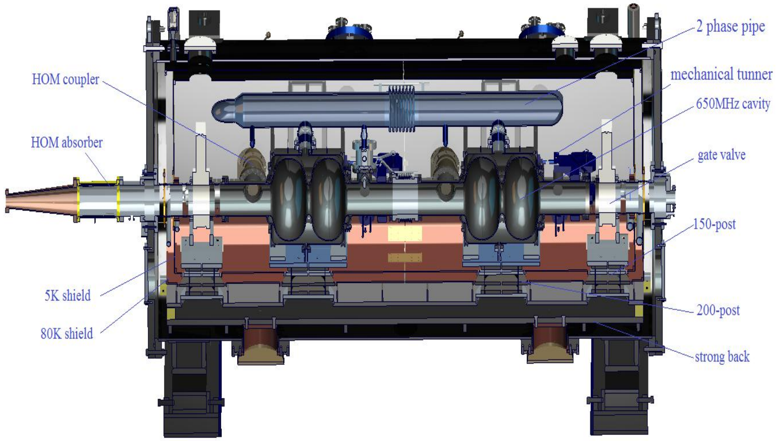
10) Civil engineering design

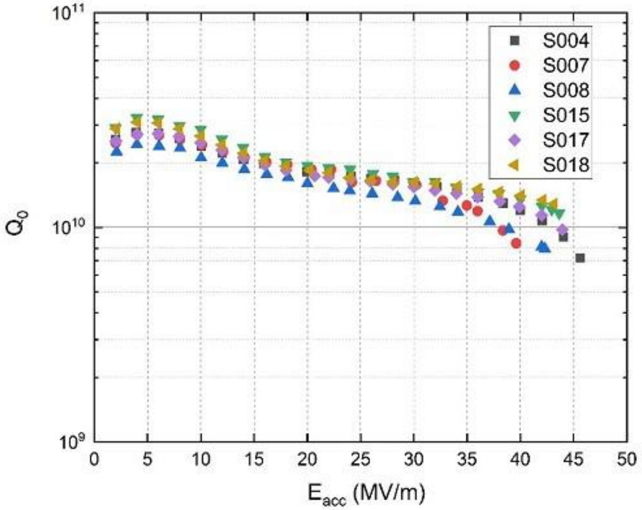
11) Plasma injector

12) 18KW@4.5K cryoplant (Company)

CEPC SCRF R&D Progresses

CEPC 2*2cell 650MHz cryomodule with beam test later





1.3GHz fine grain single cell:

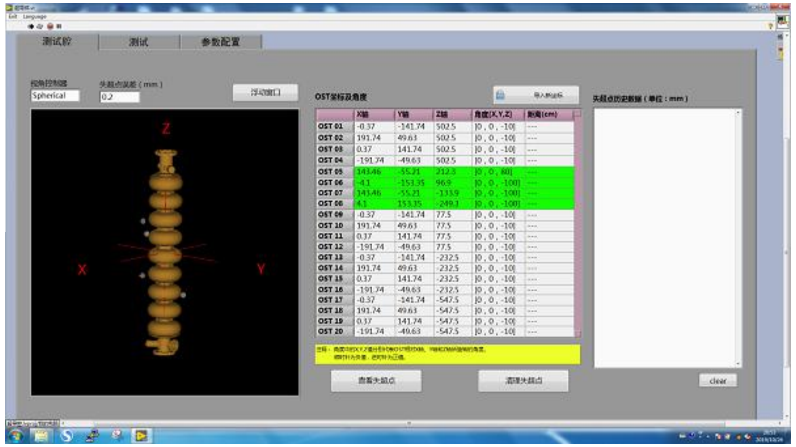
1) 45.6MV/m

2) 43MV/m@Q01.3×10¹⁰

(2020-12-25 at IHEP)

General superconducting cavity test cryomodule in IHEP New SC Lab

SC cavity vertical test temperature monitor system established



视角控制器: Spherical

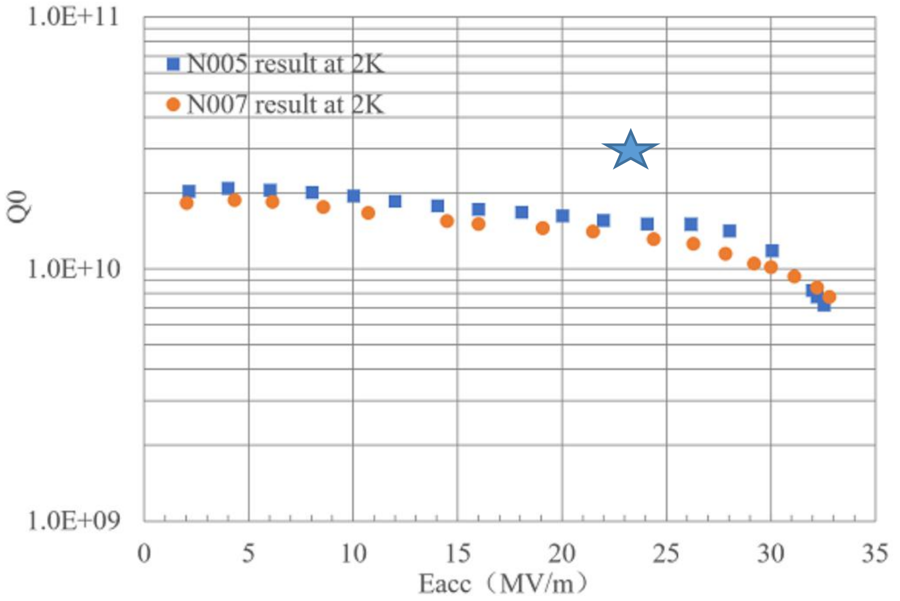
失超点误差 (mm): 0.2

OST坐标及角度

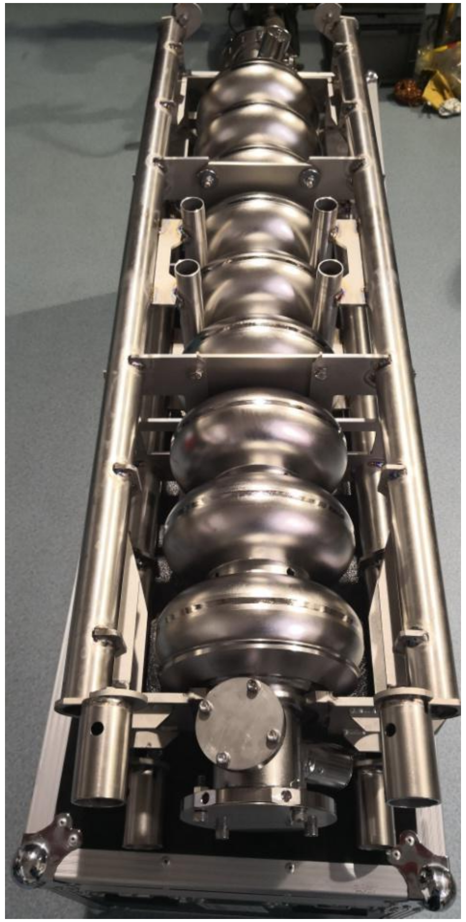
	X轴	Y轴	Z轴	角度(X,Y,Z)	距离(cm)
OST 01	-0.37	-141.74	502.5	[0 , 0 , -10]	---
OST 02	191.74	49.63	502.5	[0 , 0 , -10]	---
OST 03	0.37	141.74	502.5	[0 , 0 , -10]	---
OST 04	-191.74	-49.63	502.5	[0 , 0 , -10]	---
OST 05	143.46	-55.21	212.3	[0 , 0 , 80]	---
OST 06	-4.1	-153.35	96.9	[0 , 0 , -100]	---
OST 07	143.46	-55.21	-133.9	[0 , 0 , -100]	---
OST 08	4.1	153.35	-249.3	[0 , 0 , -100]	---
OST 09	-0.37	-141.74	77.5	[0 , 0 , -10]	---
OST 10	191.74	49.63	77.5	[0 , 0 , -10]	---
OST 11	0.37	141.74	77.5	[0 , 0 , -10]	---
OST 12	-191.74	-49.63	77.5	[0 , 0 , -10]	---
OST 13	-0.37	-141.74	-232.5	[0 , 0 , -10]	---
OST 14	191.74	49.63	-232.5	[0 , 0 , -10]	---
OST 15	0.37	141.74	-232.5	[0 , 0 , -10]	---
OST 16	-191.74	-49.63	-232.5	[0 , 0 , -10]	---
OST 17	-0.37	-141.74	-547.5	[0 , 0 , -10]	---
OST 18	191.74	49.63	-547.5	[0 , 0 , -10]	---
OST 19	0.37	141.74	-547.5	[0 , 0 , -10]	---
OST 20	-191.74	-49.63	-547.5	[0 , 0 , -10]	---

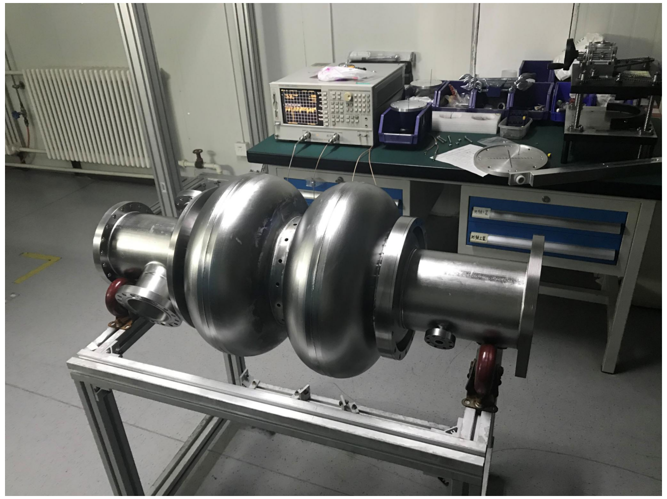
General superconducting cavity test cryomodule in IHEP New SC Lab

IHEP 650MHz 2cell and 1.3 GHz 9-cell Cavities

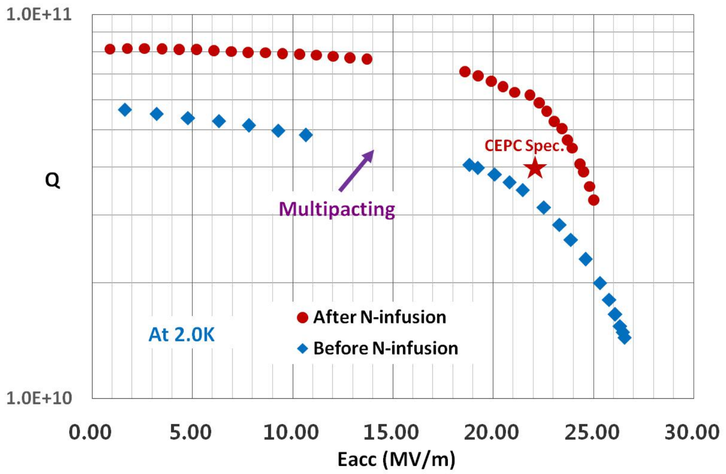


Booster 1.3GHz 9 cell cavity



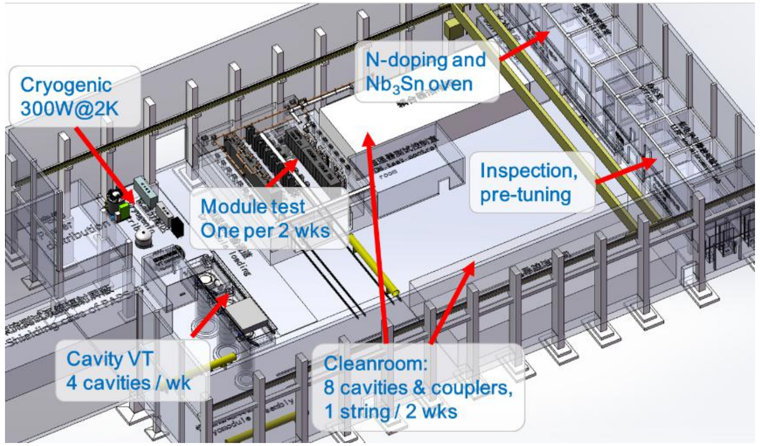


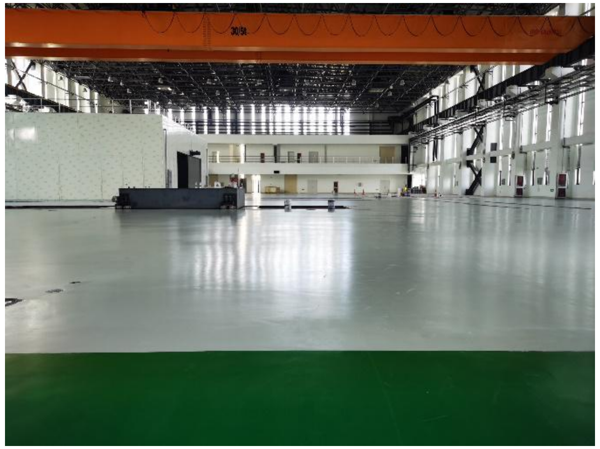
Collider ring 650Mhz 2 cell cavity



650 MHz 2-cell cavity reached **6E10@22MV/m** after N-infusion, which has exceeded CEPC Spec （**Q=4E10@Eacc=22MV/m**）.

IHEP New SC Lab under Construction (Status in Nov. 2019)





New SC Lab Design (4500m^2)

SC New Lab will be available in 2021

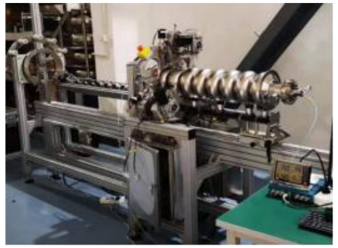
Crygenic system hall in Jan. 16, 2020

Vacuum furnace (doping & annealing)

Nb3Sn furnace

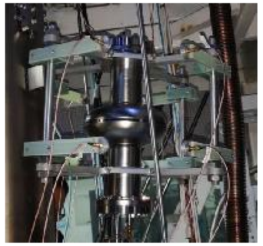
Nb/Cu sputtering device

Cavity inspection camera and grinder

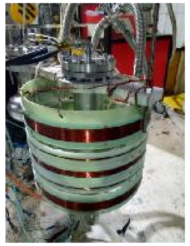


9-cell cavity pre-tuning machine

Temperature & X-ray
mapping system



Second sound cavity
quench detection system



Helmholtz coil for
cavity vertical test

Vertical test dewars

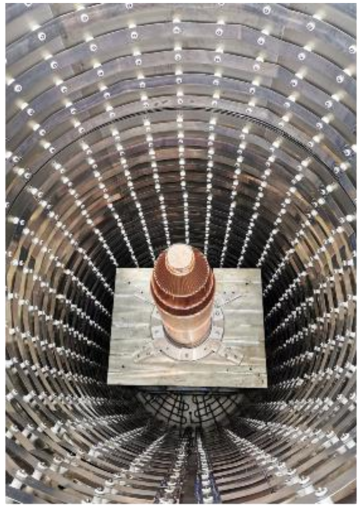
Horizontal test cryostat

CEPC 650MHz High Efficiency Klystron Development

Established "High efficiency klystron collaboration consortium", including IHEP & IE(Institute of Electronic) of CAS, and Kunshan Guoli Science and Tech.

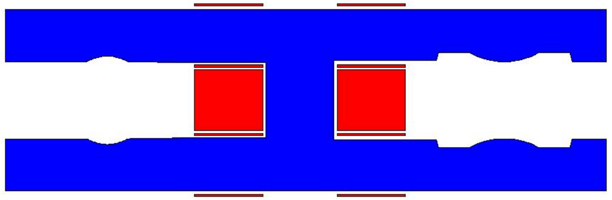
- 2016 – 2018： Design conventional & high efficiency klystron
- 2017 – 2018： Fabricate conventional klystron & test
- 2018 - 2019： Fabricate 1st high efficiency klystron & test
- 2019 - 2020： Fabricate 2nd high efficiency klystron & test
- 2020 - 2021： Fabricate 3rd high efficiency klystron & test

Parameters	Conventional efficiency	**High efficiency**
Centre frequency (MHz)	650+/-0.5	**650+/-0.5**
Output power (kW)	800	**800**
Beam voltage (kV)	80	**-**
Beam current (A)	16	**-**
Efficiency (%)	~ 65	**> 80**

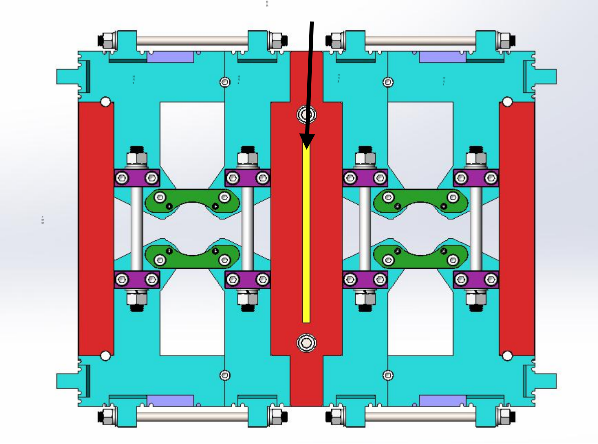


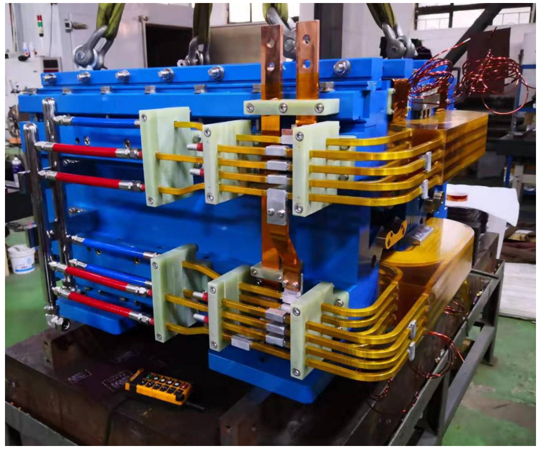
On March 10， 2020， the first CEPC650Mhz klystron output power has reached pulsed power of 800kW (400kW CW due to test load limitation), efficiency 62% and band width>+-0.5Mhz.

CEPC Collider Ring dual Aperture Dipole, Quadrupole and Sextupole Magnet Design Progress

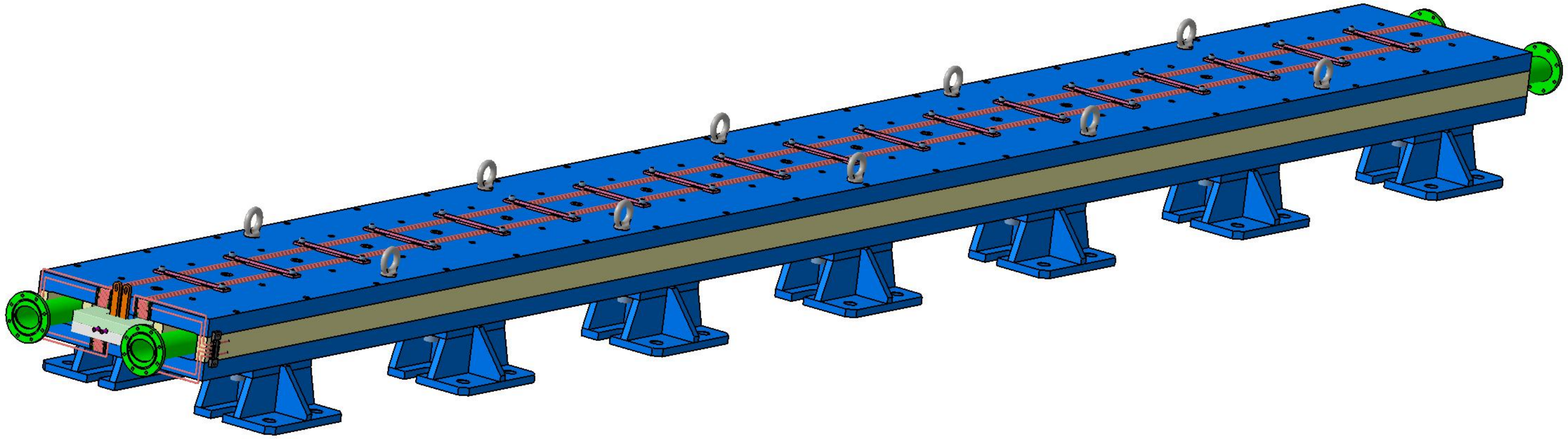


First dual aperture dipole test magnet of 1m long has been finished in Nov, 2019





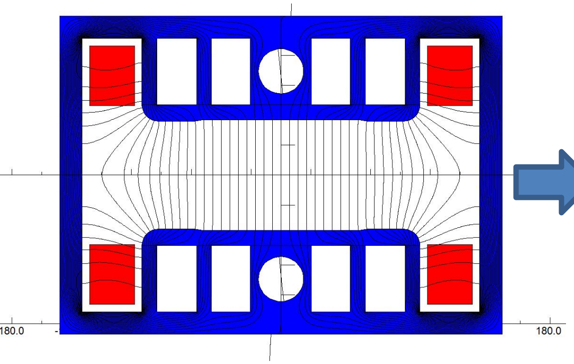
First dual aperture quadrupole magnet has been finished in Nov, 2019

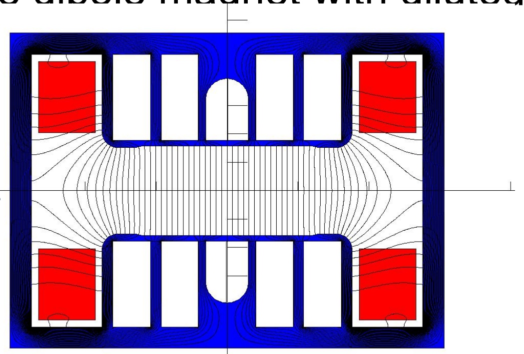


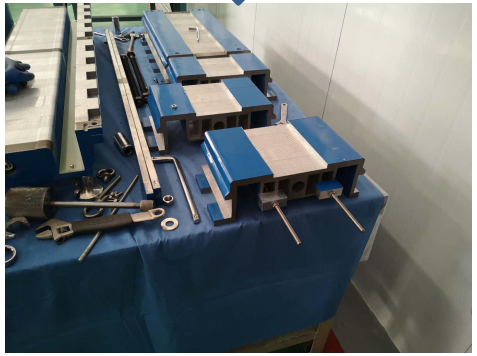
The mechanical design of a full size CEPC collider ring dual aperture dipole of 5.7m long has been designed and be fabricated at the end of 2020.

Booster High Precision Low Field Dipole Magnets

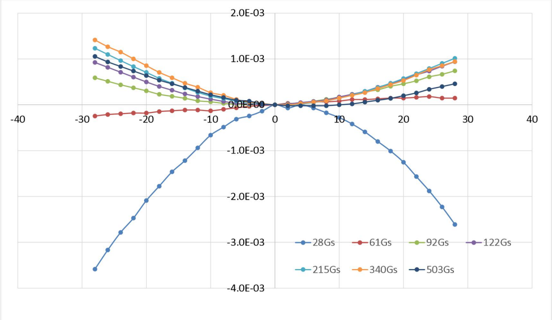
Two kinds of the dipole magnet with diluted iron cores and without iron core (CT) are proposed and designed



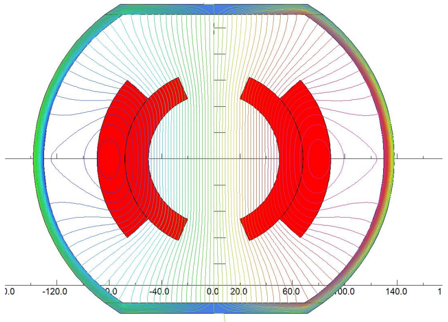


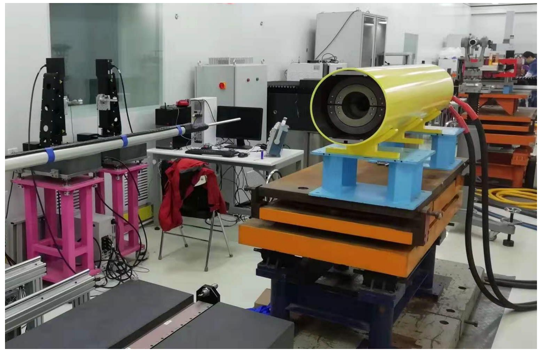


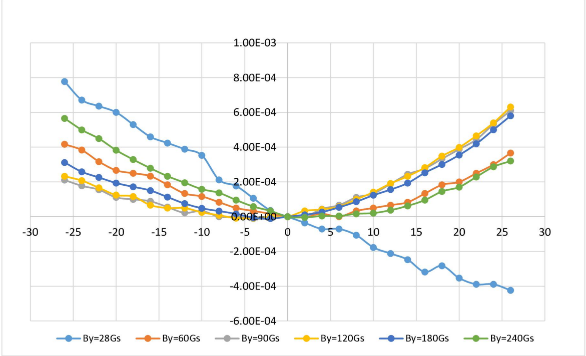
The improved model is under test



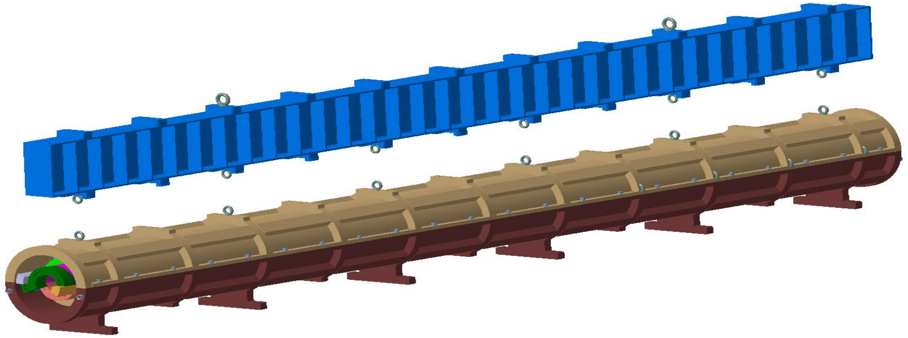
The first 1m long test booster dipole magnet with iron core, completed in Nov. 2019, and not yet reached design goal, improvement is under way







1m long CT test booster dipole magnet without iron core completed in Oct. 2019, and the test result shows that CT design reached the design goal.



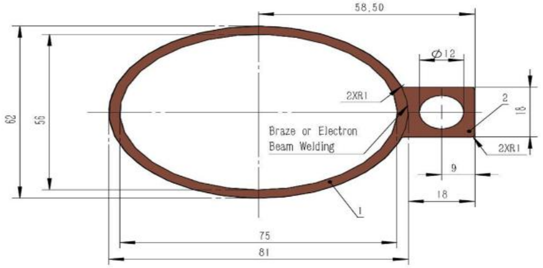
A full scale CT dipole magnet of 5.1m long is under design, and fabrication will be completed at te end of 2020

CEPC Vacuum System R&D

NEG coating suppresses electron multipacting and beam-induced pressure rises, as well as provides extra linear pumping. Direct Current Magnetron Sputtering systems for NEG coating was chosen.

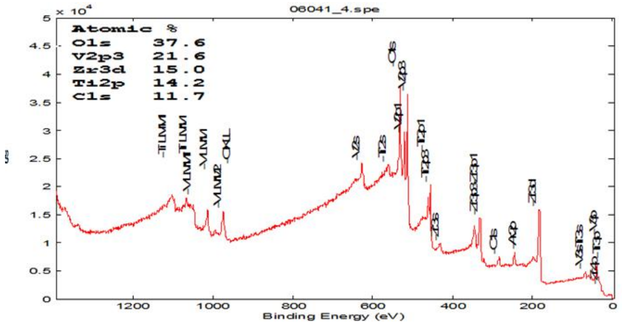
- The vacuum pressure is better than 2 x 10-10 Torr
- Total leakage rate is less than 2 x 10-10 torr.l /s.

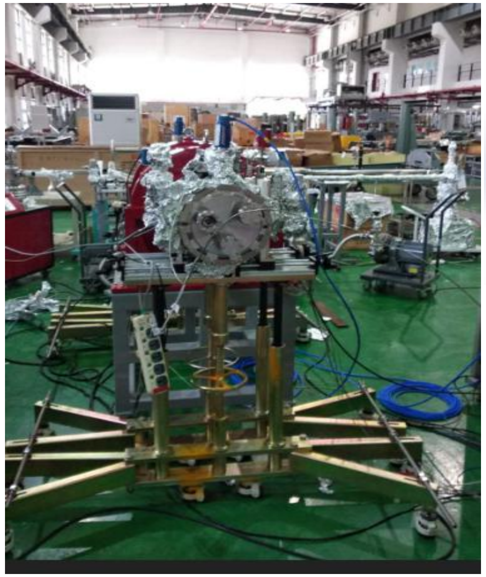
Positron ring

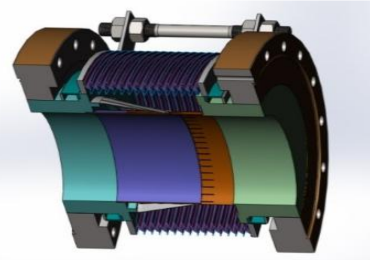


Copper vacuum chamber (Drawing) elliptic 75×56, thickness 3, length 6000)

Two 6m long vacuum chambers both for copper and aluminum

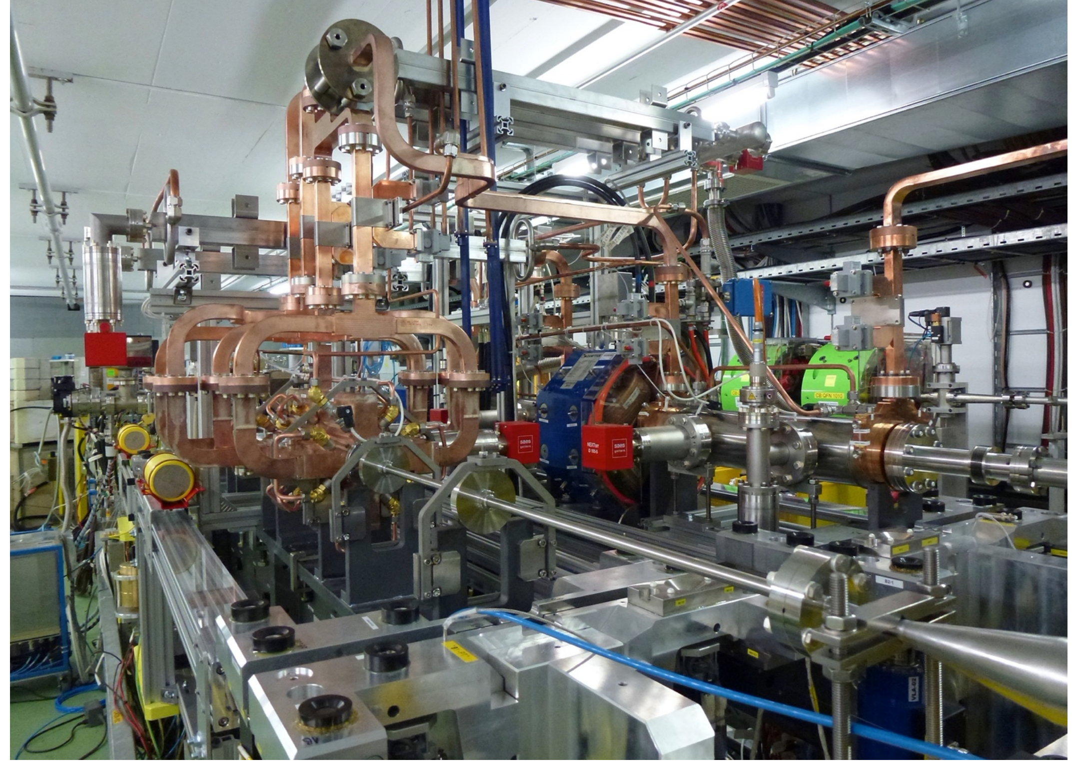




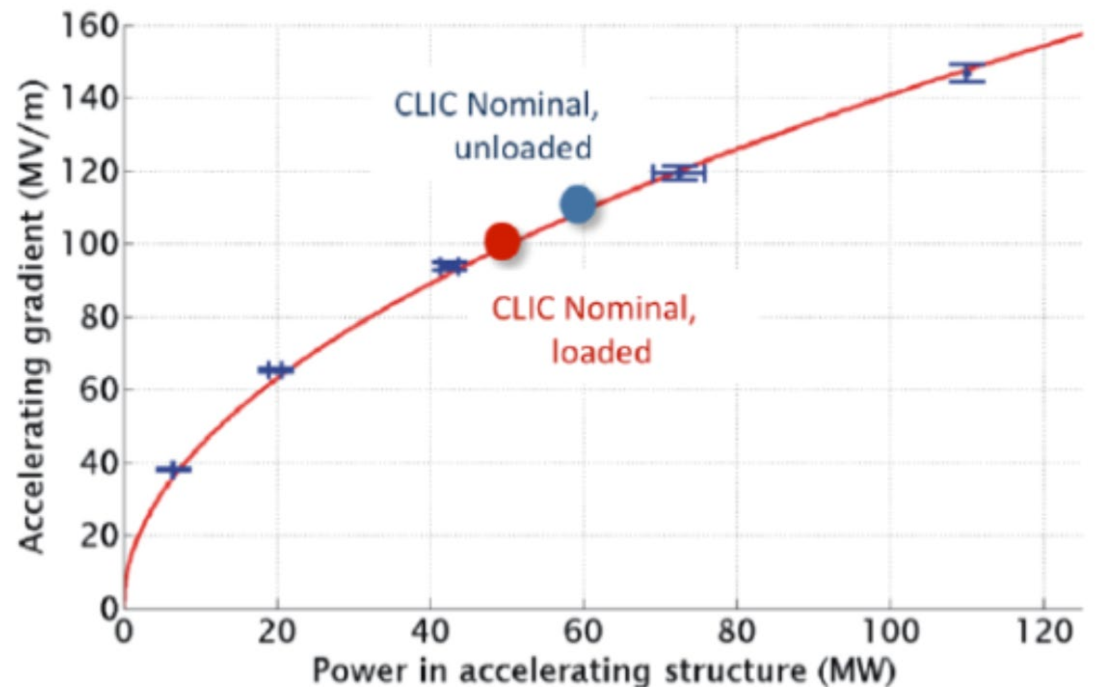


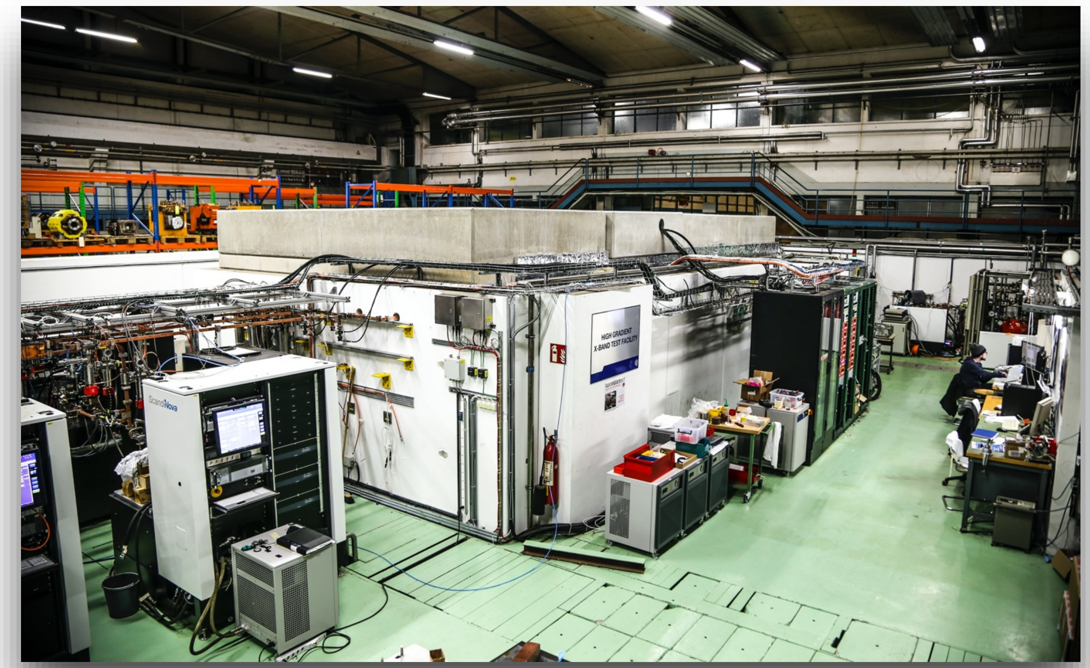
Accelerator challenges

Details in PIP, DOI: http://dx.doi.org/10.23731/CYRM-2018-004



- CLIC baseline – a drive-beam based machine with an initial stage at 380 GeV
- Four main challenges
  1. High-current drive beam bunched at 12 GHz
  2. Power transfer and main-beam acceleration
  3. Towards 100 MV/m gradient in main-beam cavities
  4. Alignment and stability ("nano-beams")
- The CTF3 (CLIC Test Facility at CERN) programme addressed all drive-beam production issues
- Other critical technical systems (alignment, damping rings, beam delivery, etc.) addressed via design and/or test-facility demonstrations
- X-band technology developed and verified with prototyping, test-stands, and use in smaller systems
- Two C-band XFELS (SACLA and SwissFEL – the latter particularly relevant) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs

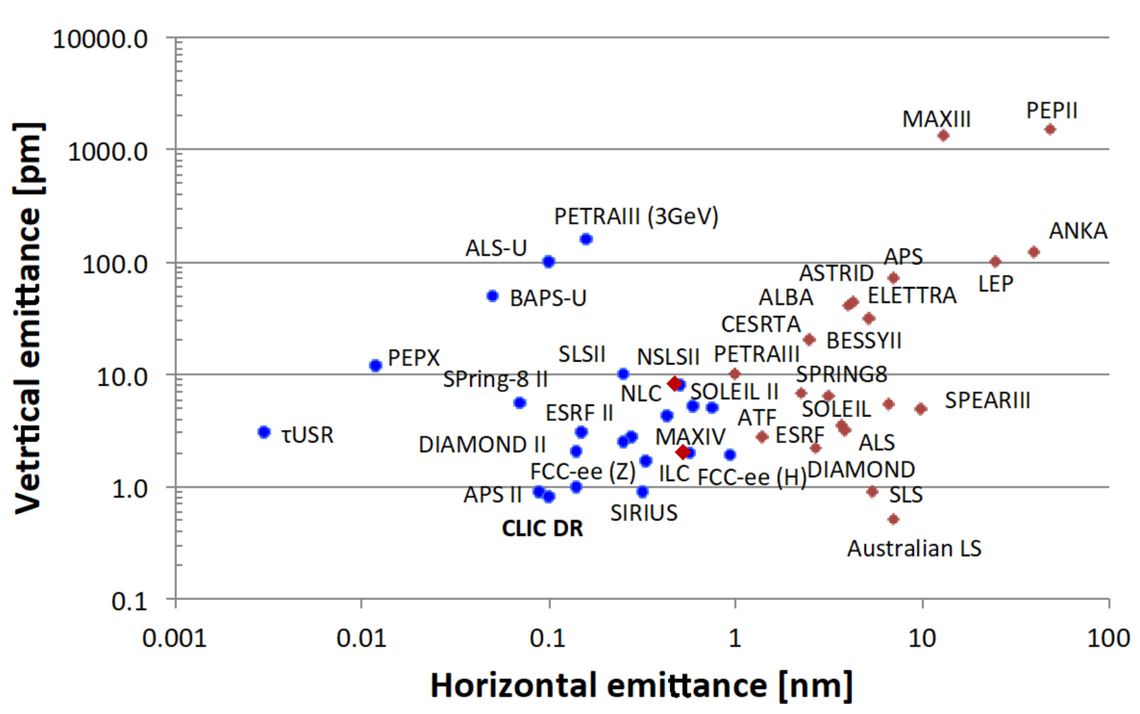


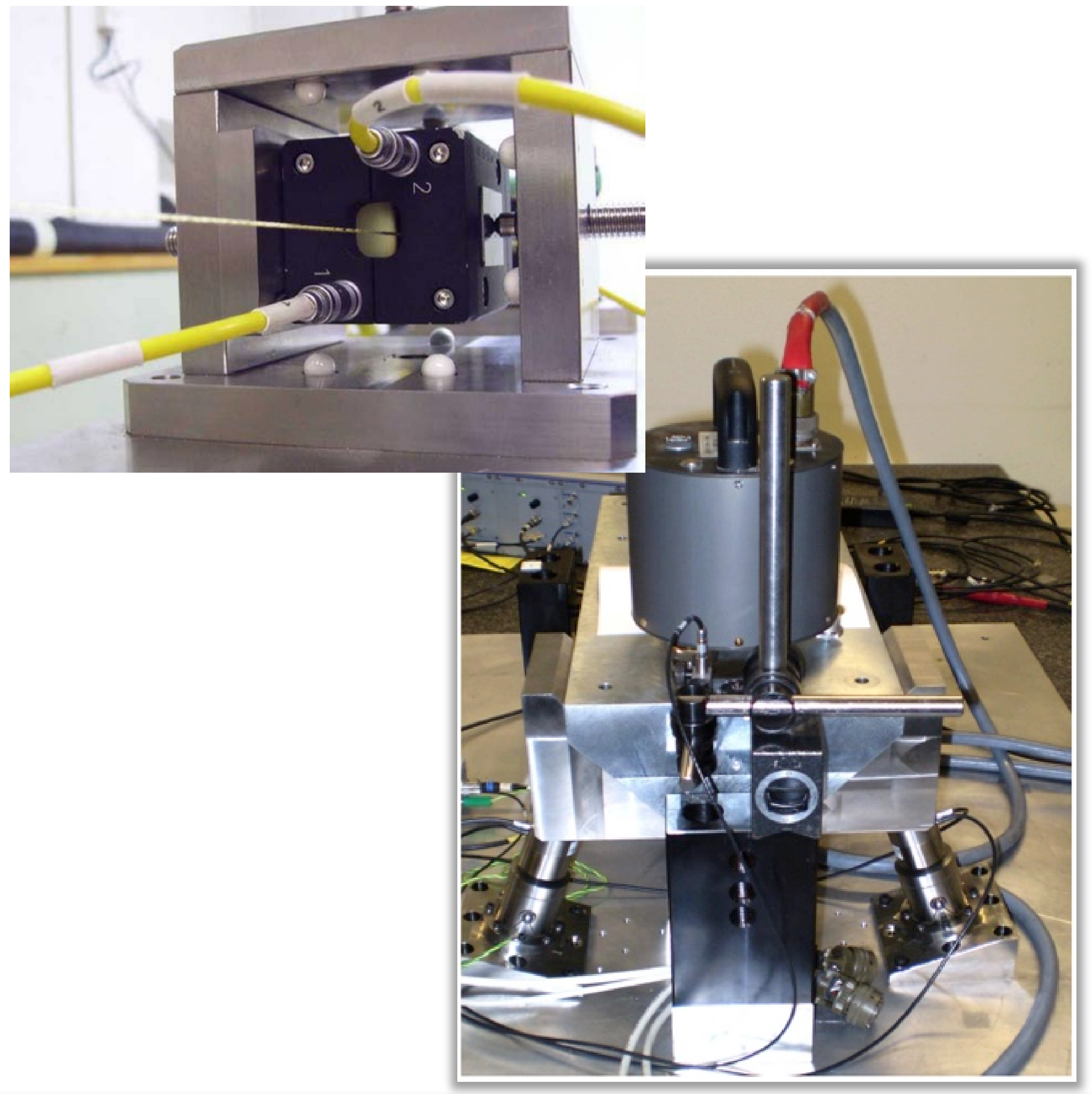


Low emittance generation and preservation

Target and achieved emittance in existing and planned machines

2018





Low emittance damping rings

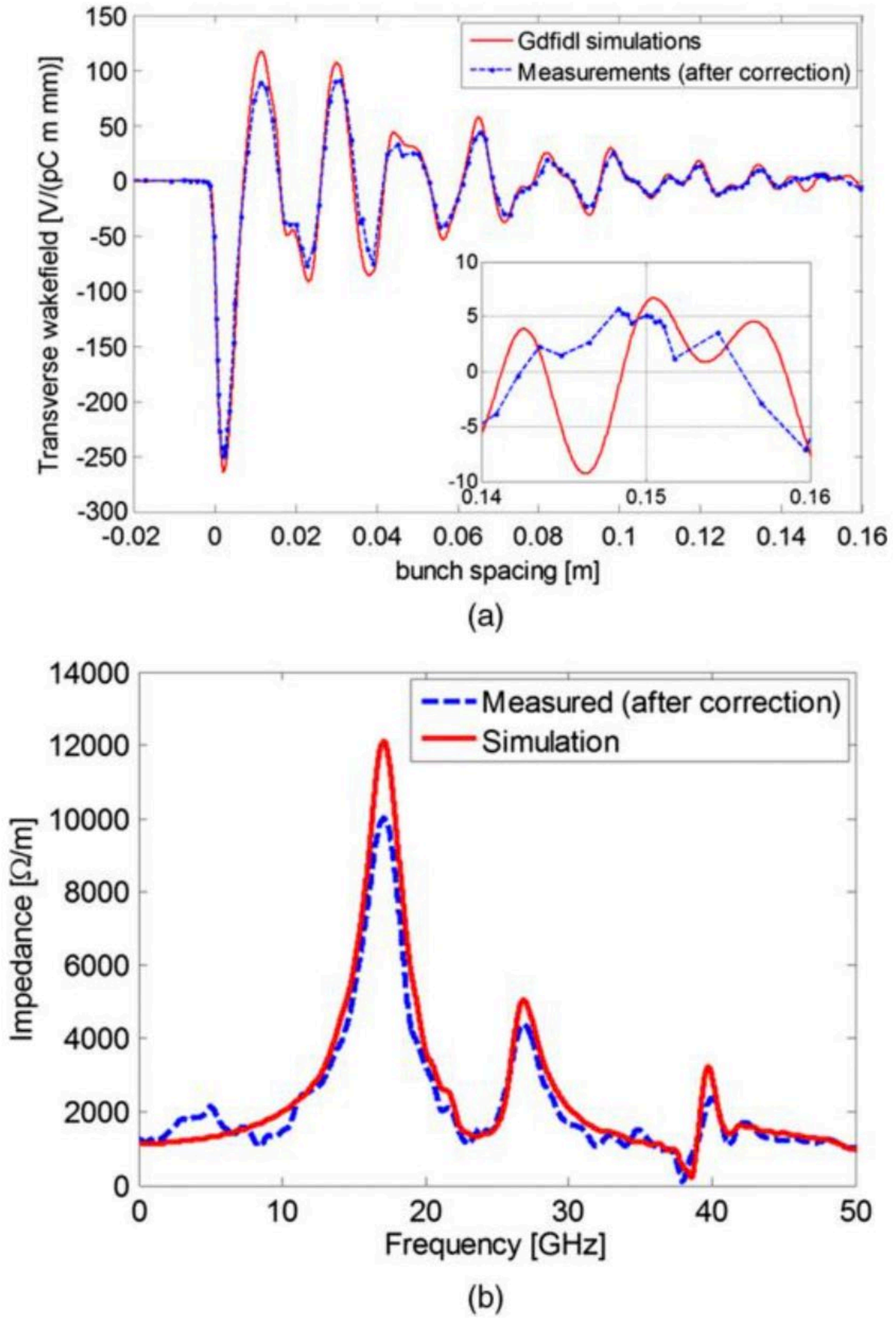
Preserve by

- Align components (10 µm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Beam based measurements
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks

- Experimental tests in existing accelerators of equipment and algorithms
  (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

iteration 0 iteration 1 iteration 3

Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.



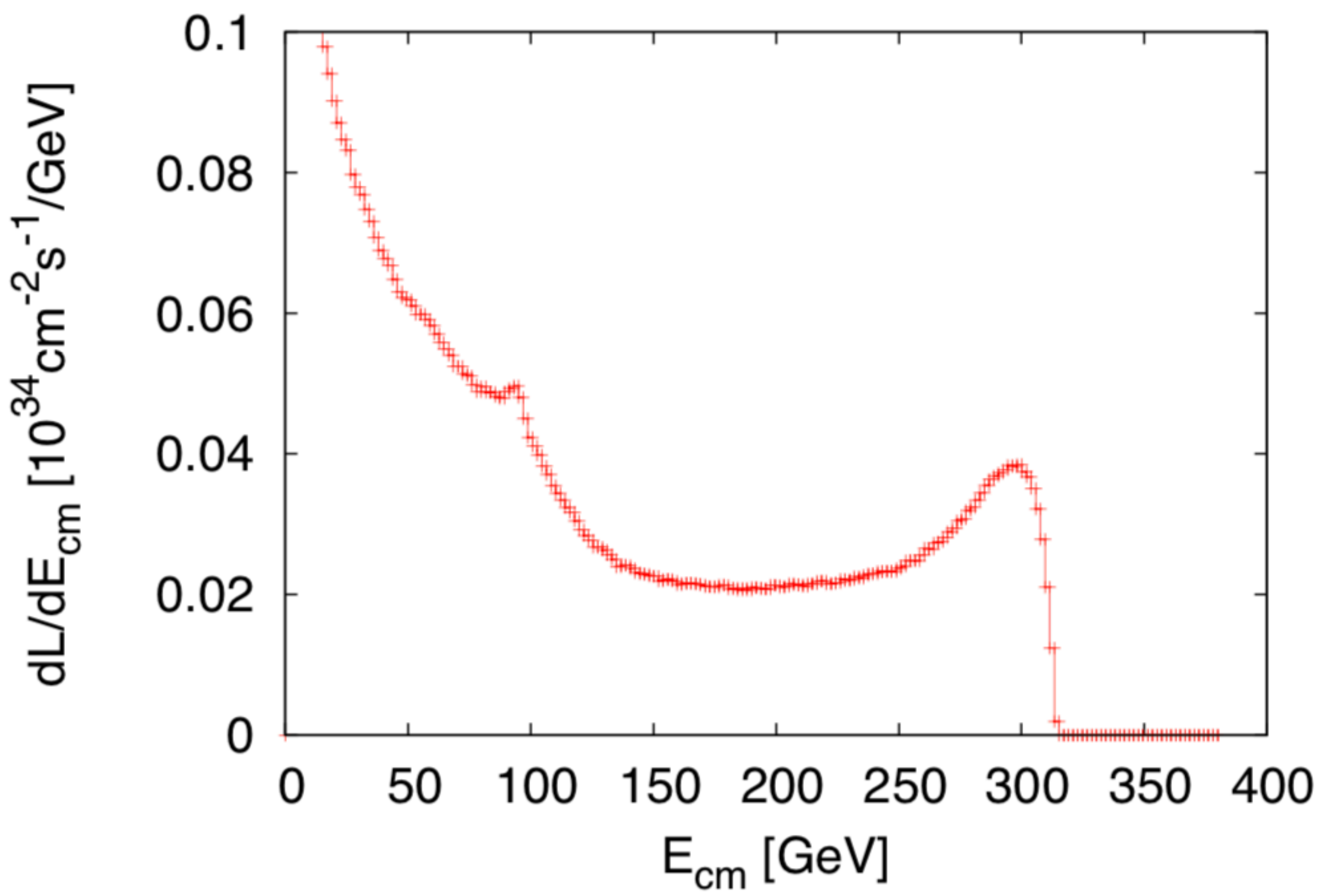
Wake-field measurements in FACET

(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

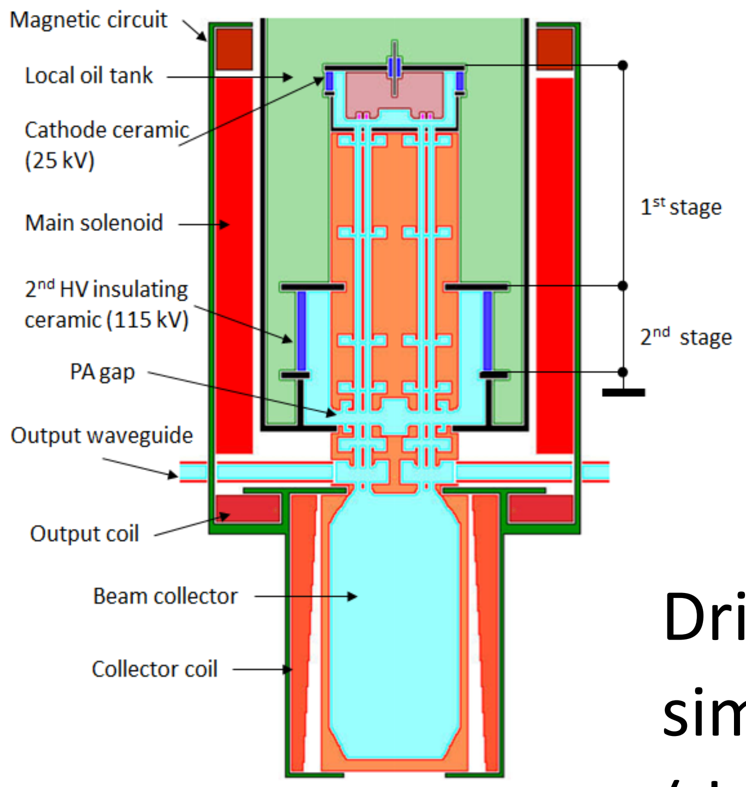
CLIC acc. studies 2019/20 – a few recent results

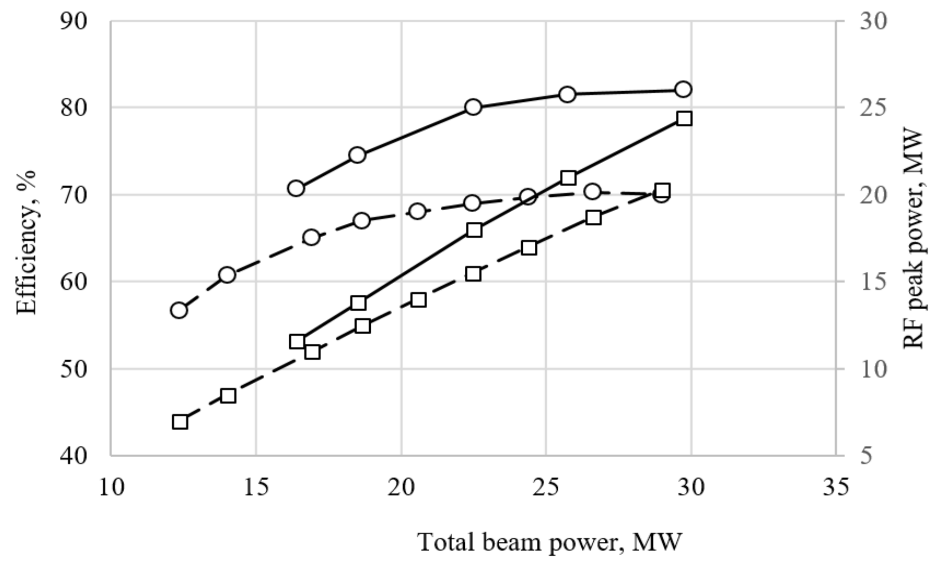
Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma

- Z pole performance, $2.3\text{x}10^{32} – 0.4\text{x}10^{34}$ cm^{-2} s^{-1}
  - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma spectrum (example)
- Luminosity margins and increases
  - Baseline includes estimates static and dynamic degradations from damping ring to IP: 1.5 x 10^{34} cm^{-2} s^{-1}, a "perfect" machine will give : 4.3 x 10^{34} cm^{-2} s^{-1}, so significant upside
  - In addition: doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of +50 MW and ~5% cost increase
- CLIC note at: http://cds.cern.ch/record/2687090 (paper in preparation)

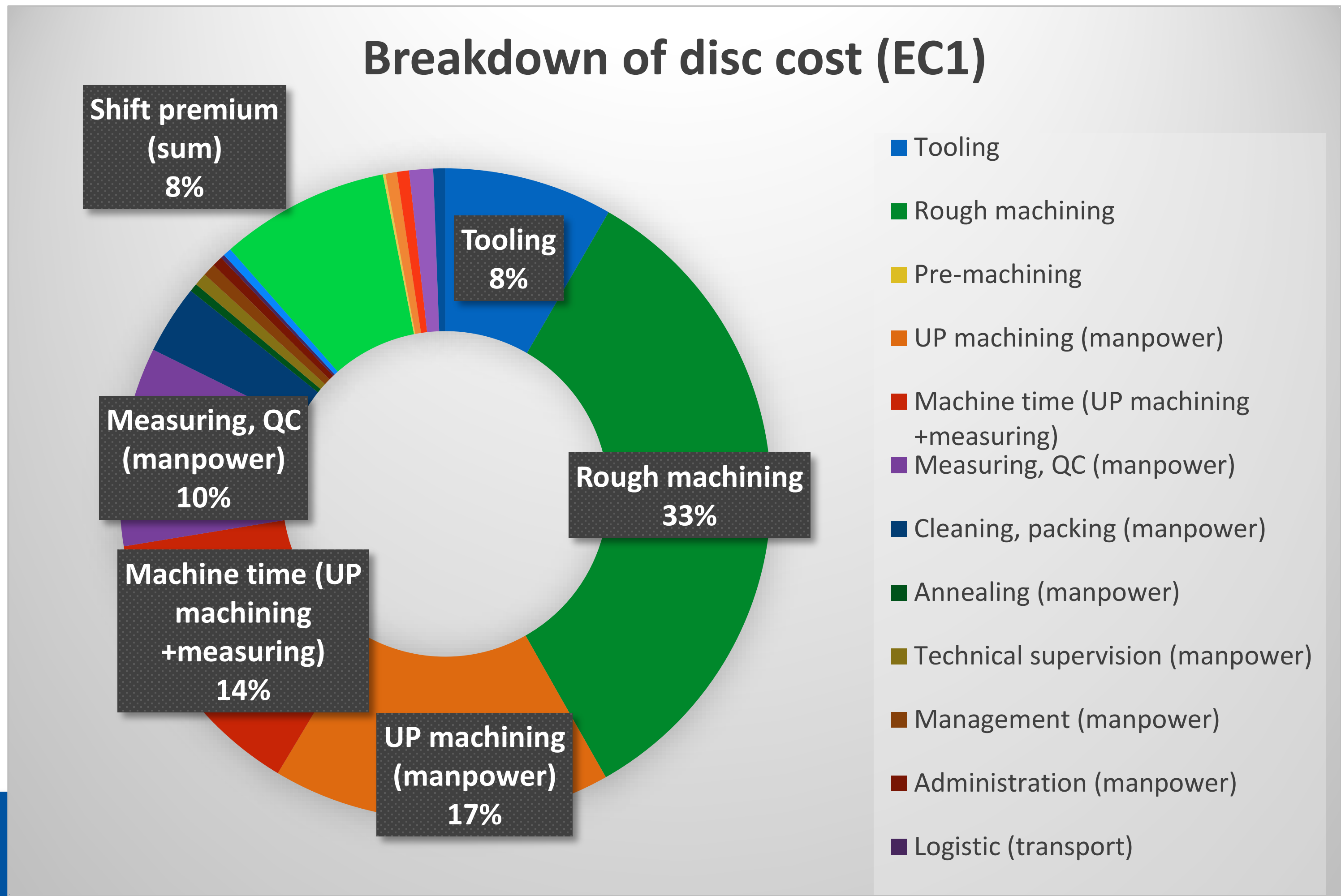


Industrial questionnaire:
Based on the companies feedback, the preparation phase to the mass production could take about five years. Capacity clearly available.





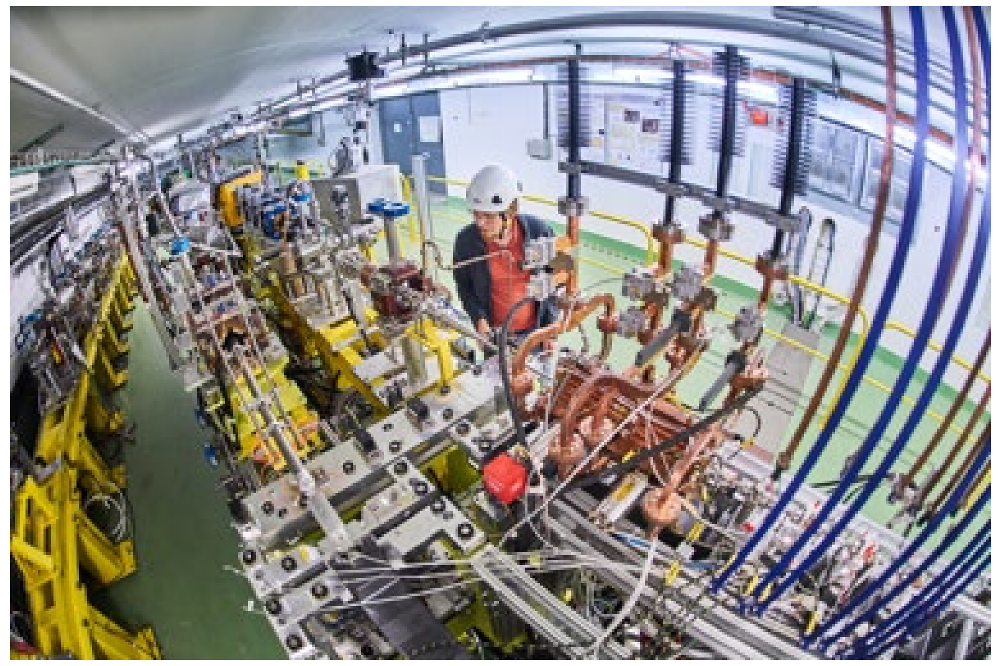
Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power.
Publication: https://ieeexplore.ieee.org/document/9115885



CLIC studies 2020-25

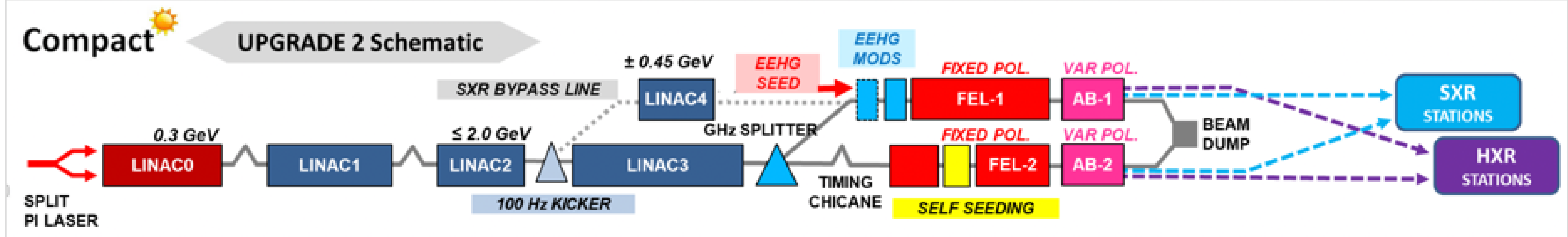
X-band technology:

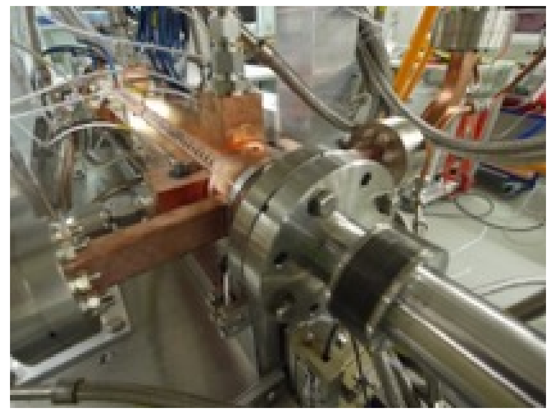
- Design and manufacturing of X-band structures and components
- Study structures breakdown limits and optimization, operation and conditioning
- Baseline verification and explore new ideas
- Assembly and industry qualification
- Structures for applications, FELs, medical, etc

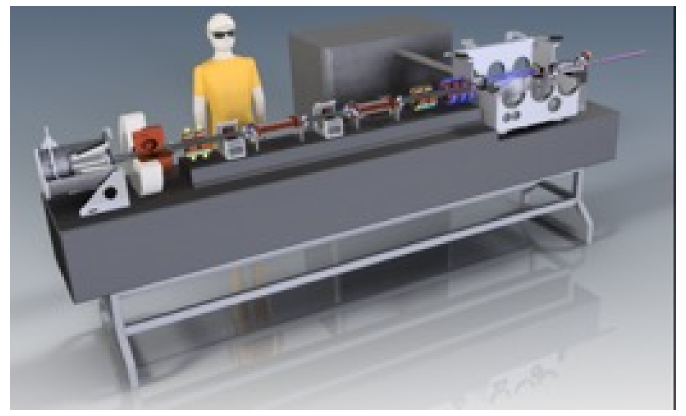


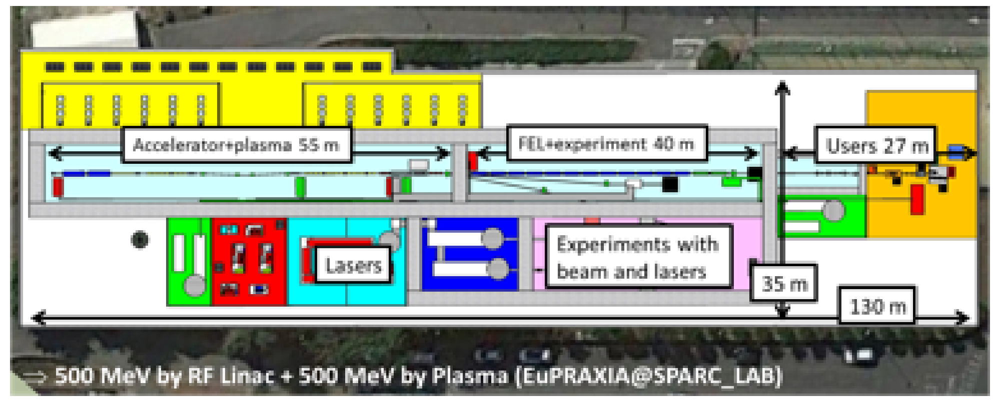
Technical and experimental studies:

- Module studies (see some targets for development below)
- Beamdynamics and parameters: Nanobeams (focus on beam-delivery), pushing multi TeV region (parameters and beam structure vs energy efficiency)
- Tests in CLEAR (wakefields, instrumentation) and other facilities (e.g. ATF2)
- High efficiency klystrons
- Injector studies suitable for X-band linacs (coll. with Frascati)









⇒ 500 MeV by RF Linac + 500 MeV by Plasma (EuPRAXIA@SPARC_LAB)

⇒ 1 GeV by high gradient RF Linac only (EuSPARC)

Application of X-band technology (examples):

- A compact FEL (CompactLight: EU Design Study 2018-21)
- Compact Medical linacs (proton and electrons)
- Inverse Compton Scattering Source (SmartLight)
- Linearizers and deflectors in FELs (PSI, DESY, more)
- 1 GeV X-band linac at LNF
- eSPS for light dark matter searches (within the PBC-project)

More information: Overview talk, CompactLight

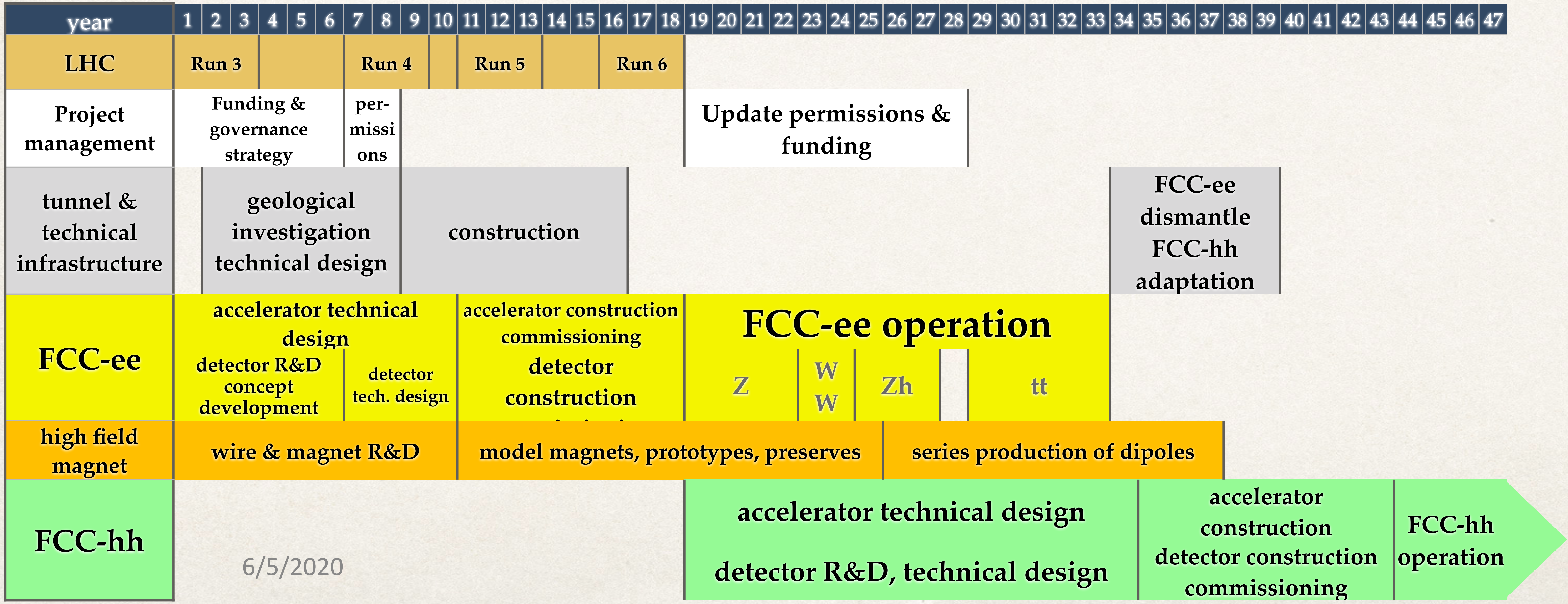
Challenges and opportunities of ERL collider

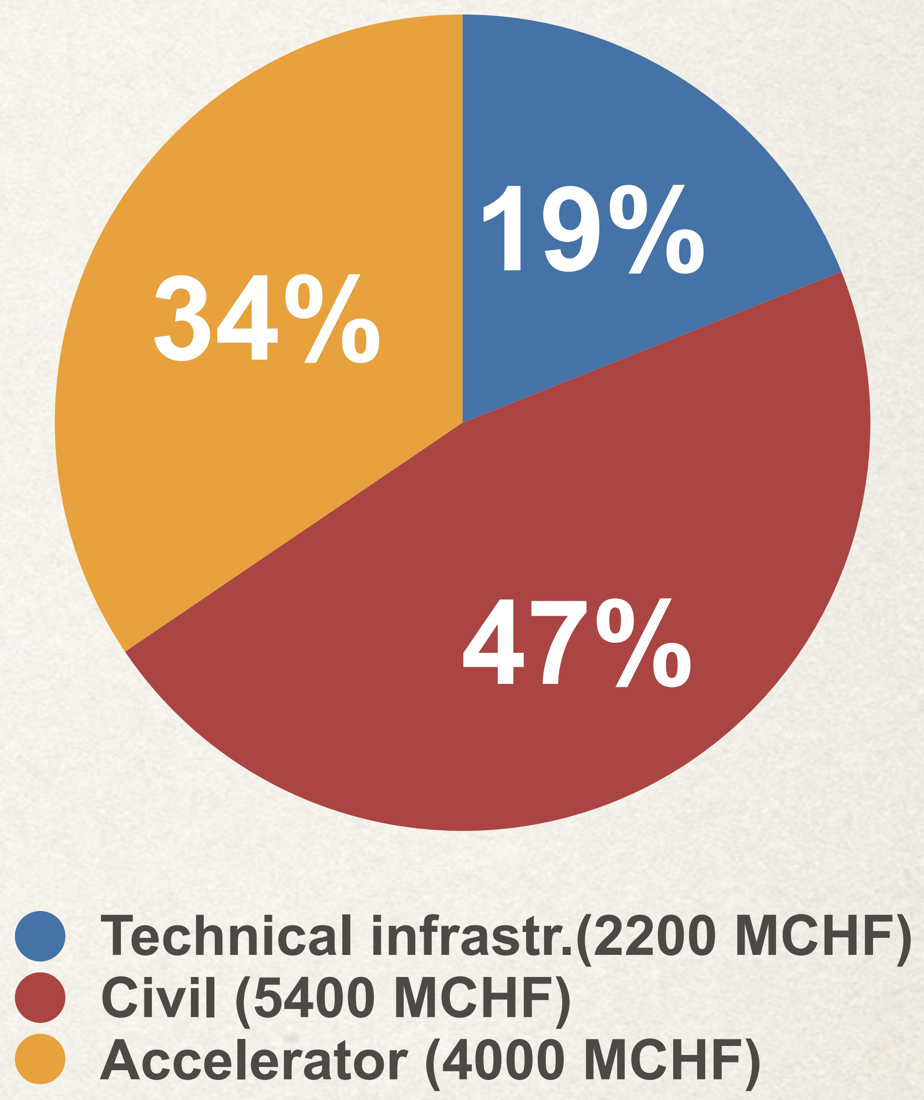
- Design challenges and R&D
  - Multi-pass, high energy ERL R&D
  - Transport beamline lattice preserving a small vertical emittance with large beam aspect ratio
  - Full 3D simulation of electron-positron collisions with flat beams and high disruption parameter
  - Using small gap magnets to reduce power consumption and cost of the multiple 100 km beamlines
  - Absolute beam energy measuring systems with accuracy $\sim 10^{-5}$ at IRs as pioneered at CEBAF
  - High repetition rate ejection and injection kickers for 2 GeV damping rings
  - Compressing and de-compressing electron and positron bunches to match energy acceptance of the 2 GeV damping rings

- Opportunities
  - Building the next generation high luminosity particle collider as a sustainable facility
  - A high degree of longitudinal polarization of electron and positron beams
  - Alternate locations with different circumference: very preliminary estimate for an ERL collider in the LHC tunnel indicates that it could reach $\sqrt{s} = 240$ GeV (HZ) with 40×10^{34} cm^{-2}s^{-1} luminosity and 30 MW SR power.

FCC-ee: Technology, cost, schedule

- Technologies are basically experienced and matured.
  - Some R&Ds are on-going for NbCu RF cavities, high-efficiency RF sources, machine detector interface, beam energy, luminosity & polarization measurements & handling, online operation software, etc.
- Detailed engineering needs 5 years from now to finalize.
- Commissioning assumes a startup run for 2 years at Z.
- One-year break before $t\bar{t}$ operation to install additional RF systems.
- The cost of accelerator is only 34% of the total cost. The most of civil and TI are reused for FCC-hh.



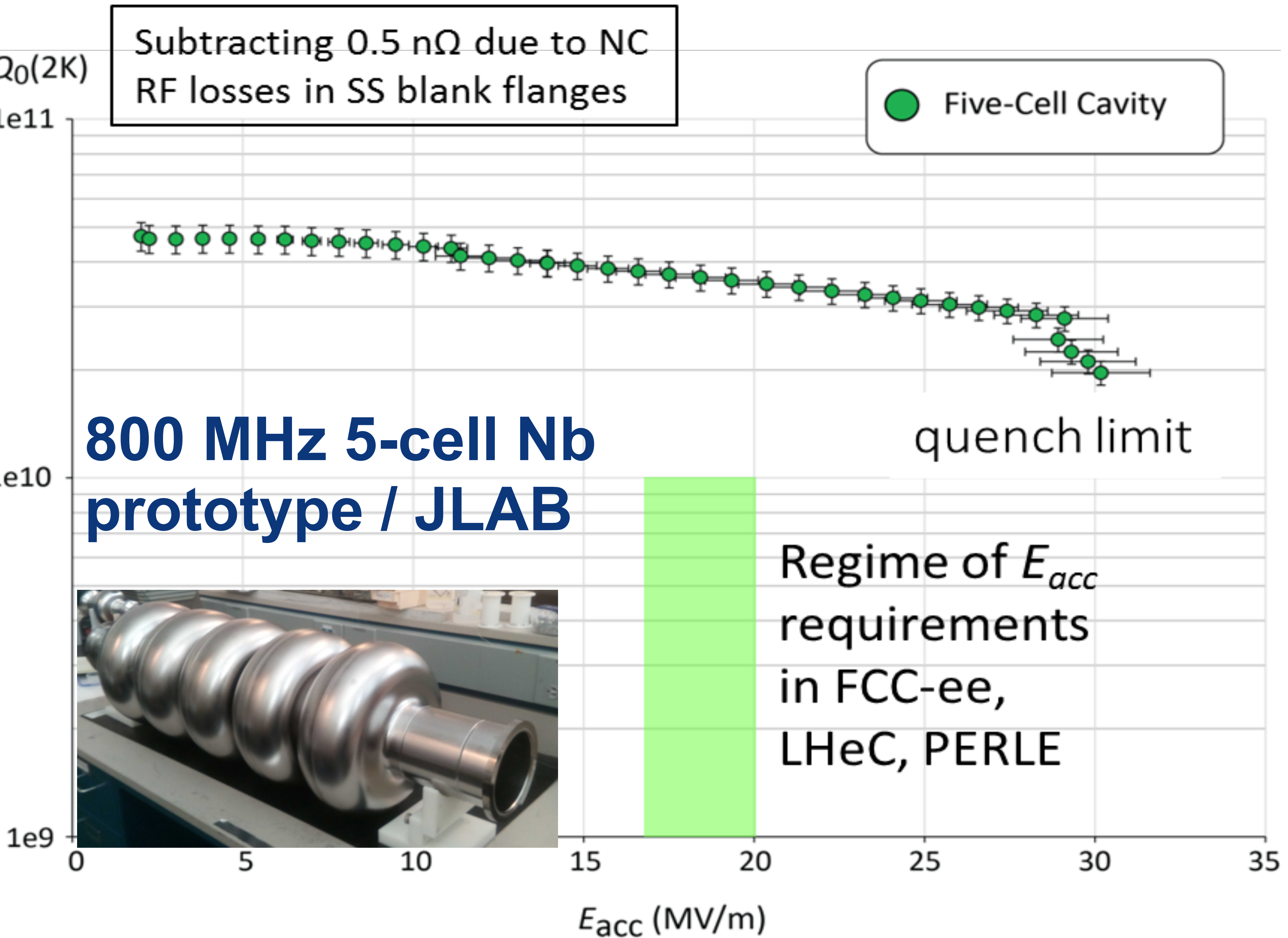


FCC-ee R&D: RF, cryo-modules, power sources

R&D aimed at improving performance & efficiency and reducing cost:

- improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques (e.g. EHF, improved polishing, seamless…)
- coating of A15 superconductors (e.g. Nb_3Sn), · cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- MW-class fundamental power couplers for 400 MHz; · novel high-efficiency klystrons

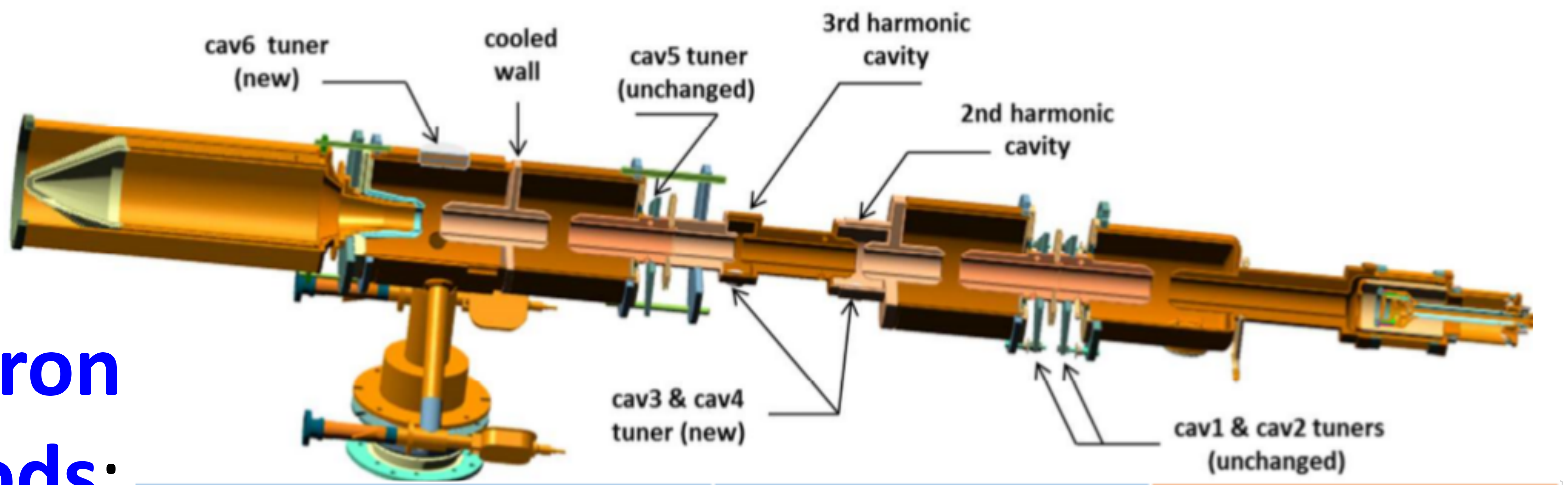
prototype FCC SRF cavities at JLAB



Jefferson Lab

New klystron bunching methods: **LHC klystron retrofit** as proof of principle for FCC

high-efficiency klystron at CERN



Parameter	present TH2167	CSM upgrade
Frequency [MHz]	400	
Beam voltage [kV]	54	
Saturated RF power [kW]	**300**	**350**
Efficiency [%]	**60**	**70**

SRF for FCC-ee

Snowmass Community Planning Meeting, 5-8 October 2020

Frank Gerigk, 6 October 2020

FCC-ee, 2019 Conceptual Design Report

- Is built on SRF technology that is available basically today: 400 MHz coated Cu cavities 1-4 cells with 10 MV/m (LHC cavities nominal 5.3 MV/m, in tests up to 8 MV/m).
- 800 MHz 4-cell cavities with conservative gradients (20 MV/m).
- New power couplers with up to 1 MW CW and adjustable Q_{ex}. A back-up version is 2 couplers of 0.5 MW/cavity.

FCC-ee, 2019 Conceptual Design Report

HOM limited

ee-machine/booster

Configuration	gradient [MV/m]	frequency [MHz]	cells/cav	N_{cav}	P_{cav} [MW]
Z	5.1/8	400	1/4	52/12	0.96
WW	9.6	400	4	52/52	0.96
ZH	9.8	400	4	136/136	0.37
tt-bar1	10	400	4	272/136	0.18
	20	800	5	296/400	0.18
tt-bar2	10	400	4	272/136	0.16
	20	800	5	372/480	0.16

FPC limited

room for improvement

.. room for improvement

Coating Techniques

Coating materials

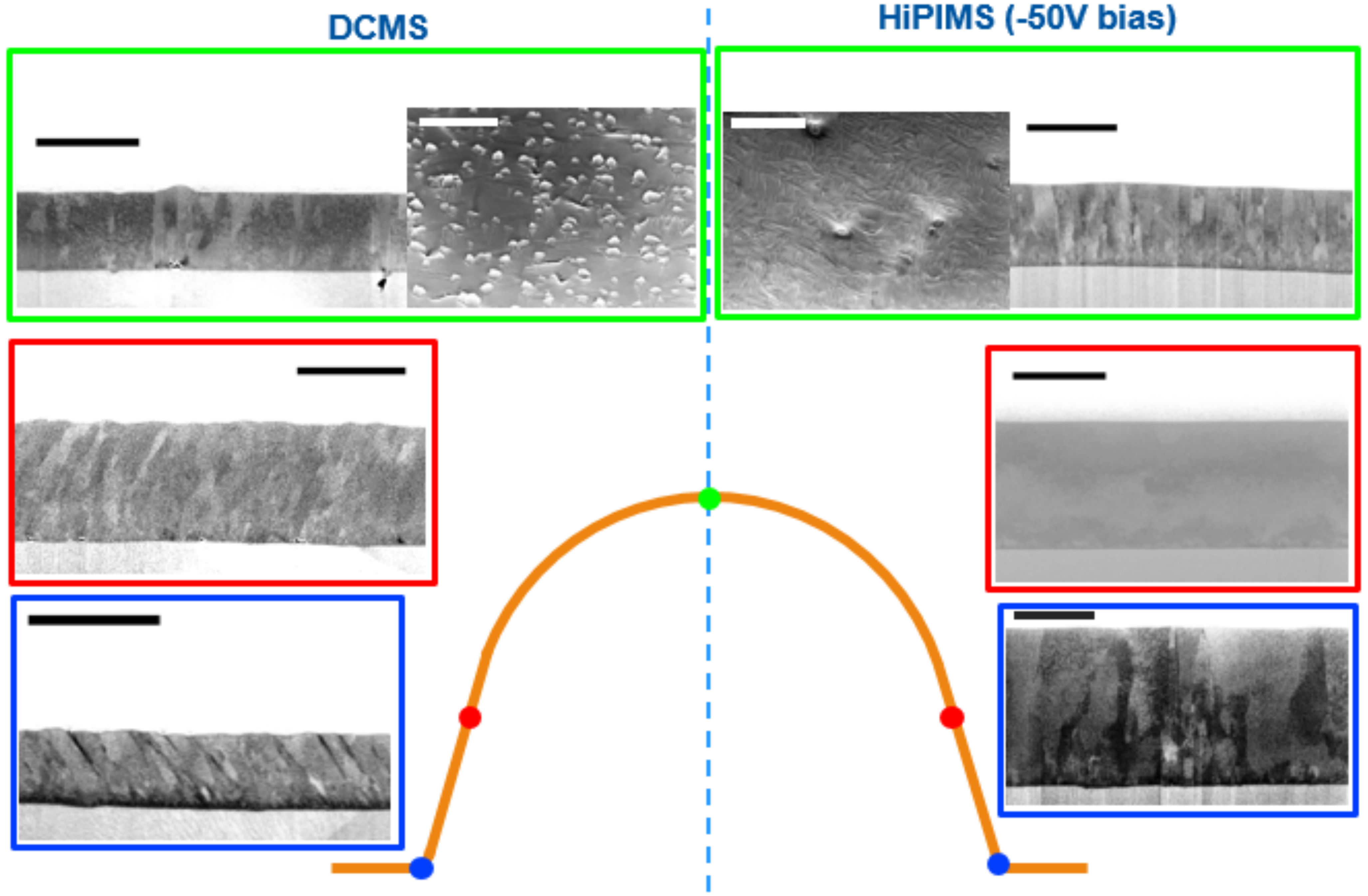
Cu substrate fabrication

Cavity shapes

.. room for improvement I

HIPIMS coating

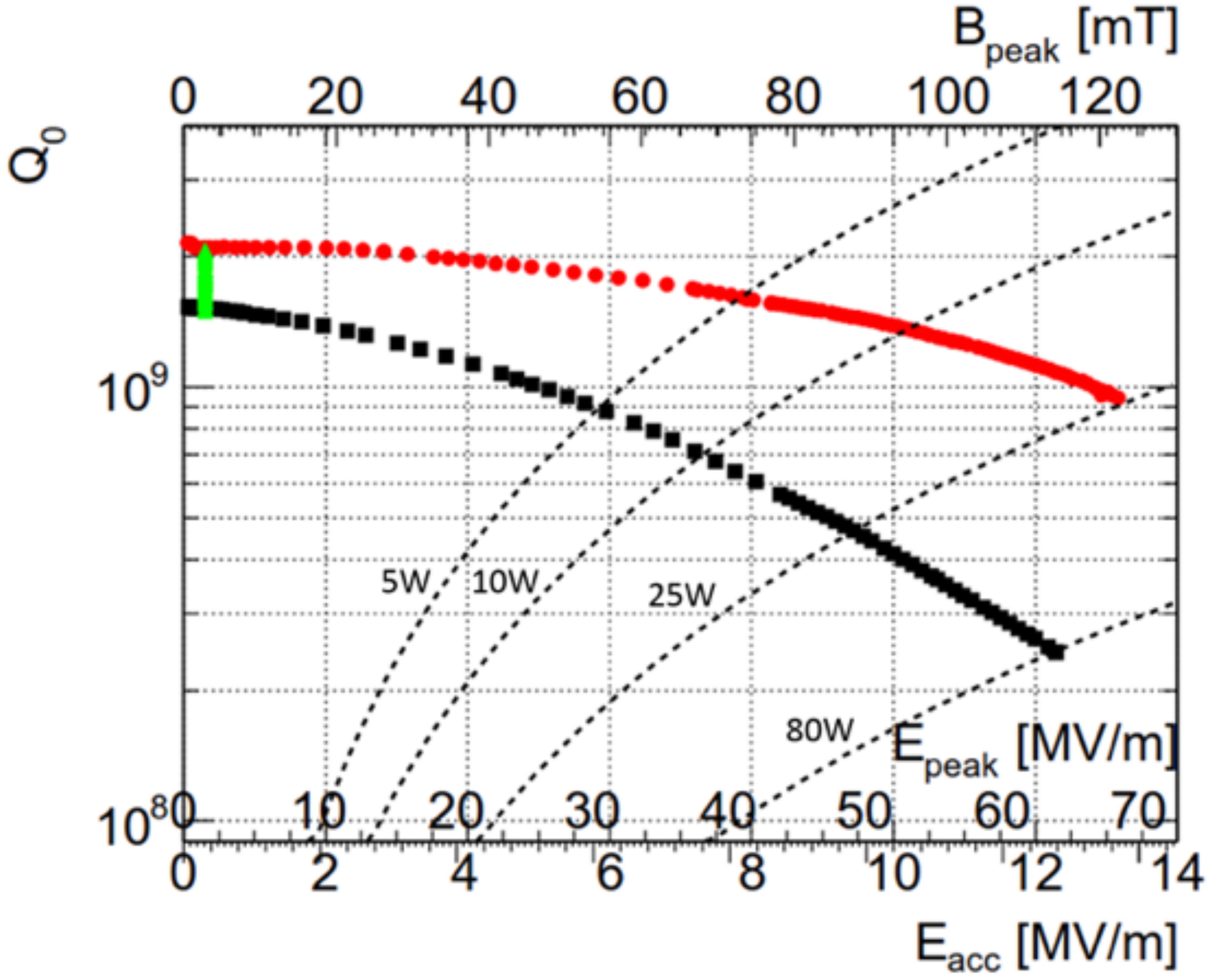
- Much denser layer in all orientations.
- Sample tests showed much flatter Q-curves than for DCMS sputtering.
- First 1.3 GHz seamless cavity with HIPIMS coating is waiting for its test.



.. room for improvement II

Fabrication of Cu substrates, understand the influence of the weld

- Can the results of seamless 100 MHz Nb coated HIE-ISOLDE cavities be extrapolated to 400 MHz seamless elliptical cavities?
- Currently preparing tests with seamless and welded 1.3 GHz cavities, which are coated by HIPIMS.



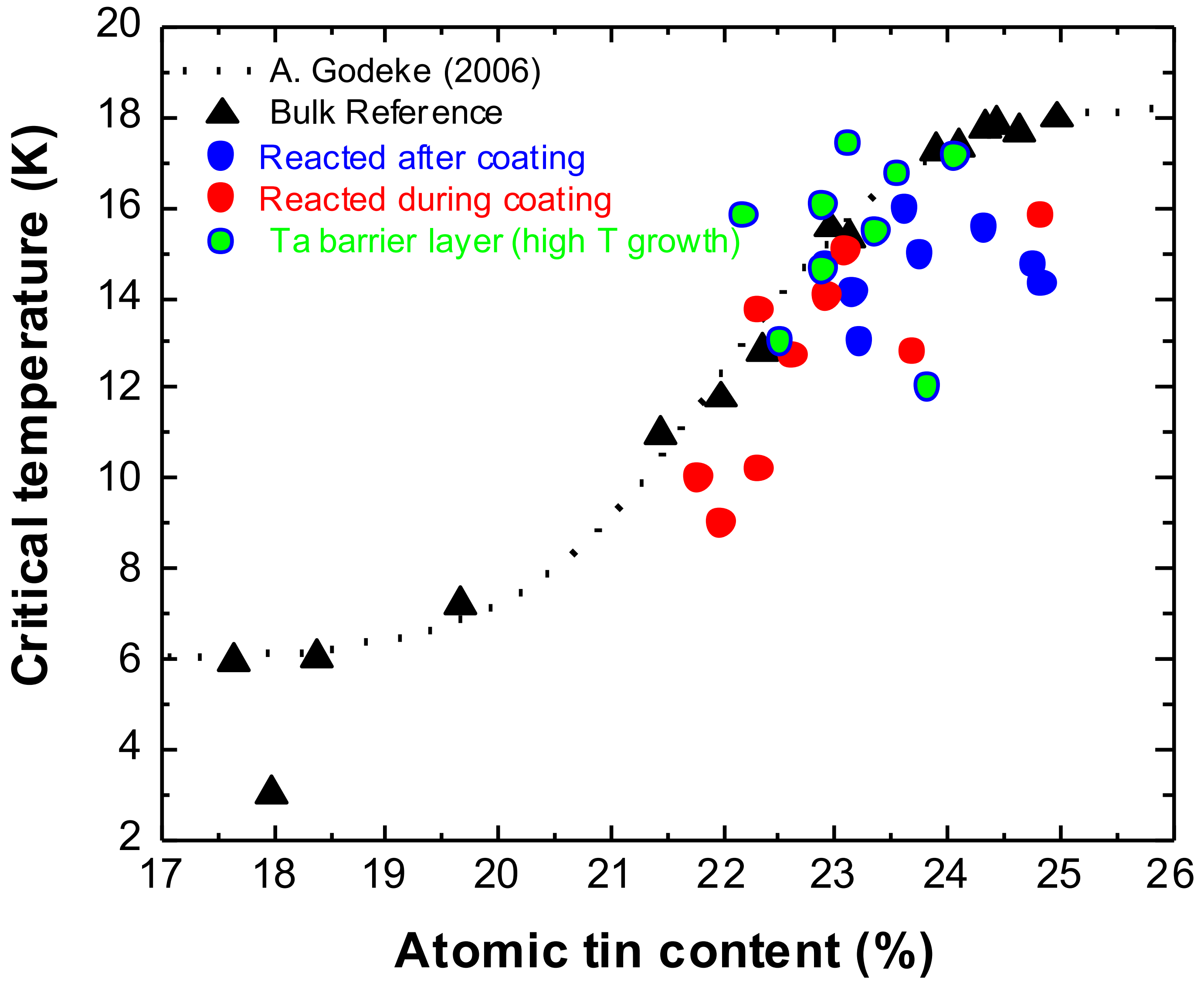
.. room for improvement III

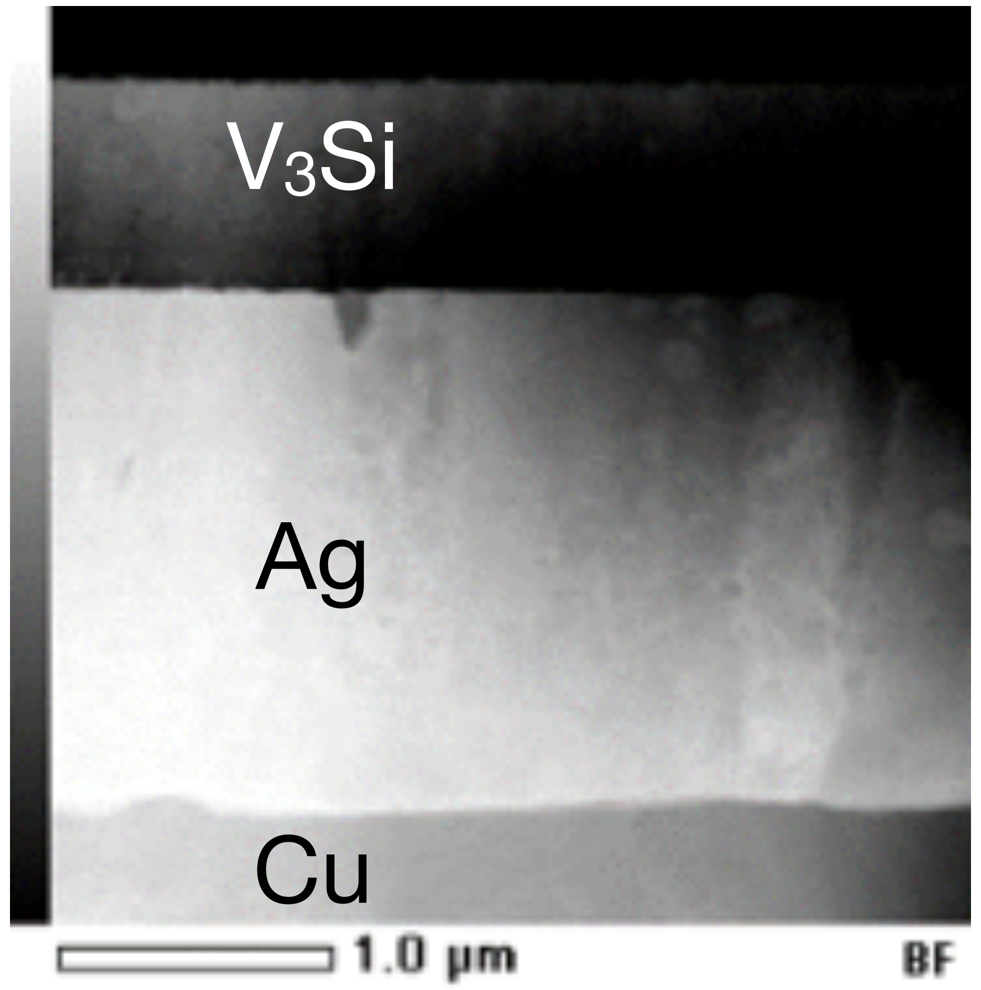
A15, operating at higher temperature?

Sputtering of A15 onto a copper substrate.

- **Nb_3Sn:** promising results with intermediate Ta layer to avoid intermixing of Cu and Nb_3Sn
- **Vn_3Si:** more stable than Sn, promising results with intermediate Ag layer.

Both methods still require a long-term effort before having complete cavities.



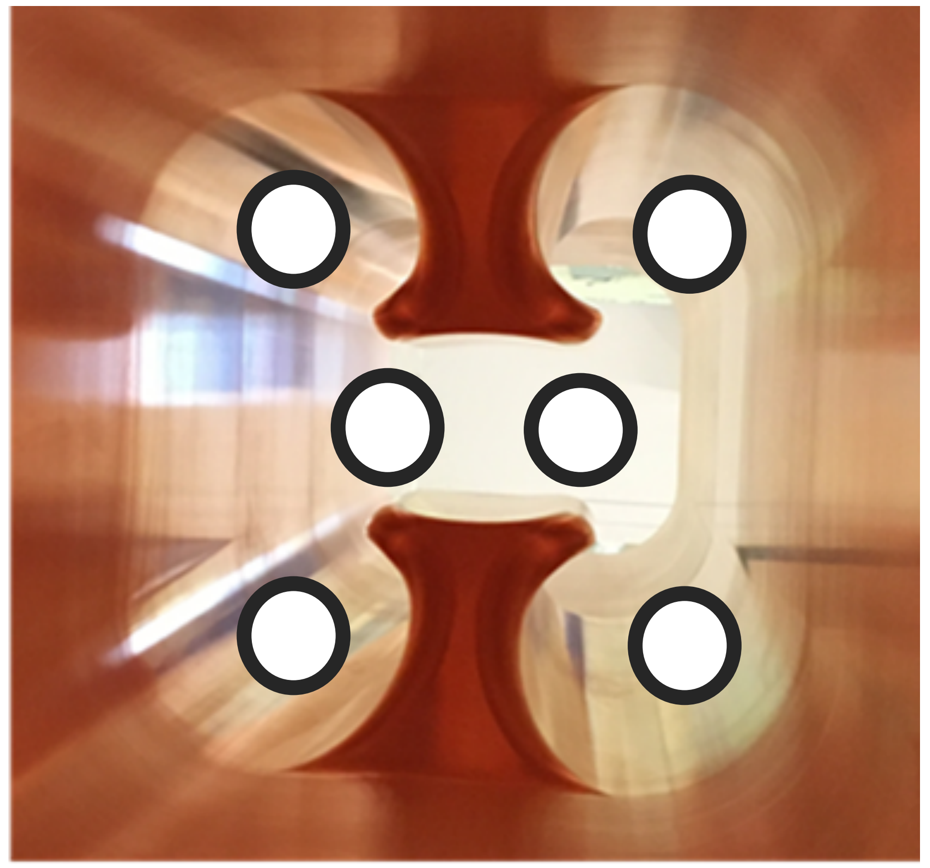


.. room for improvement IV

Cavity shapes

The present choice of cavity shapes may not be optimum. Consider also:

- 2-cell 400 MHz elliptical,
- 400 MHz quarter-wave or half-wave, 1/4-wave may be small enough to use bulk Nb and has a favourable HOM spectrum.
- Wide-open-waveguide crab cavities, …



WOW cavity with 6 coating cathodes

SRF R&D outlook for FCC

for the next ~5-10 years

- Parallel development of cavities, cryo-modules and power couplers (+HOMs)
- A 2-cavity 400 MHz cryo-module with low static loss, 2 FPCs/cavity, cavity tuners, improved alignment, low fabrication cost, …
- Cavities: understand if seamless elliptical cavities can lift the performance of coated cavities.
- Fabrication technologies for seamless elliptical cavities (e.g. hydroforming)
- Power coupler development towards 1 MW CW adjustable…
- 800 MHz bulk Nb cavities
- Alternative cavity shapes
- High-efficiency klystrons

HE-LHC topics requiring special attention

many aspects extrapolated/copied from HL-LHC or FCC-hh. most important exceptions:

tunnel integration and magnet technology

- **compact 16 T magnets** (magnetic cryostat, shielding) (LHC tunnel 3.8 m vs. FCC-hh 5.5 m)
- **HE-LHC Nb_3Sn magnets must be bent**: 9 mm horizontal orbit shift over 14 m (vs. 2 mm for FCC-hh)

arc optics optimization

- **dipole filling factor**: energy reach versus strong focusing for lower energy injection
- **strength of quadrupoles and sextupoles**
- **dynamic aperture, beam size, physical apertures at injection**

limited length of straight sections

- low-beta insertions, **longer triplet than HL-LHC, β^* reach**
- collimation insertions, **LHC or FCC-hh optics scaling not applicable**, warm dipole length !
- extraction straights – **length of kicker & septum sections**

optics for dispersion suppressor (DS) and collimation

- need DS collimators, HL-LHC approach probably not viable (22 T inserts?)

injector and injection energy

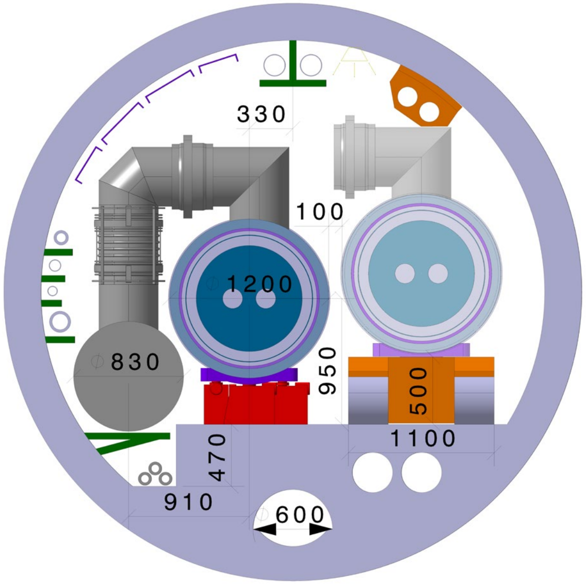
- **physical & dynamic aperture, impedance and beam stability, swing of 16 T magnets…**

HE-LHC integration aspects

Working hypothesis: no major CE modifications on tunnel and caverns

- similar geometry and layout as LHC machine and experiments
- **maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **classical cryostat design gives ~1500 mm diameter!**

LHC tunnel diameter 3.8 m

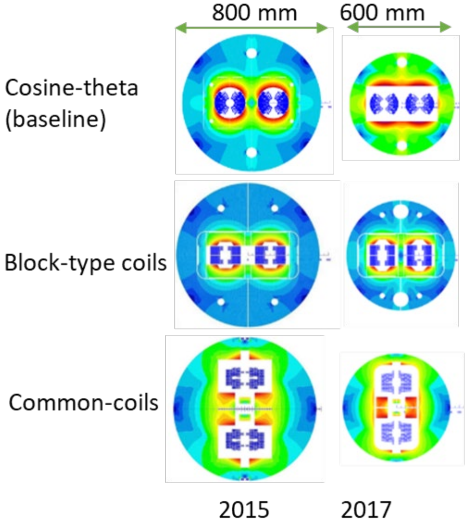


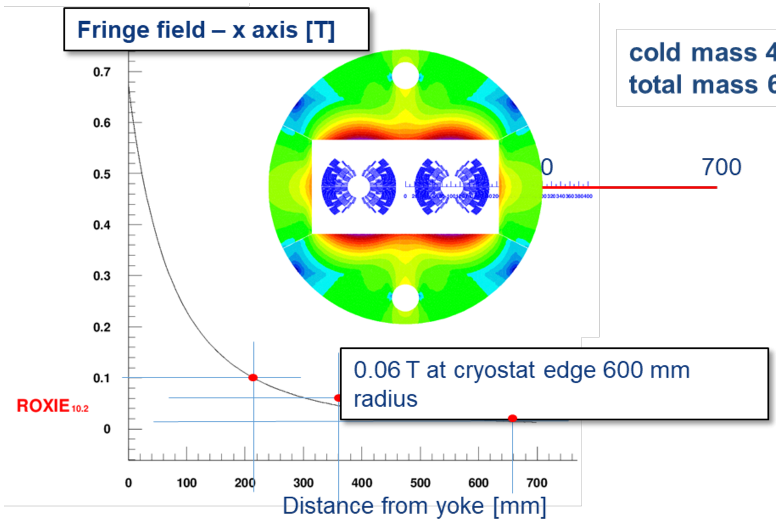
Strategy:

- **allow stray-field and/or cryostat as return-yoke**
- **optimization of inter-beam distance (compact)**

→ **smaller diameter also relevant for FCC-hh cost**

16 T cryo-dipole integration approach





0.06 T at cryostat edge 600 mm radius

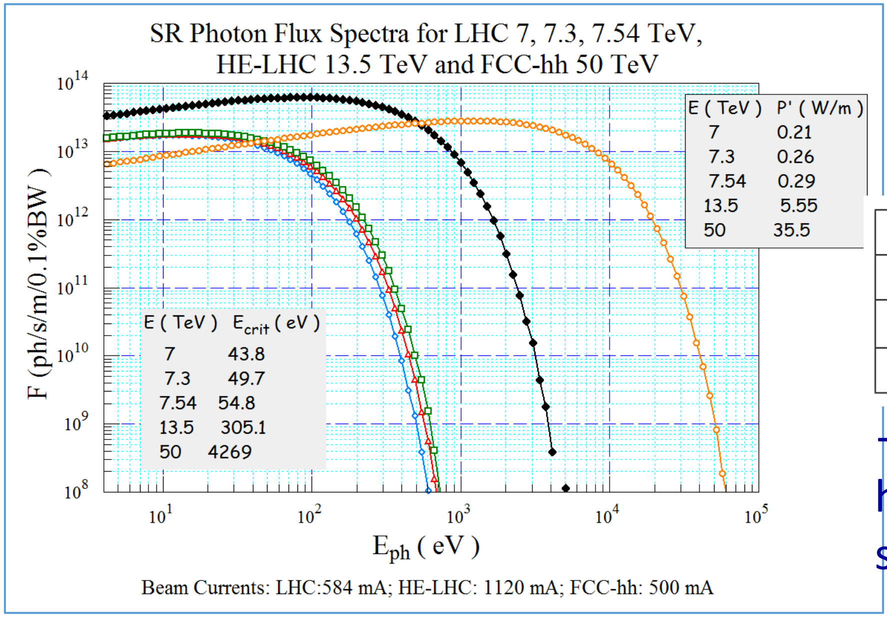
cold mass 40t
total mass 62t

QRL Φ830 mm (LHC 650)
MB Φ1200 mm (LHC 1106)

Description	ID in mm	OD in mm
Iron yoke	-	600
Aluminium shrinking cylinder	600	740
Stainless steel He tight shell	740	760
Al radiation shield	934	940
Vacuum vessel (magnetic steel)	1120	1220

2018: intrabeam distance → 250 mm (194 mm for LHC)

HE-LHC synchrotron radiation (SR)



SR Photon Flux Spectra for LHC 7, 7.3, 7.54 TeV, HE-LHC 13.5 TeV and FCC-hh 50 TeV

Beam Currents: LHC:584 mA; HE-LHC: 1120 mA; FCC-hh: 500 mA

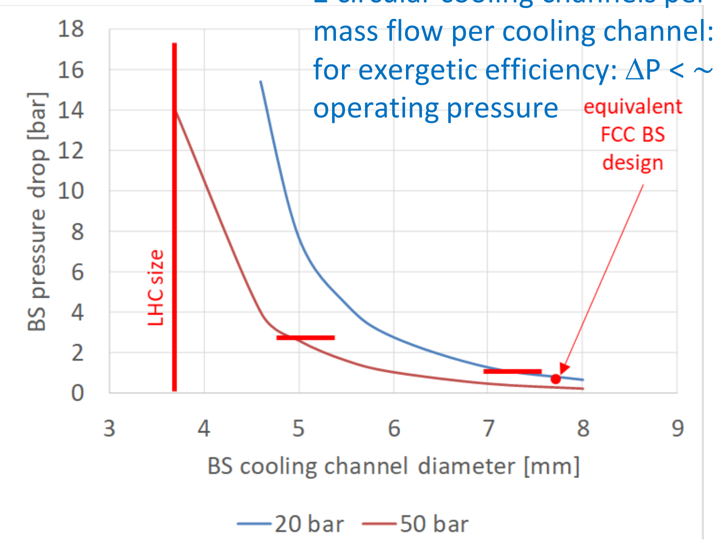
HE-LHC photon flux per meter = 5.4x LHC (7 TeV) and 1.8x FCC-hh (50 TeV)

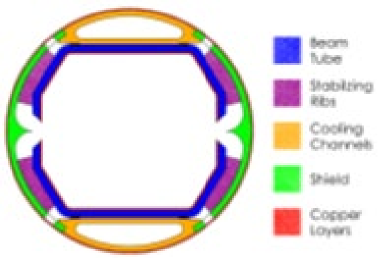
parameter	LHC	HE-LHC	FCC-hh
linear SR power [W/m]	0.25	5.5	35
linear photon flux [10^{16} photons/m/s]	5	27	15
critical photon energy [eV]	44	320	4300

→ ***FCC-hh beam-screen*** for intercepting SR at higher *T*, efficient cooling, **low impedance,** e-cloud suppression and **adequate cryo-pumping**

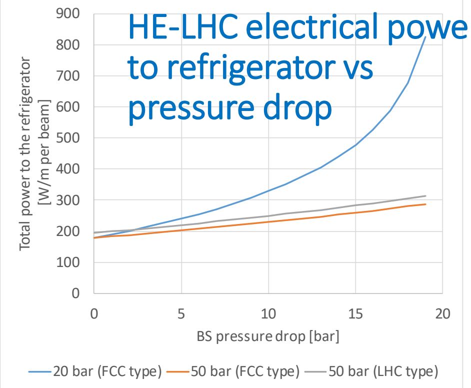
HE-LHC beam-screen pressure drop

2 circular cooling channels per BS (LHC like)
mass flow per cooling channel: ~ 5 g/s
for exergetic efficiency: ΔP < ~5 % of operating pressure





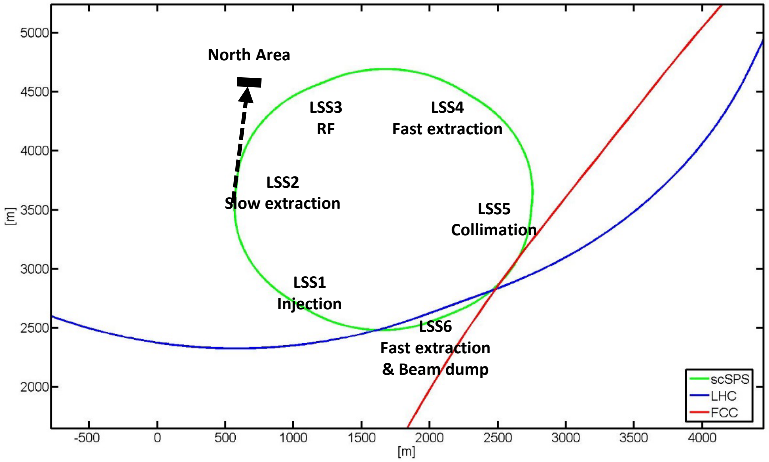
FCC-hh BS compatible w 20 bar operating pressure



HE-LHC electrical power to refrigerator vs pressure drop

BS type	Operating Pressure [bar]	DP [bar] BS (+ CV)	Power to ref. [W/m/beam]	Operation cost (10 y) [MCHF]	Distribution cost
LHC-type beam screen	20	N/A	N/A	N/A	N/A
	50	14 (+3)	300	52	+
FCC-type beam screen	20	0.8 (+1)	200	35	-
	50	0.3 (+1)	184	32	+

HE-LHC injector options



1. **injection from present SPS at 450 GeV excluded**

- **physical aperture** (~1/2-2/3 of present LHC)
- energy swing (**field quality** and dynamic aperture
- **beam instabilities**

options retained:

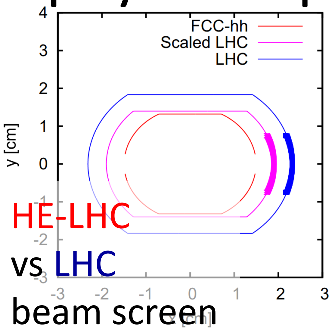
2. new fast ramping SC SPS with single-layer SC dipole (scSPS), max. field 4 T → extract at 900 GeV

3. scSPS with double-layer SC dipole, max. field 6 T → extract at 1.3 TeV

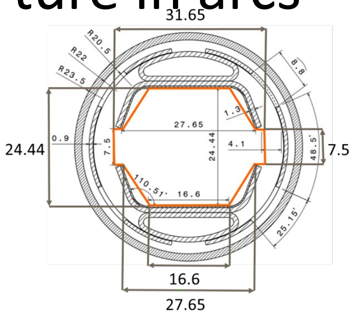
downsides: large energy swing in scSPS,

also new transfer-line magnets from scSPS to HE-LHC

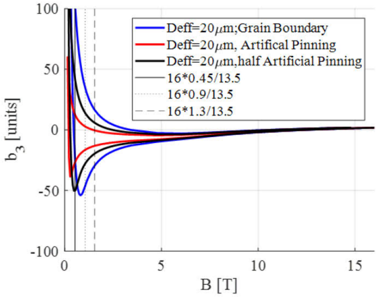
physical aperture in arcs



HE-LHC
vs LHC
beam screen



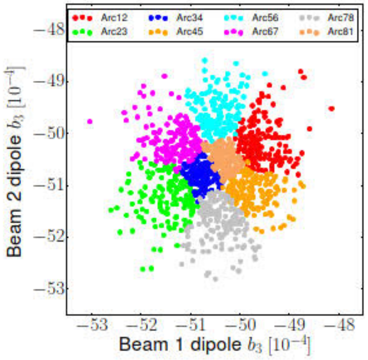
magnet field quality: effective filament size **20 µm**, APCs, with **50% pinning efficiency**, **interbeam distance →250 mm**, and **magnet sorting** (+ **dipole bending**)



dynamic aperture [σ] in arcs

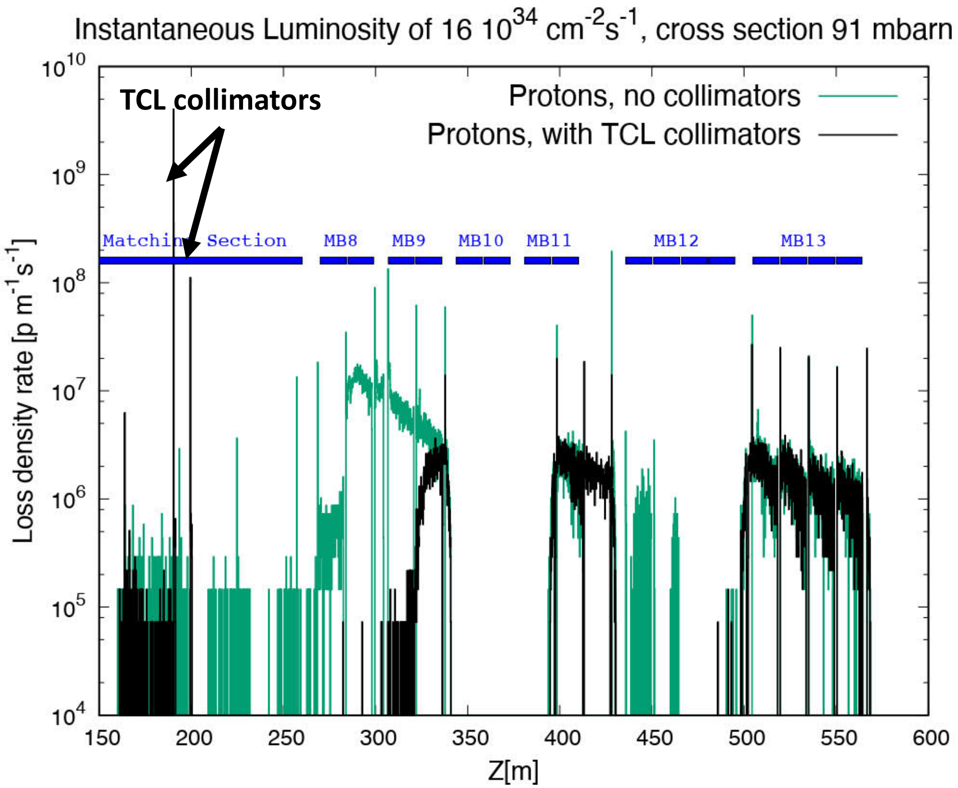
	# of arc cells	Energy [GeV]		
		450	900	1300
without sorting	18	2.7	7.4	11.2
	23	5.4	12.3	15.9
with sorting	18	3.8	9.0	14.4
	23	6.2	13.9	18.1

sorting

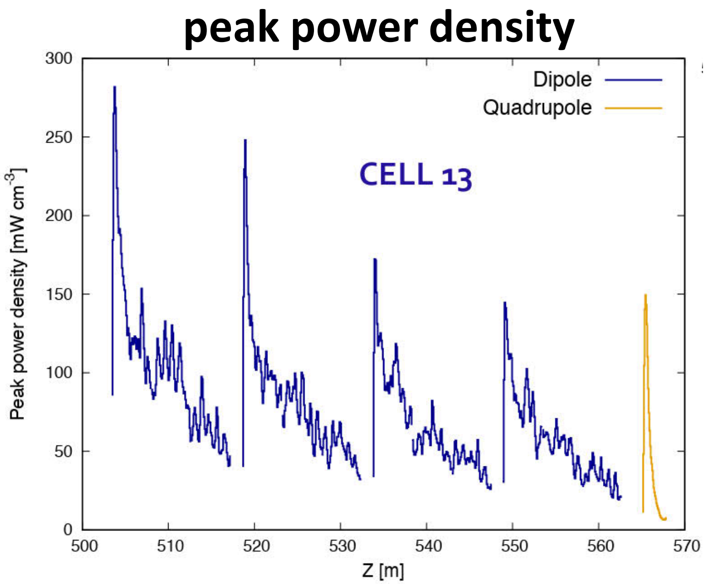


HE-LHC collision debris challenge

- Loss density rate as a function of the distance from the IP:



Collimators in the matching section



impact of particle debris including TCLs , two dipoles absorbs ~600 W each, peak power density high for some dipoles : maximum at entrance > 250 mW cm^{-3}, at center of magnets around 100 mW cm^{-3} , values too high → local protection devices "dispersion-suppressor collimators" needed, with same footprint (no complete optics for CDR)

Technical Maturity

- Overall Technical Maturity

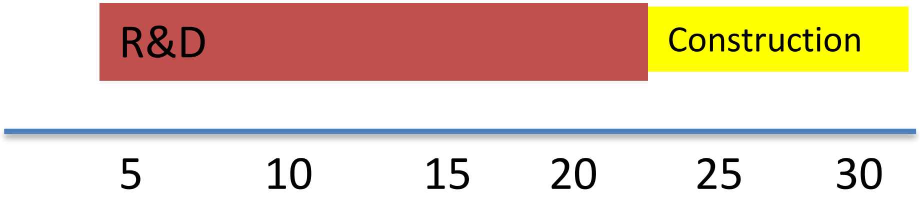
  1

1- Significant R&D required
2– Some R&D in a few key areas required
3 – Shovel ready

- Critical Technologies and TRL level
  - 1250 compact curved 16 T magnets fitting transversely into existing arrow tunnel with sufficiently low magnetization heat during ramp and sufficient field quality (and at target price). **HE-LHC magnets (compact, curved, large beams at inj.) more challenging than FCC-hh magnets !** **TRL 2-3**
  - detector technology for pile up ~500 and high radiation **TRL2-3**
  - Cryoplants and cryogenic distribution systems **TRL 4-6**
  - Beam handling and beam loss technologies (materials & collimators & dumps, injection & extraction elements, etc.) **TRL 4-7**

- Technically limited timeline

  starts after end of HL-LHC, dismantling LHC & SPS + installation ≥10 years



(Modify as appropriate)

Technical Maturity

- ILC based on superconducting radiofrequency (SRF) technology started its R&D from 2005 (GDE). Reference Design Report (RDR) was published in 2007 and TDR was published in 2013.
- More than 2,400 researchers contributed to the TDR.

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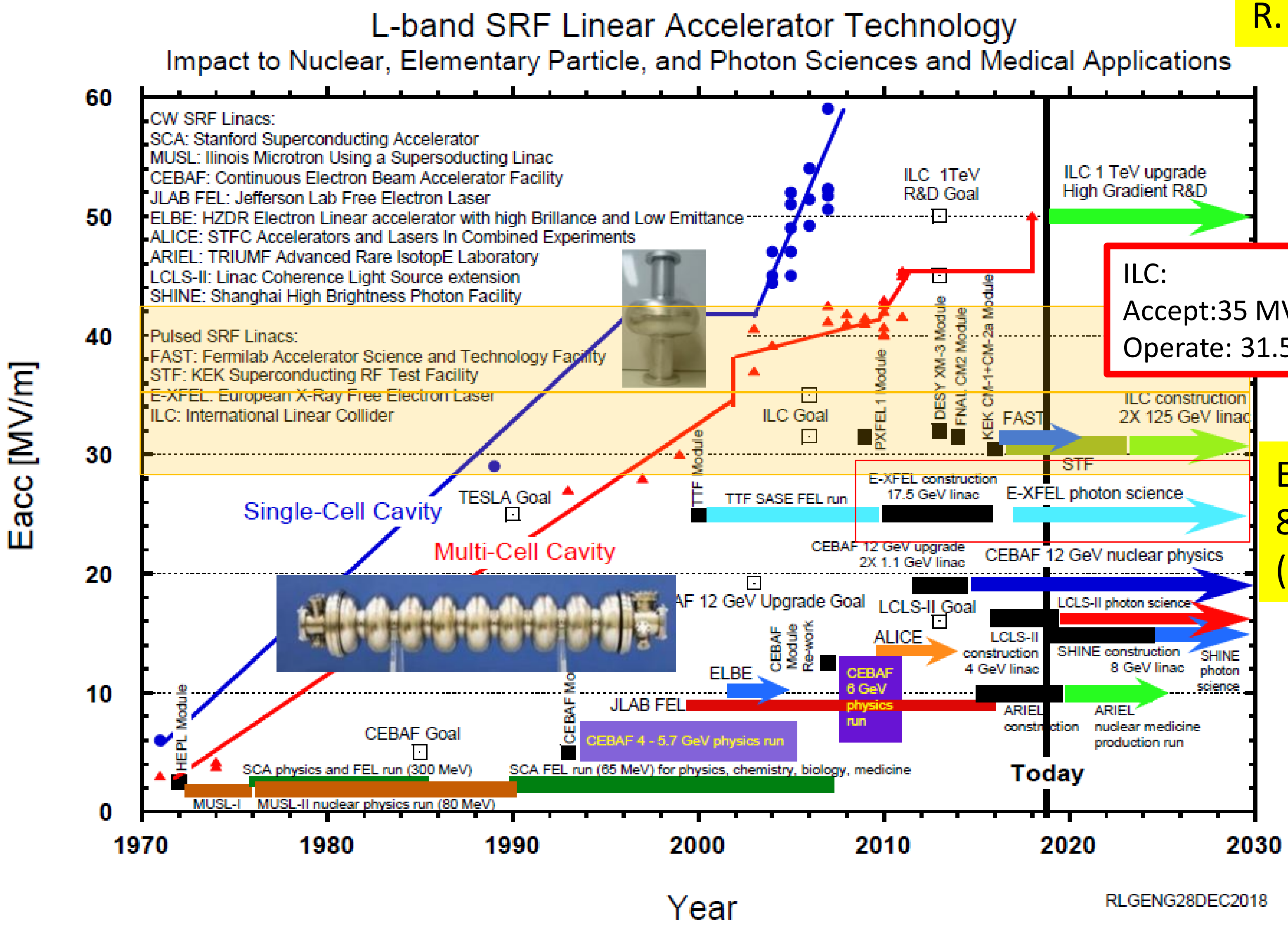
- Remaining technical preparation (such as mass-production of SRF cavities, positron source, beam dump) can be carried out during the preparation phase before ILC construction. These are listed in "Recommendations on ILC Project Implementation" [7].

ILC : 3 – Shovel-ready

Matured SRF technologies

R. Geng (JLAB)



ILC:
Accept:35 MV/m +/-20%
Operate: 31.5MV/m +/-20%

European XFEL
800 cavities
(10% of ILC ML)

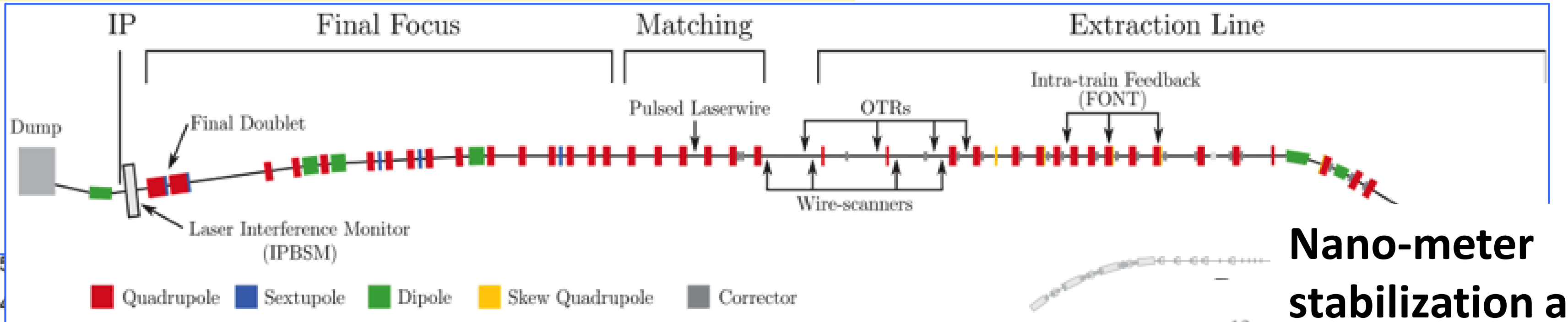
Nano-beam R&D

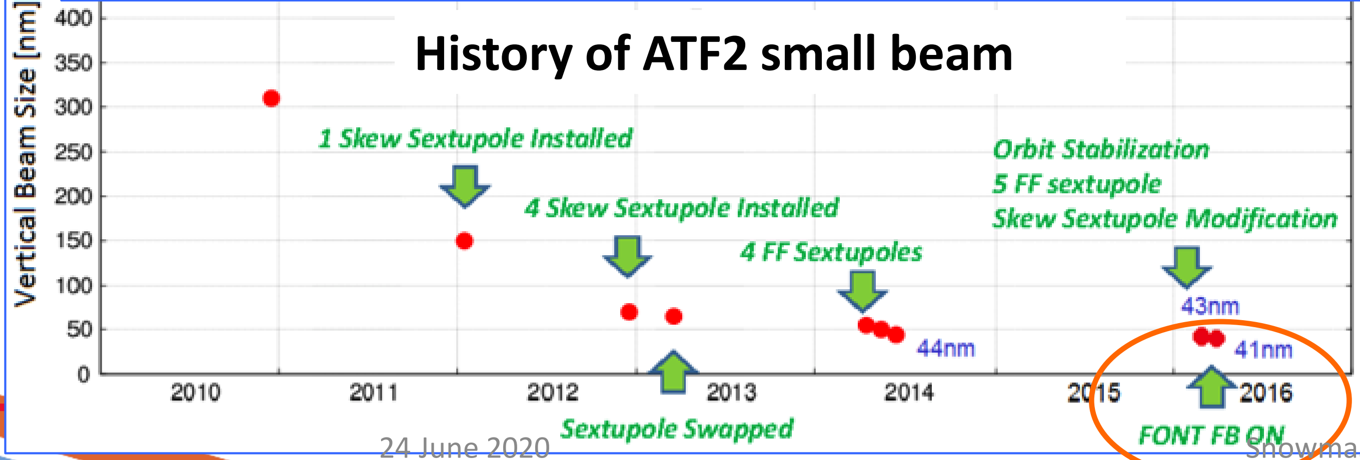
Goal 1: Establish the ILC final focus method with same optics and comparable beamline tolerances

- ATF2 Goal : **37** nm → ILC **7.7** nm (ILC250)
  - Achieved **41 nm** (2016)

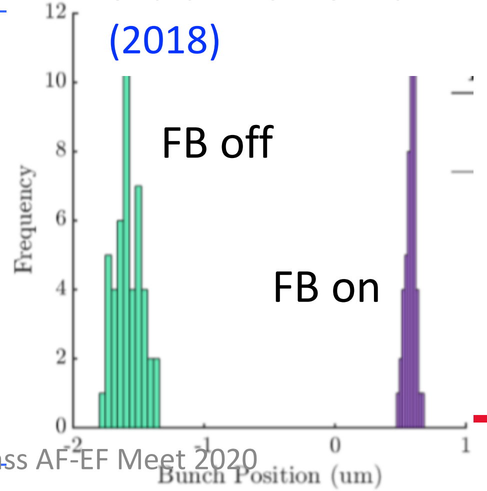
Goal 2: Develop a few nm position stabilization for the ILC collision

- **FB latency 133 nsec achieved** (target: < 366 nsec)
- **positon jitter at IP: 106 → 41 nm (2018)** (limited by the BPM resolution)





Nano-meter stabilization at IP (2018)



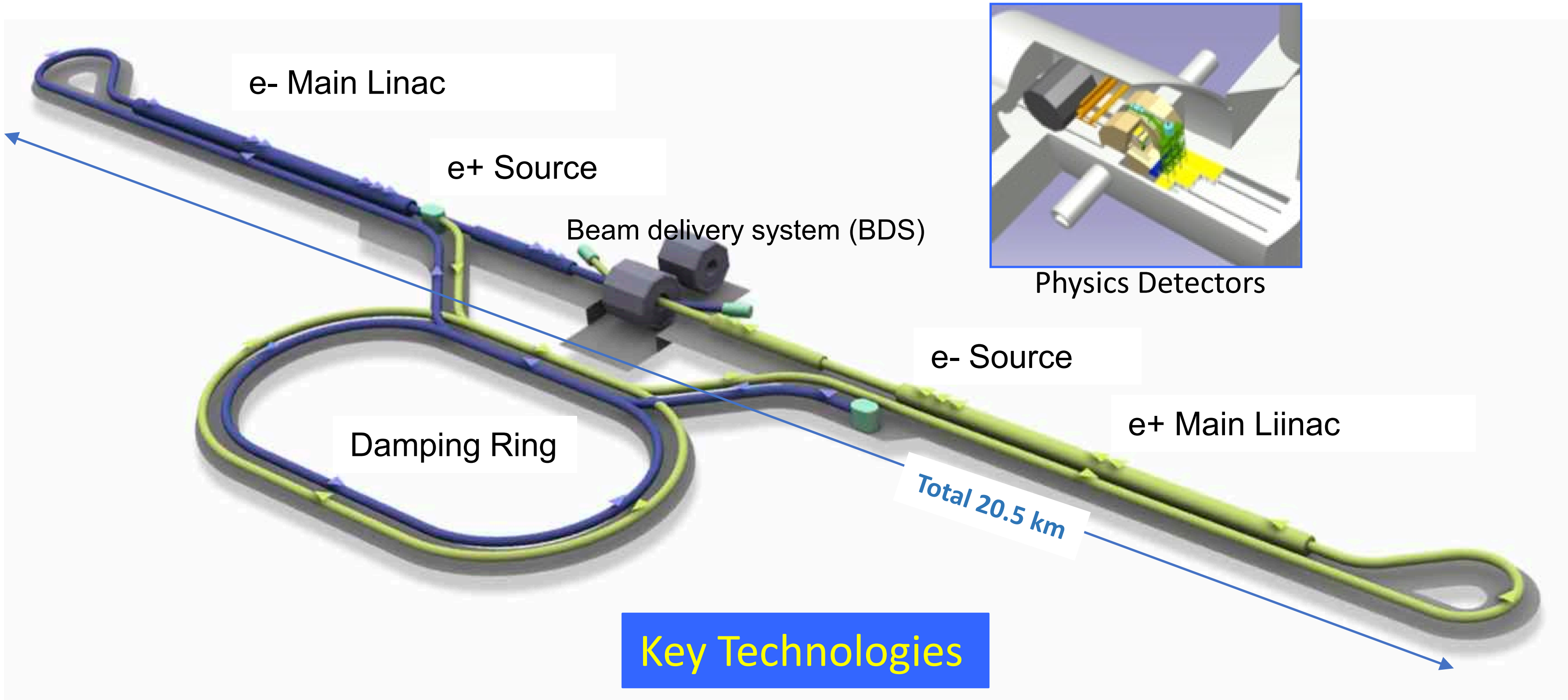
SRF for
Linear Collider Higgs Factories

Snowmass Community Planning Meeting

2020/Oct/6

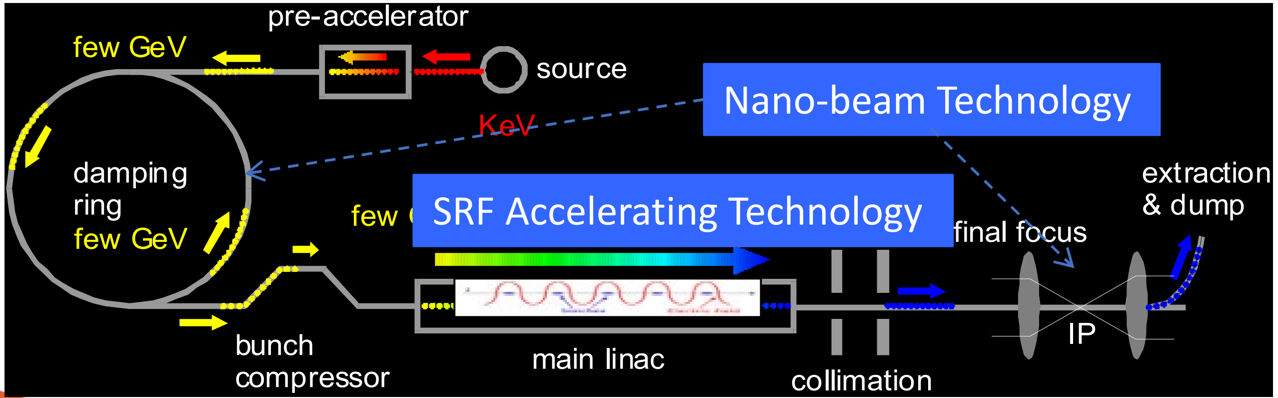
KEK CASA Kensei Umemori, Shin Michizono

ILC250 accelerator facility



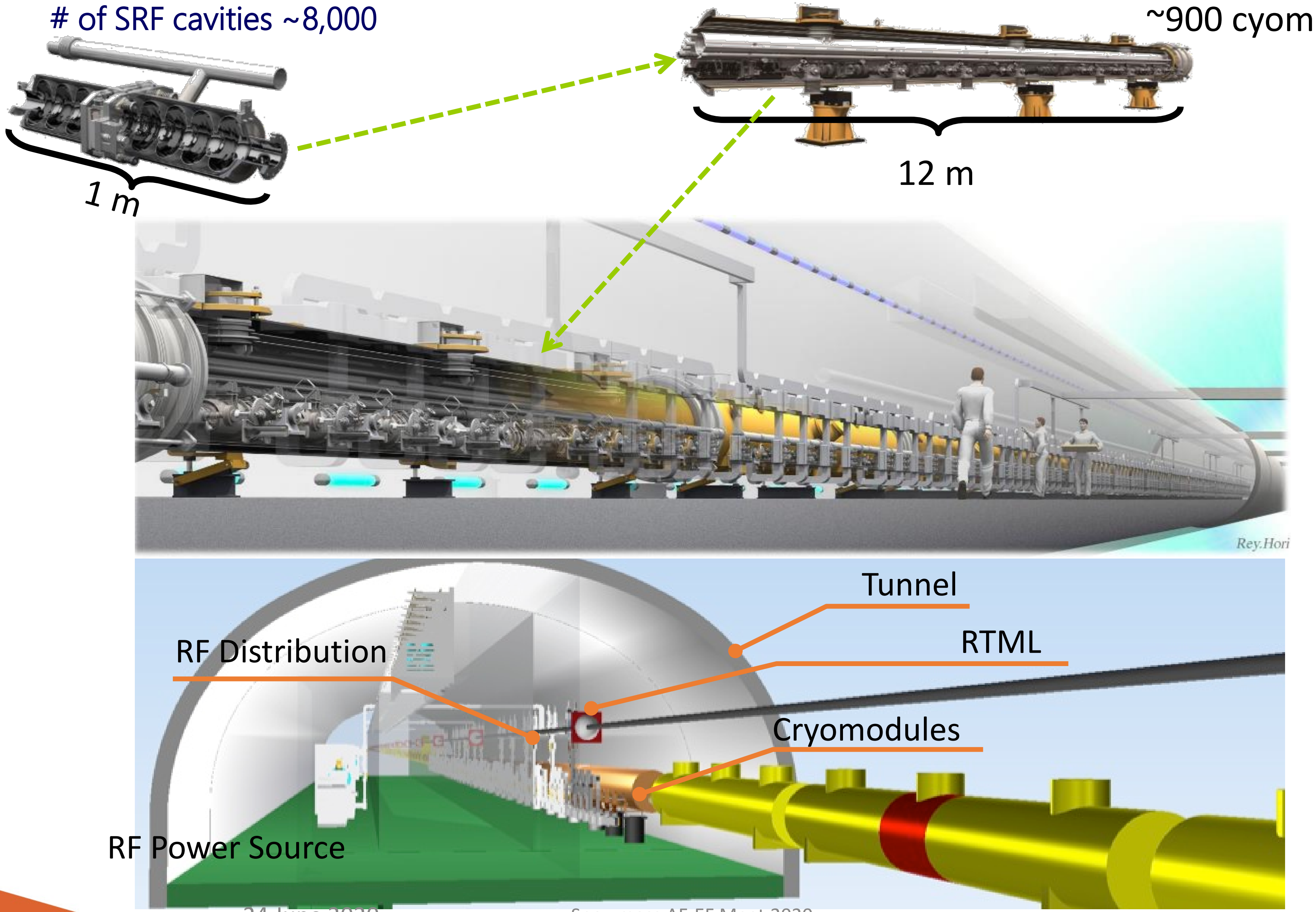
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}

Key Technologies



8,000 SRF cavities will be used.

Main Linac at the ILC



# of SRF cavities ~8,000

1 m

~900 cyomodules

12 m

Tunnel

RTML

RF Distribution

Cryomodules

RF Power Source

Technical Maturity

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- Remaining technical preparation (such as mass-production of SRF cavities, positron source, beam dump) can be carried out during the preparation phase at Pre-lab before ILC construction. These are listed in "Recommendations on ILC Project Implementation" [3].

Worldwide large scale SRF accelerators

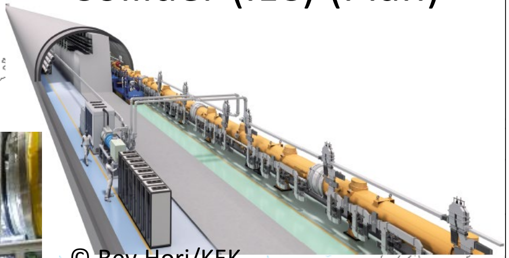
European XFEL

Euro-XFEL

Operation started from 2017

- -100 cyromodules
- -800 cavities
- -17.5 GeV (Pulsed)

International Linear Collider (ILC) (Plan)



© Rey.Hori/KEK

ILC

- -900 cyromodules
- -8,000 cavities
- -250 GeV (Pulsed)

LCLS-II + HE (under construction)

- -35 + 20 cyromodules
- -280 + 160 cavities
- - 4 + 4 GeV (CW)

SLAC

FNAL

Cornell

JLab

DESY

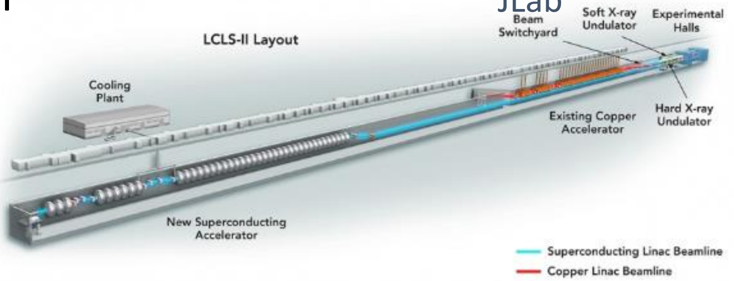
LAL/Sacray

INFN

KEK

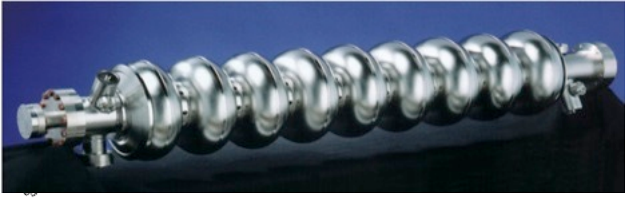
SINAP

LCLS-II



SHINE (under construction)

- -75 cyromodules
- -~600 cavities
- - 8 GeV (CW)



1.3GHz 9 cell cavity

International Development Team (IDT)

IDT: Smooth transition to the ILC Pre-lab

- Prepare a proposal for the organization and governance of the ILC Pre-Lab
- Prepare the work and deliverables of the ILC Pre-laboratory and workout a scenario for contributions with national and regional partners

Accelerator activities at ILC Pre-lab phase

- Technical preparations /performance & cost R&D [shared across regions]
- Final technical design and documentation [central project office in Japan with the help of regional project offices (satellites)]
- Preparation and planning of deliverables [distributed across regions, liaising with the central project office and/or its satellites]
- CE, local infrastructure and site [host country assisted by selected partners]

ICFA

ILC International Development Team

Executive Board

Americas Liaison	Andrew Lankford (UC Irvine)
Working Group 2 Chair	Shinichiro Michizono (KEK)
Working Group 3 Chair	Hitoshi Murayama (UC Berkeley/U. Tokyo)
Executive Board Chair and Working Group 1 Chair	Tatsuya Nakada (EPFL)
KEK Liaison	Yasuhiro Okada (KEK)
Europe Liaison	Steinar Stapnes (CERN)
Asia-Pacific Liaison	Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

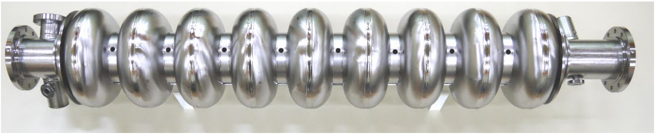
Working Group 2
Accelerator

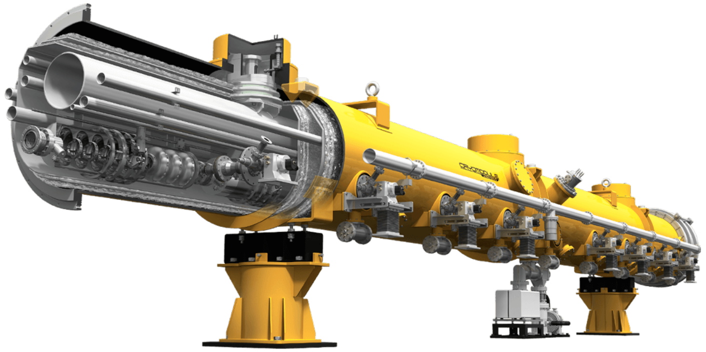
Working Group 3
Physics & Detectors

Technical preparation of SRF

ILC spec. should be satisfied!

- Mass production
  - Cavity production by cost effective method
    - Japan: 50 cavities, Others: 50 cavities
  - Ancillaries production (power coupler, tuner, HOM antenna, etc.)
  - Cryomodule production (Prototype, Type A, Type B)
- CM transportation
  - After marine transportation, CM test is done in Japan (maybe in others)
  - After CM test, CM may return to home country





In case of Japan;

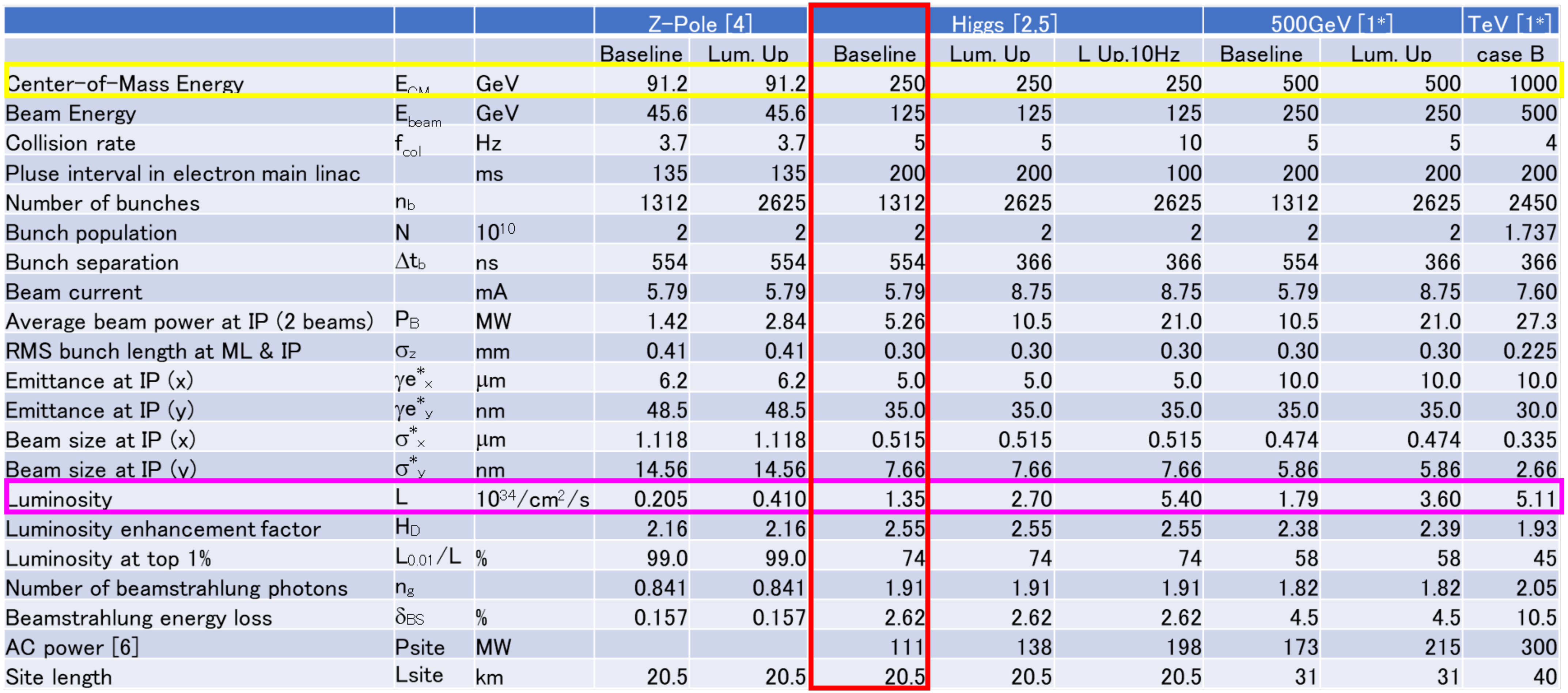
- **Construction of hub-laboratory for mass production**
- **Demonstration of beam acceleration satisfied with ILC spec.**

Remarks:

- Necessary cost should be considered **based on TDR**.
- Another important point is whether new technology can be (or prospectively) **reliable**.

Potential for upgrades

The ILC can be upgraded to higher energy and luminosity.



			Z-Pole [4]		Higgs [2,5]			500GeV [1*]		TeV [1*]
			Baseline	Lum. Up	Baseline	Lum. Up	L Up.10Hz	Baseline	Lum. Up	case B
Center-of-Mass Energy	E_{CM}	GeV	91.2	91.2	250	250	250	500	500	1000
Beam Energy	E_{beam}	GeV	45.6	45.6	125	125	125	250	250	500
Collision rate	f_{col}	Hz	3.7	3.7	5	5	10	5	5	4
Pluse interval in electron main linac		ms	135	135	200	200	100	200	200	200
Number of bunches	n_b		1312	2625	1312	2625	2625	1312	2625	2450
Bunch population	N	10^{10}	2	2	2	2	2	2	2	1.737
Bunch separation	Δt_b	ns	554	554	554	366	366	554	366	366
Beam current		mA	5.79	5.79	5.79	8.75	8.75	5.79	8.75	7.60
Average beam power at IP (2 beams)	P_B	MW	1.42	2.84	5.26	10.5	21.0	10.5	21.0	27.3
RMS bunch length at ML & IP	σ_z	mm	0.41	0.41	0.30	0.30	0.30	0.30	0.30	0.225
Emittance at IP (x)	γe^*_x	µm	6.2	6.2	5.0	5.0	5.0	10.0	10.0	10.0
Emittance at IP (y)	γe^*_y	nm	48.5	48.5	35.0	35.0	35.0	35.0	35.0	30.0
Beam size at IP (x)	σ^*_x	µm	1.118	1.118	0.515	0.515	0.515	0.474	0.474	0.335
Beam size at IP (y)	σ^*_y	nm	14.56	14.56	7.66	7.66	7.66	5.86	5.86	2.66
Luminosity	L	$10^{34}/cm^2/s$	0.205	0.410	1.35	2.70	5.40	1.79	3.60	5.11
Luminosity enhancement factor	H_D		2.16	2.16	2.55	2.55	2.55	2.38	2.39	1.93
Luminosity at top 1%	$L_{0.01}/L$	%	99.0	99.0	74	74	74	58	58	45
Number of beamstrahlung photons	n_g		0.841	0.841	1.91	1.91	1.91	1.82	1.82	2.05
Beamstrahlung energy loss	δ_{BS}	%	0.157	0.157	2.62	2.62	2.62	4.5	4.5	10.5
AC power [6]	Psite	MW			111	138	198	173	215	300
Site length	Lsite	km	20.5	20.5	20.5	20.5	20.5	31	31	40

Energy

Lumi.

Summary

- *ILC250 accelerator is 20 km long e-/e+ collider for the Higgs factory.*
- *The ILC is upgradable in energy and luminosity.*
- *International collaborations (GDE, LCC and IDT(International Development Team from summer 2020)) have been leading the R&Ds of the ILC since 2005.*
- *TDR was published in 2013 and these technologies are matured.*
- *Key technologies at the ILC are superconducting rf (SRF) and nano-beam.*
  - *SRF technology has been widely adopted at XFELs such as European XFEL.*
  - *Nano-beam technology has been demonstrated at ATF hosted by KEK*
- *Construction cost (value) is ~5 B$ and we assume 4-year preparation and 9-year construction.*
- *Preparation phase activities are*
  - *Technical preparation*
  - *Final engineering design*
  - *Preparation for mass production, …*

Backup slide

Superconducting RF (SCRF)

Technical Preparation of SCRF

Technical concern pointed out by SCJ and MEXT's advisory panel

- ✓ *Mass production : New production method (cost reduction) and the yields*
- ✓ *Cryomodule transport.*

Technical preparation at preparation phase

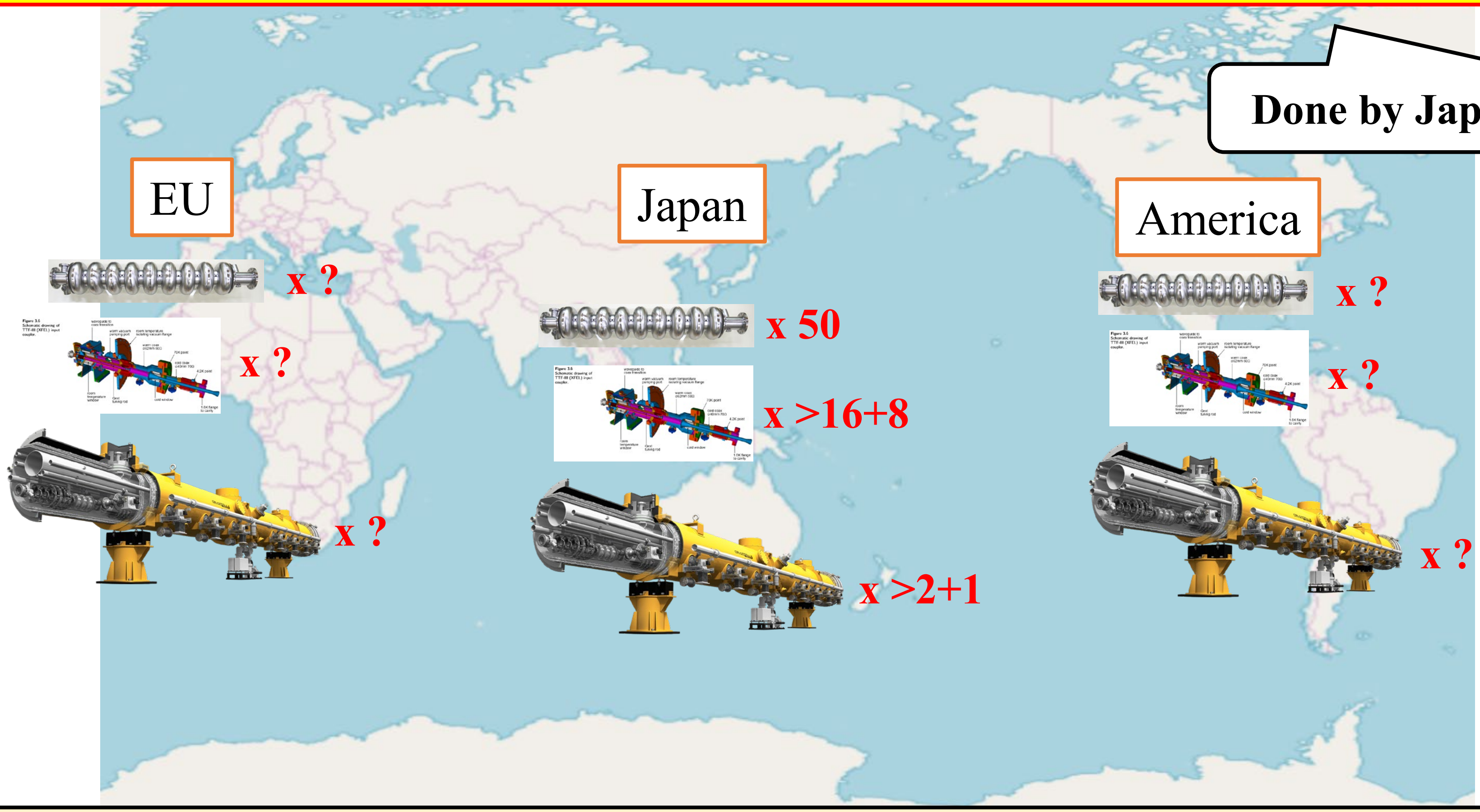
- ✓ ***International collaboration***
  - *- Performance test of cost reduction and mass production preparation*
  - *- Transport of the cryomodules produced by the different regions*

Issue	***Tasks***	***Cooperation candidates***
Mass production	*Performance / mass production technology*	*France, Germany, USA*
Cryomodule transport	*Performance assurance after transport*	*France, Germany, USA*

Mass production

Before mass production starts, tuner design should be fixed!!

Done by Japan-U.S. collaboration



EU

x ?

x ?

x ?

Japan

x 50

x >16+8

x >2+1

America

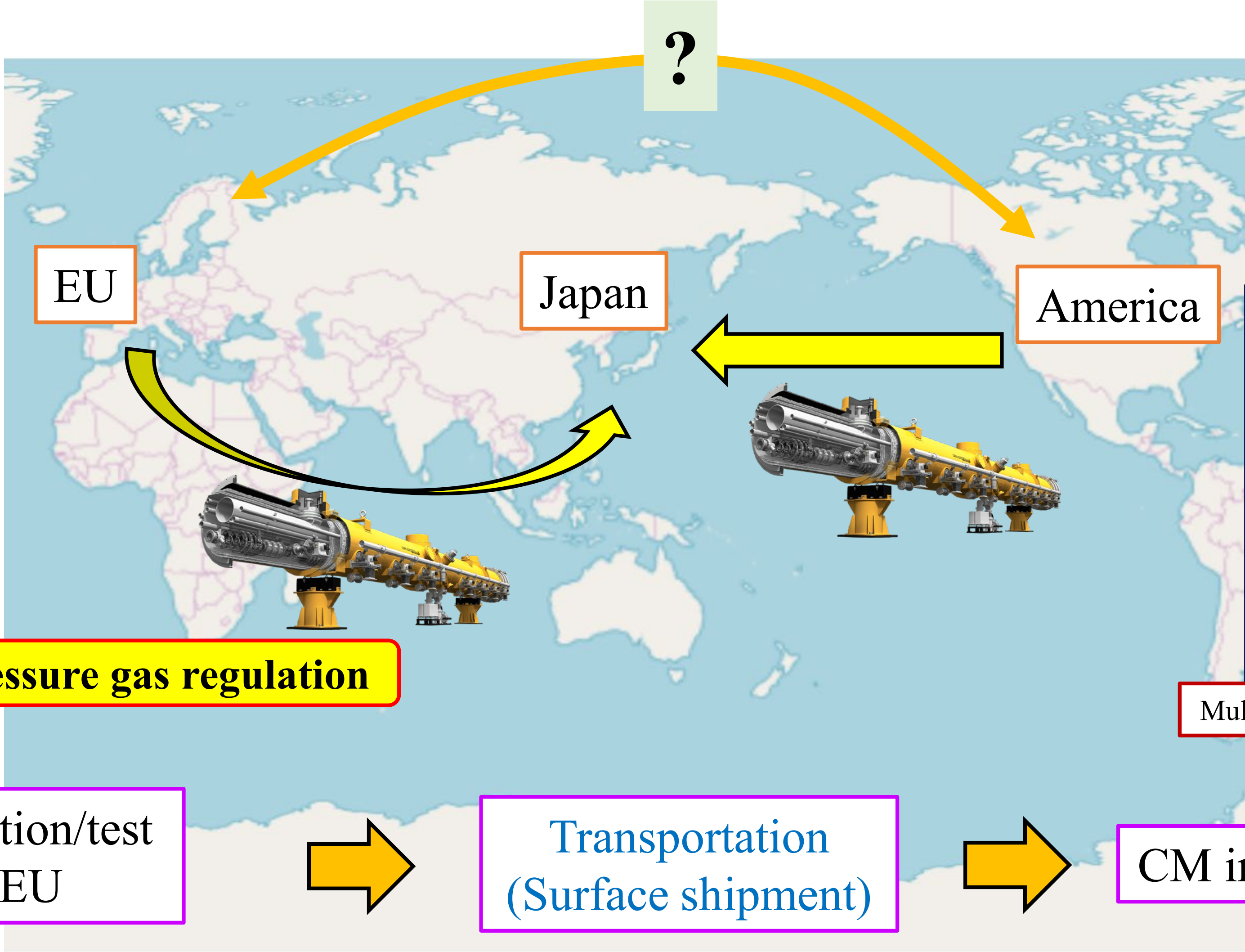
x ?

x ?

x ?

Which lab. is responsible for cavity, power coupler, tuner, CM, etc.?
How many cavities, couplers, CMs are produced?

Cryomodule transportation from overseas




1-1. Unloading of the MBK Package from Truck

Check the shock indicators before unloading.
Lift the package from the truck to the ground using a crane.

MBK PACKAGE SIZE: 3108x1713x1993 mm
WEIGHT: Approx. 3.5 ton

Multi-beam klystron transportation from Japan to EU

conforming to high-pressure gas regulation

New CM production/test @America/EU → Transportation (Surface shipment) → CM inspection/test @Japan

Note: Returning the CMs to Europe/Americas for redundant confirmations, to be discussed.

In case of Japan (KEK)…

Center for Applied Superconducting Accelerator

Demonstration of beam acceleration satisfied with ILC spec.

STF

Infrastructure upgrade for hub-lab. is mandatory!

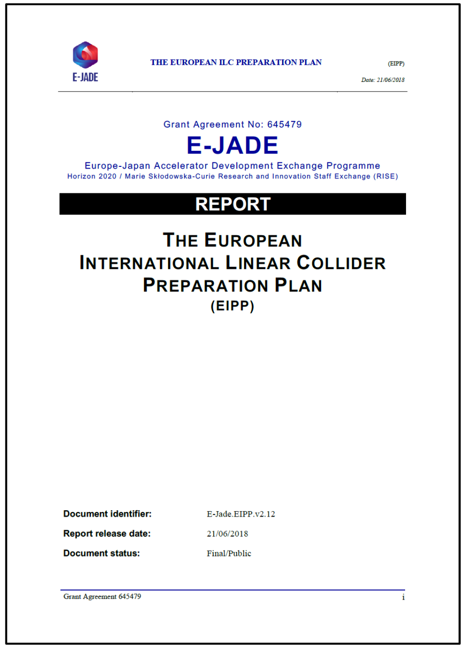
COI

Mass production of CM

CFF

Mass production of cavity

Contribution from each lab. (case of E-JADE)



THE EUROPEAN ILC PREPARATION PLAN (EIPP)

Date: 21/06/2018

Grant Agreement No: 645479

E-JADE

Europe-Japan Accelerator Development Exchange Programme

Horizon 2020 / Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE)

REPORT

THE EUROPEAN
INTERNATIONAL LINEAR COLLIDER
PREPARATION PLAN
(EIPP)

Document identifier:	E-Jade.EIPP.v2.12
Report release date:	21/06/2018
Document status:	Final/Public

Grant Agreement 645479 i

Item/topic	Brief description	CERN	France CEA	Germany DESY	Time line
SCRF	Cavity fabrication including forming and EBW technology,	✓			2017-18
	Cavity surface process: High-Q &–G with N-infusion to be demonstrated with statics, using High-G cavities available (# > 10) and fundamental surface research		✓	✓	2017-18
	Power input-coupler: plug compatible coupler with new ceramic window requiring no-coating	✓			2017-19
	Tuner: Cost-effective tuner w/ lever-arm tuner design	✓	✓		2017-19
	Cavity-string assembly: clean robotic-work for QA/QC.		✓		2017-19
Cryogenics	Design study: optimum layout, emergency/failure mode analysis, He inventory, and cryogenics safety management.	✓			2017-18
HLRF	Klystron: high-efficiency in both RF power and solenoid using HTS	✓			2017- (longer)
CFS	Civil engineering and layout optimization, including Tunnel Optimization Tool (TOT) development, and general safety management.	✓			2017-18
Beam dump	18 MW main beam dump: design study and R&D to seek for an optimum and reliable system including robotic work	✓			2017- (longer)
Positron source	Targetry simulation through undulator driven approach			✓	2017-19
Rad. safety	Radiation safety and control reflected to the tunnel/wall design	✓			2017 – (longer)

Table 1: Current common studies between European institutions and Japan relevant for ILC.

- SRF sub-groups need to make similar table for each region (Asia, America).
- Addition to these items, some new contents need to be added to the table.
  - CM transportation, automation, etc.
- And, budget, human resources…

KEK starts development of automation technique

	Germany	France		Italy	Poland			Russia	Spain
	DESY	CEA Saclay	LAL	INFN Milan	IFJ PAN	WUT	NCBJ	BINP	CIEMAT
Linac									
Cryomodules	✓	✓		✓					
SCRF Cavities	✓			✓					
Power Couplers	✓		✓						
HOM Couplers							✓		
Frequency Tuners	✓								
Cold Vacuum	✓							✓	
Cavity String Assembly	✓	✓							
SC Magnets	✓				✓				✓
Infrastructure									
AMTF	✓				✓	✓		✓	
Cryogenics	✓								
Sites & Buildings									
AMTF hall	✓								

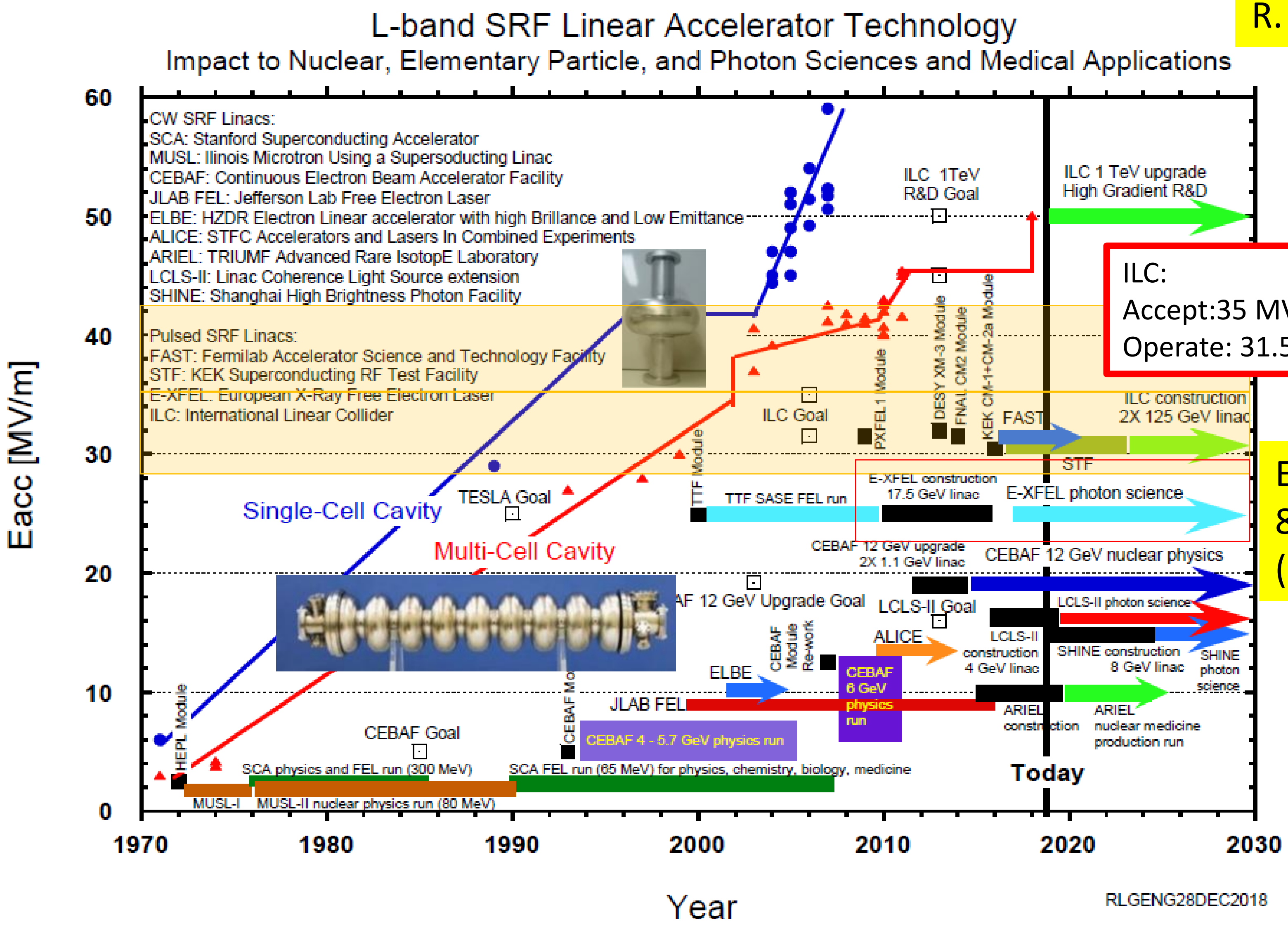
Table 2: Responsibility matrix for cryomodule production and testing for the European XFE

	Germany	France		Italy		Poland	Spain	Sweden		UK
	DESY	CEA	IPNO	Elettra	INFN-LASA	IFJ-PAN	ESS Bilbao	ESS	Uppsala	STFC
RF systems				✓			✓	✓		
LLRF									✓	
Cryomodules		✓	✓							
SCRF Cavities		✓	✓		✓					✓
Power Couplers		✓	✓							
HOM couplers										
Frequency Tuners		✓	✓							
Cold Vacuum		✓	✓					✓		
Cavity String Assembly		✓	✓							
RF Tests (Cavites)	✓									✓
RF Tests (Cryomodules)		✓	✓			✓		✓	✓	

Table 3: Responsibility matrix for the cryomodule production and testing for the ESS.

Matured SRF technologies

R. Geng (JLAB)



ILC:
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Operate: 31.5MV/m +/-20%

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800 cavities
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Nano-beam R&D at ATF2

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Goal 2: Develop the position stabilization for the ILC collision

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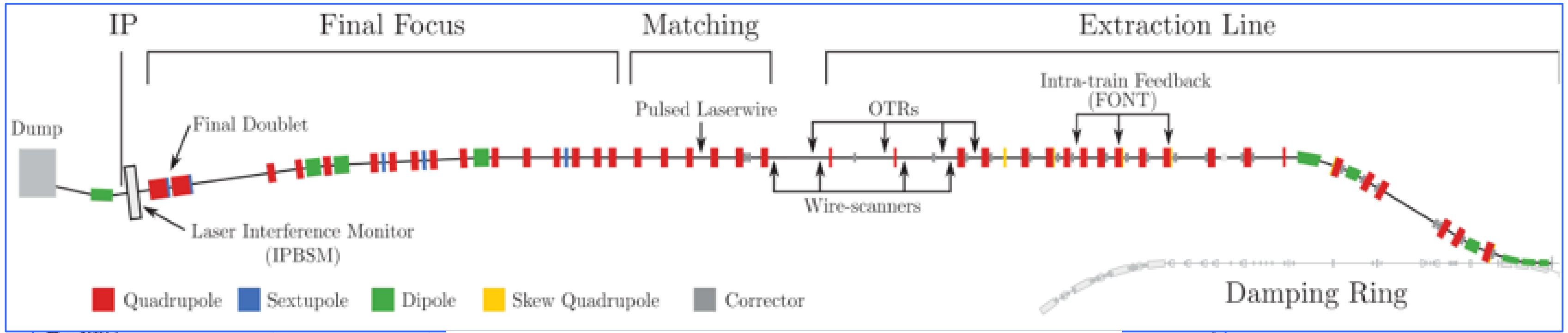
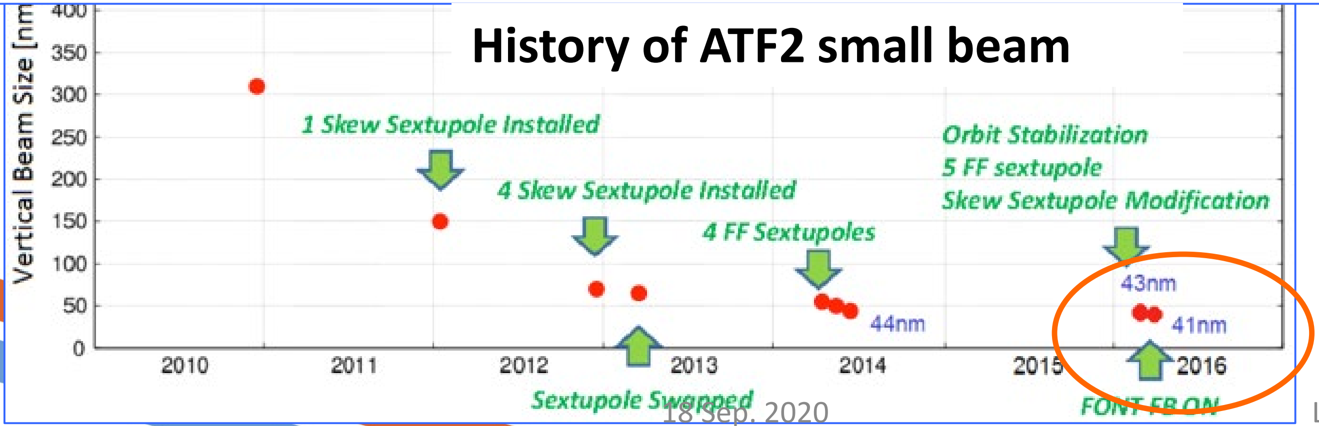
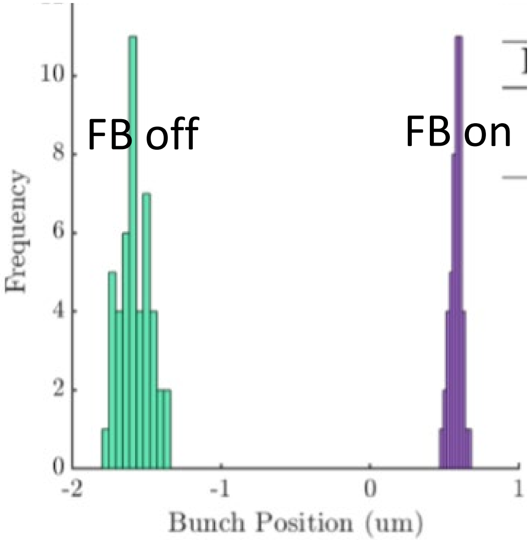
- **positon jitter at IP: 106 → 41 nm (2018)** (limited by the BPM resolution)



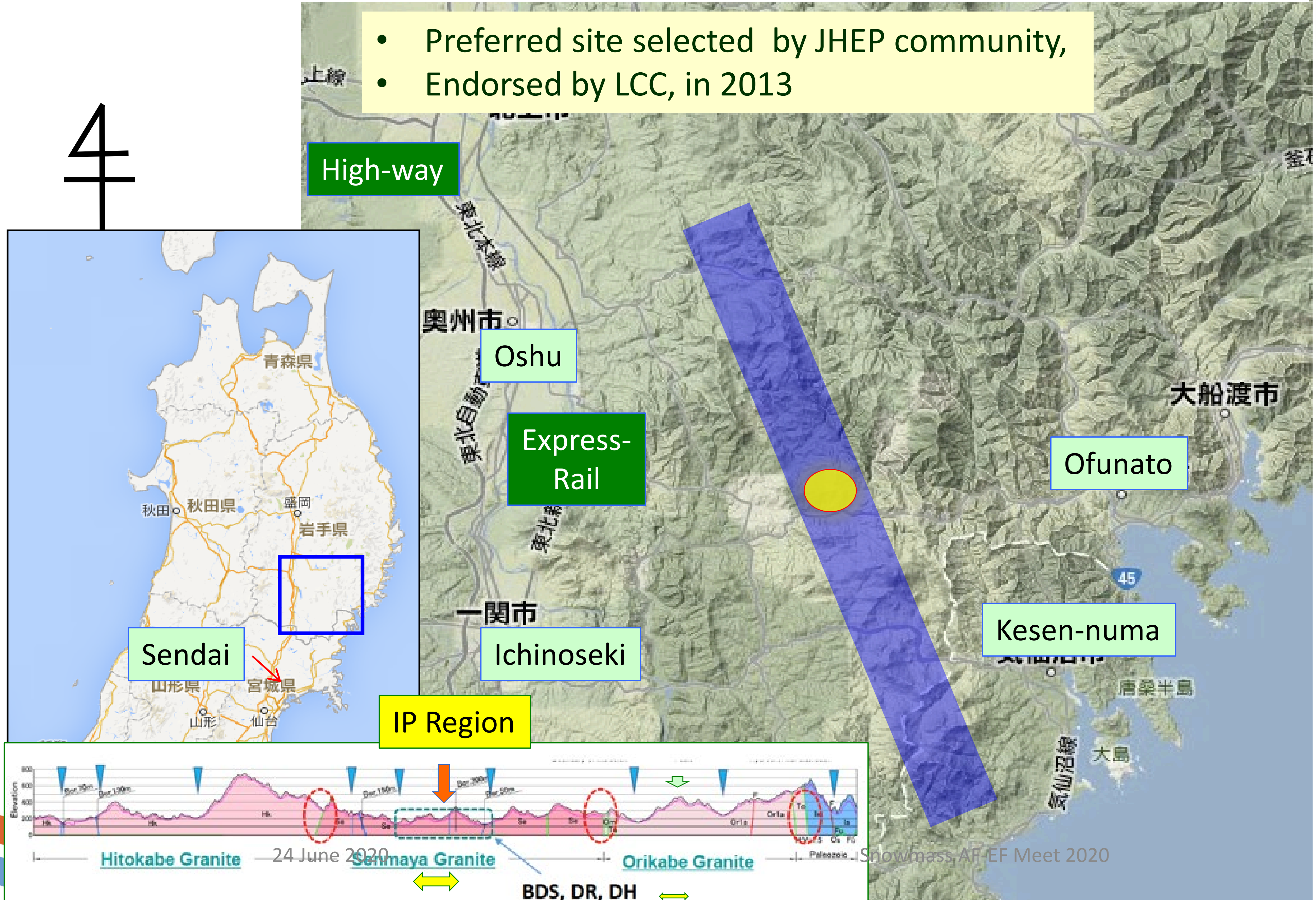

History of ATF2 small beam

Nano-meter stabilization at IP
(2018)



ILC Site Candidate Location in Japan: Kitakami

- Preferred site selected by JHEP community,
- Endorsed by LCC, in 2013

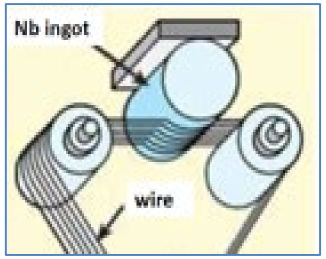


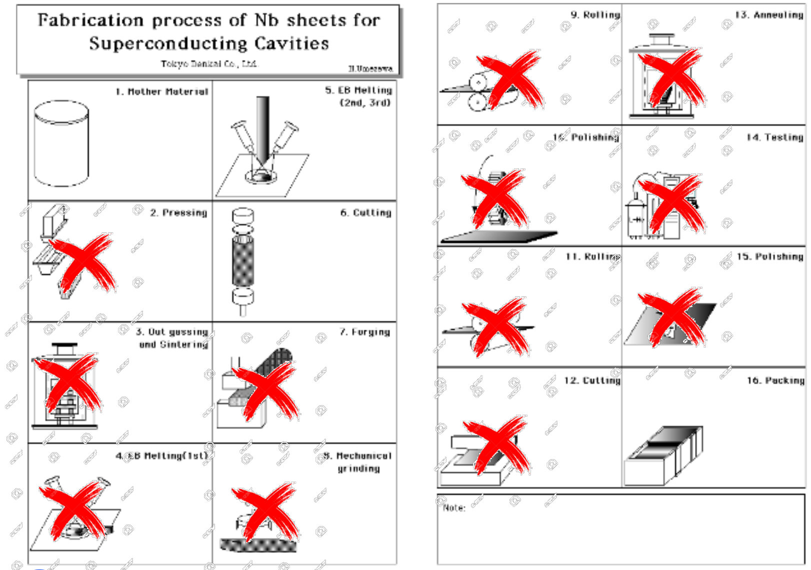
ILC Cost-Reduction R&D in US-Japan Cooperation

Based on recent advances in technologies;

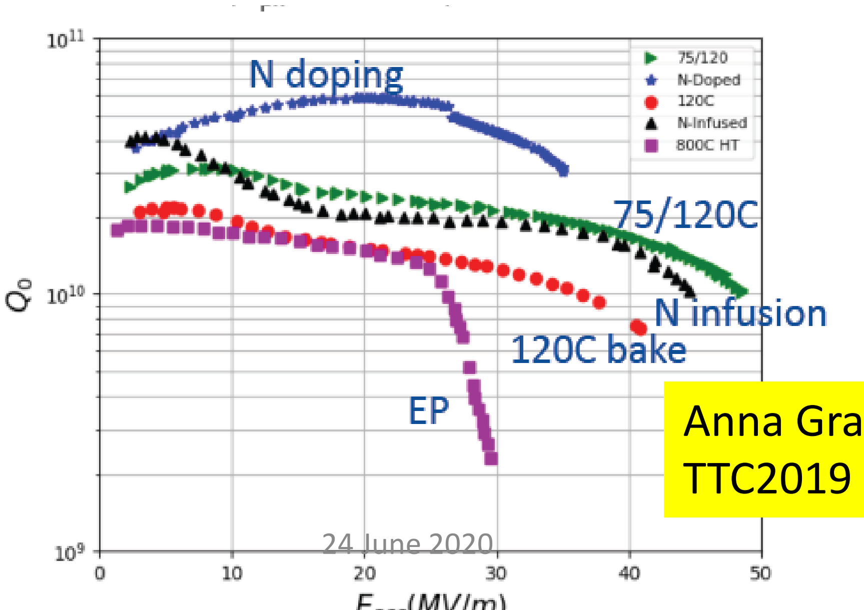
- Nb material/sheet preparation

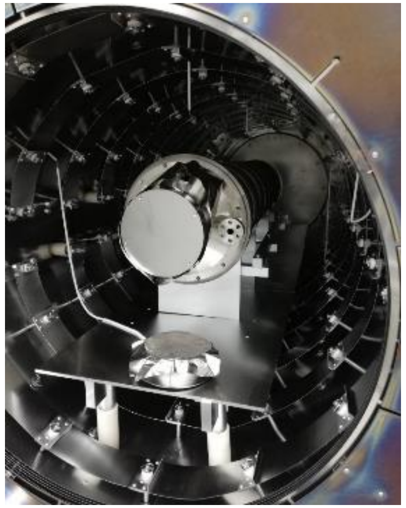
  - w/ optimum Nb purity and clean surface





- Surface treatments for high-Q and high-G



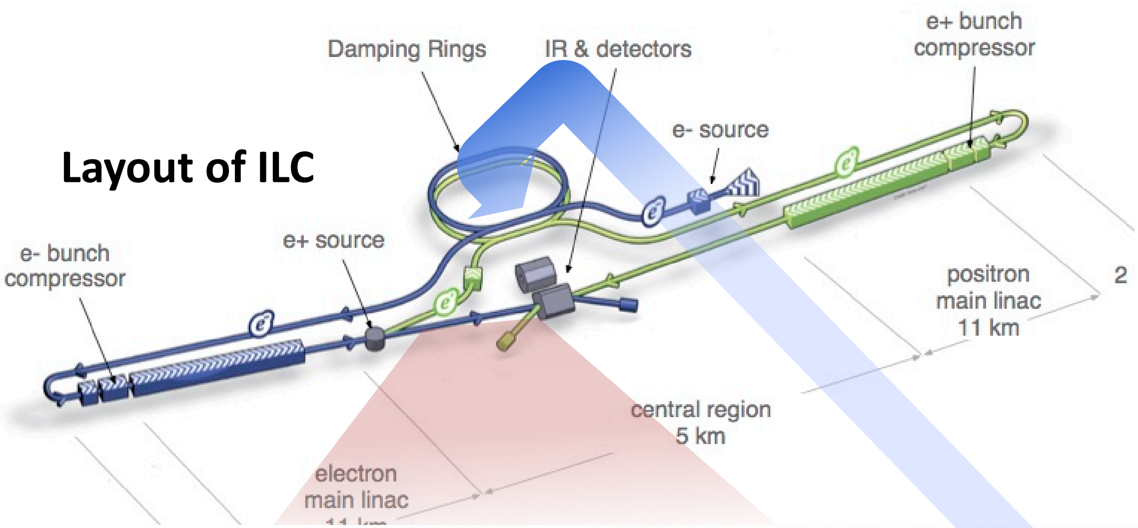


Anna Grassellino
TTC2019 Vancouver

ATF/ATF2: Accelerator Test Facility

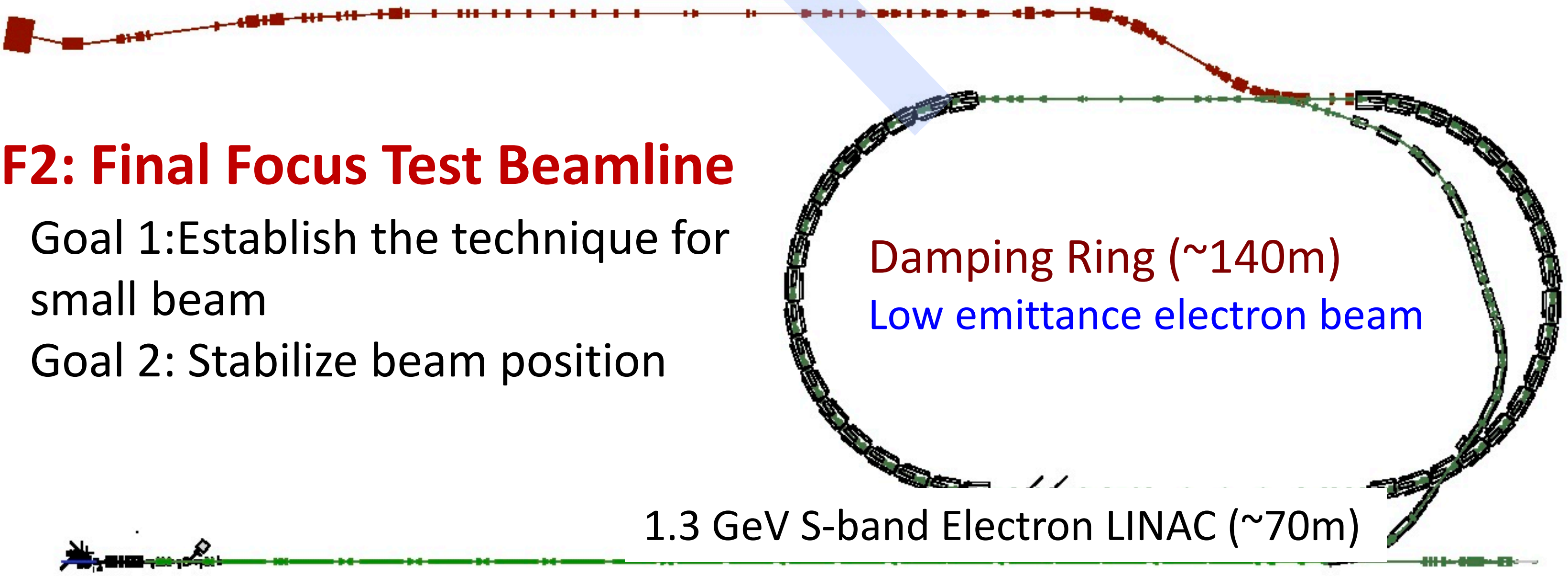
Center for Applied Superconducting Accelerator
応用超伝導加速器センター

Layout of ILC



Develop the nanometer beam technologies for ILC

- Key of the luminosity maintenance
- 7.7 nm beam at IP (ILC250)



ATF2: Final Focus Test Beamline

Goal 1:Establish the technique for small beam

Goal 2: Stabilize beam position

Damping Ring (~140m)

Low emittance electron beam

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

Advanced SRF R&D for Higgs Factory Luminosity (and Energy) Upgrades to 380 GeV Top Factory

Hasan Padamsee

Cornell University

Discussed in Snowmass LOI and accompanying paper:
Perspectives on International Superconducting Linear Colliers (ILC) to the Next Century Part A: **High Luminosity Higgs Factory and Top Factory**

General Remarks

- Best gradient for ILC start at 250 GeV is 31.5 MV/m for Cryomodule gradients
- Demonstration of CM gradients > 32 MV/m has been achieved at Fermilab with beam.
- > 30.5 MV/m in full scale cryomodule at KEK
- Many Cryomodules at EXFEL showed average gradient near the administrative limit of 30.5 MV/m

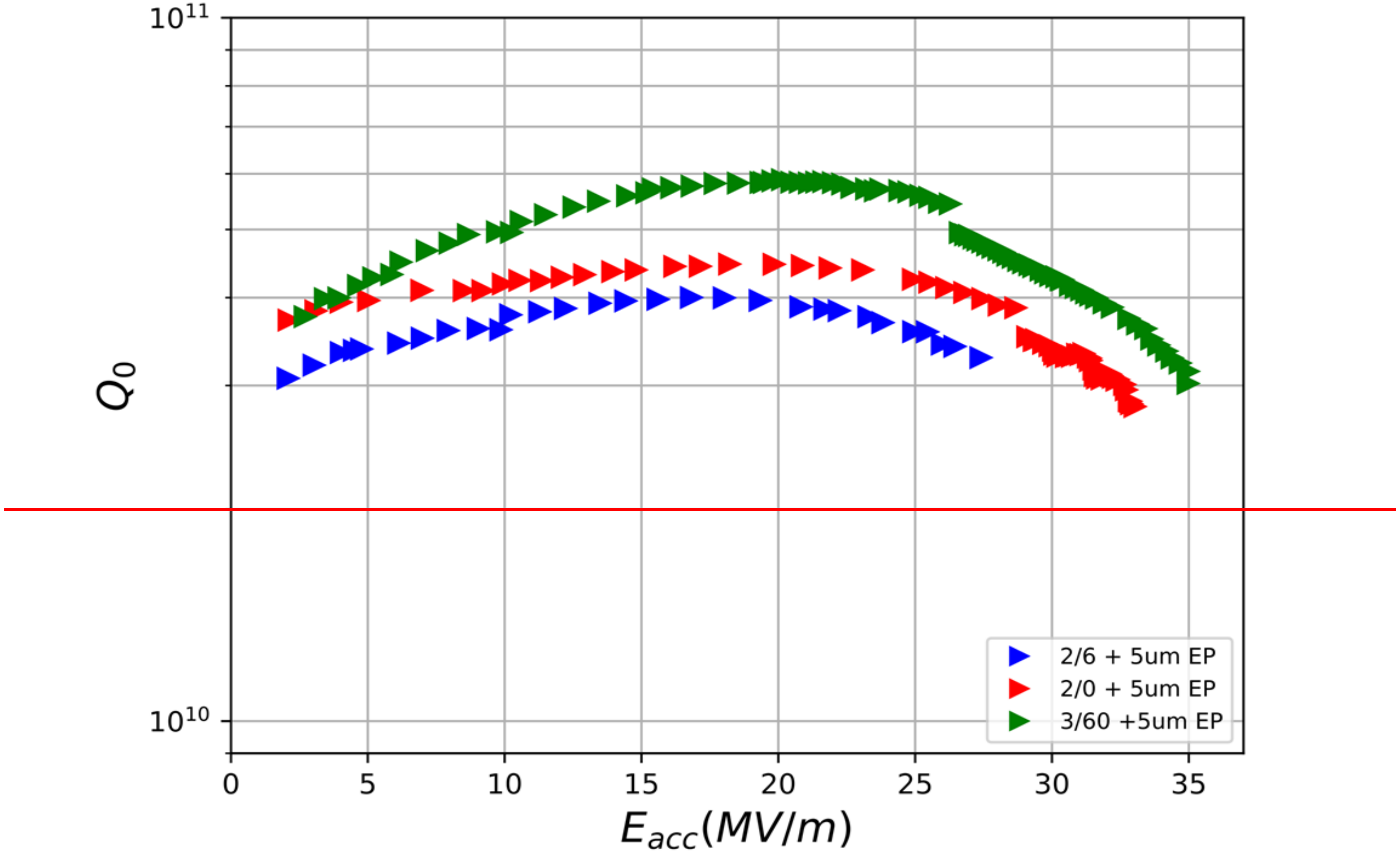
Paths for Luminosity Upgrades for ILC- Higgs

- A key area of further SRF development is higher *Q* values with the invention of new techniques of *Nitrogen Doping*
- Higher gradient at higher *Q,* with *Nitrogen infusion*
- Higher gradient at higher *Q* with *Cold Electropolishing /Two-Step baking*
- LCLS-II and LCLS-II_HE are benefitting from high Q cavities.
- A new and exciting development (harder to implement, but revealing potential)
  - $Q = 5 \times 10^{10}$ at 32 MV/m by baking at 300 C to dissolve the natural oxide (and other surface layer) into the bulk, but not exposing the cavity to air or water before RF measurements.

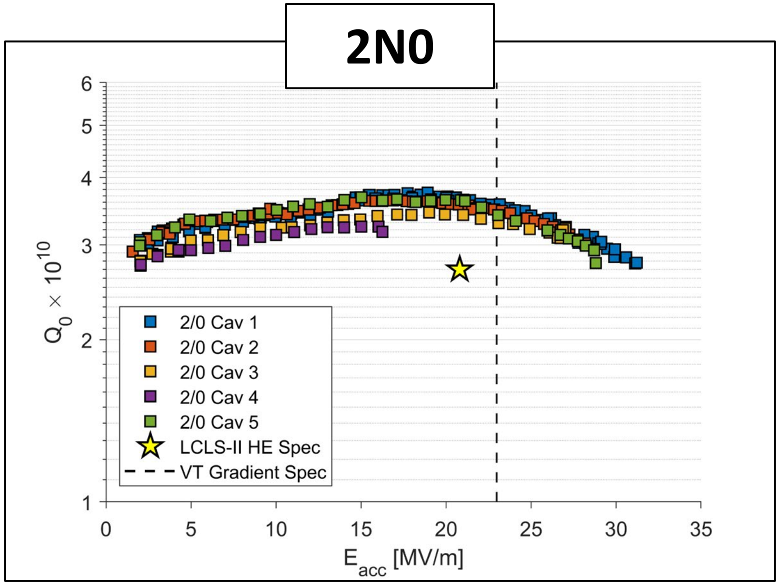
Luminosity Benefits from Higher Q

- *Q* values (2×10^{10} at 31.5 MV/m) can lead to higher Luminosity Upgrades for ILC via higher beam power (no change in bunch charge or final spot size)
- Higher *Q* opens the option of increasing the RF pulse length (and so the beam-on duty cycle)
- Allowing the population of the RF pulse with more bunches (e.g. 2,624 instead of 1312) at the same bunch spacing in the linac as for the 250 GeV baseline
- which helps to preserve emittance in the linac.
- Higher Q allows increase of the repetition rate of the pulses from 5 Hz to give corresponding luminosity increase of a factor of 4 - 6.
- The paper discusses the corresponding challenges for RF power, cryopower, damping rings, damping time reduction, positron source, and beam dumps for higher beam power (skip here)

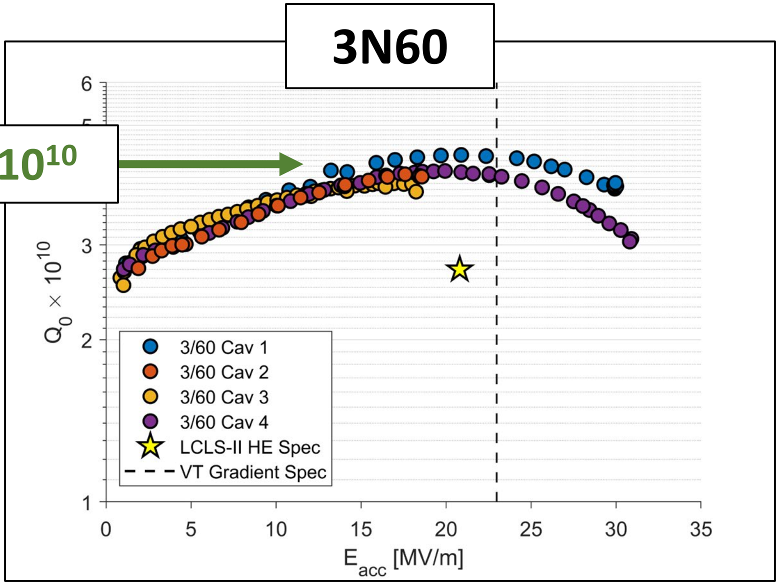
Path 1: N-Doping Recipes for LCLS-II-HE
2/0 and 3/60 Doping
1-cell Results: G near 35 MV/m, Q > 2×10^{10}



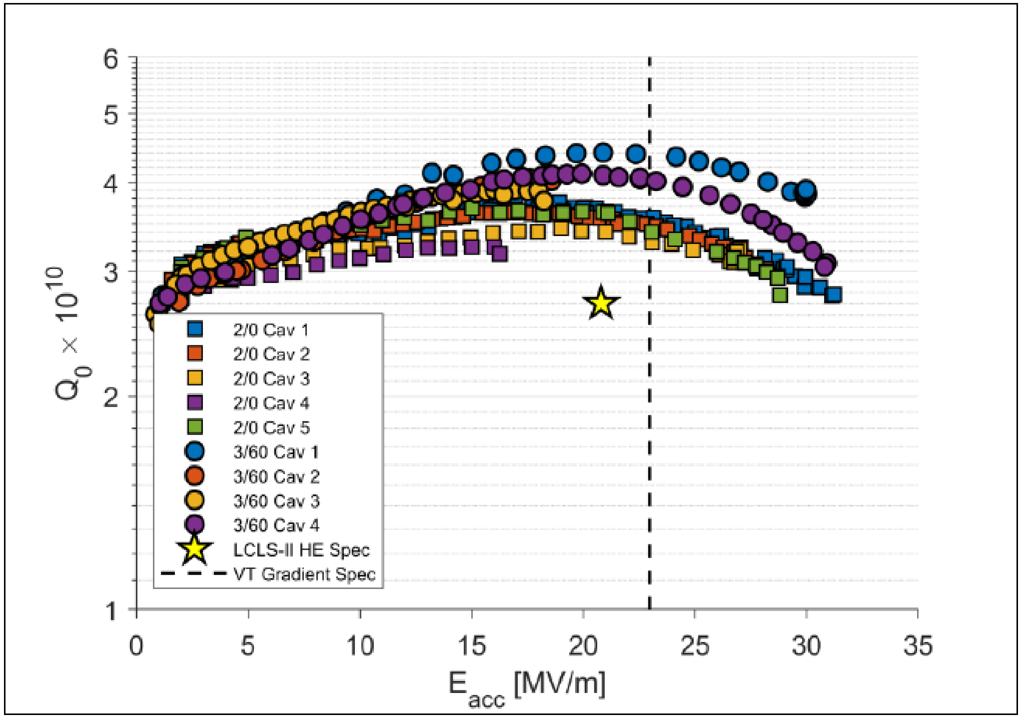
9-Cells N-Doping for LCLS-II - HE


2N0

$Q_0 > 4x10^{10}$


3N60

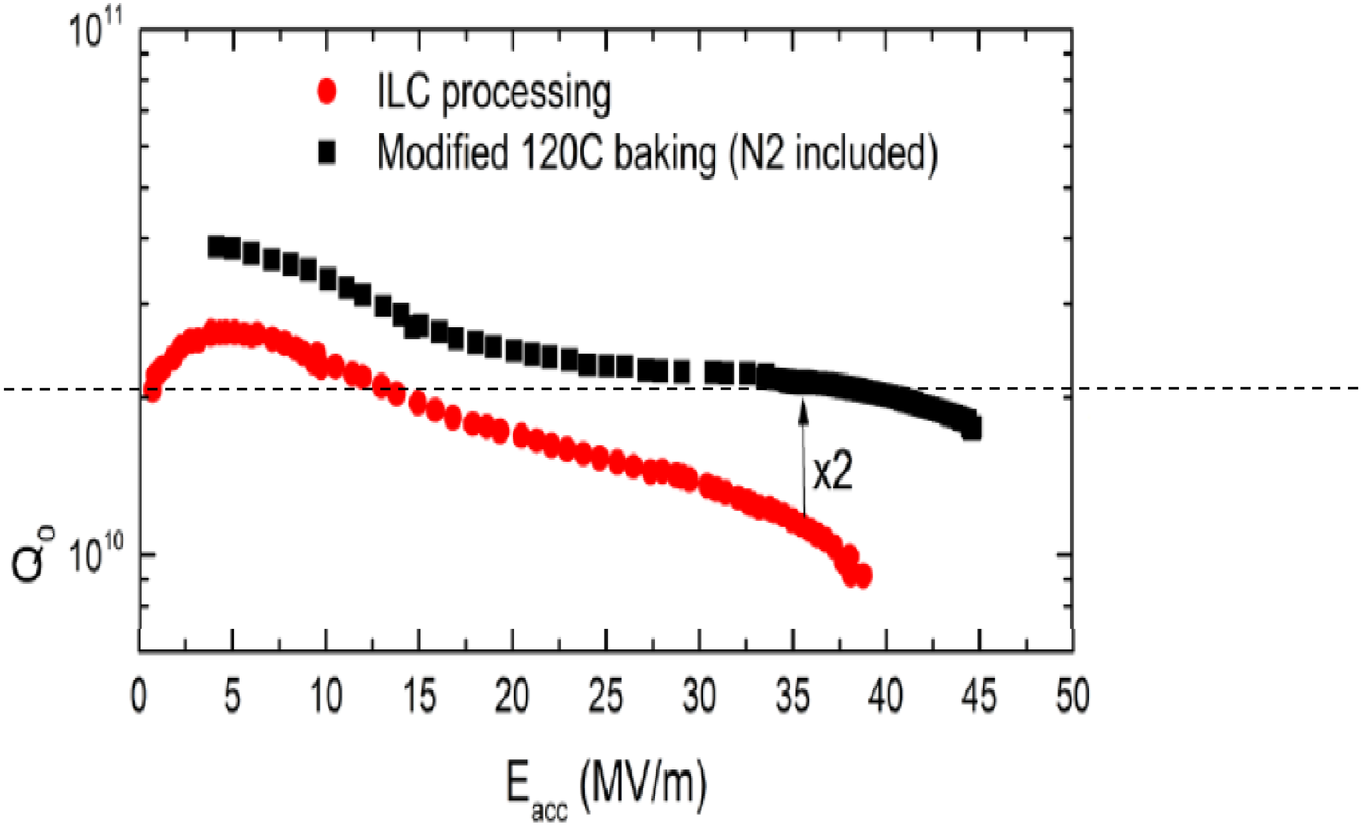
New Recipes + Cold EP @ Labs



- 5 9-cell cavities prepared with 2/0 @ FNAL (cavities from Fermilab stock)
- 4 9-cell cavity prepared with 3/60 @ JLab (cavity from 16 EZ cavity lot)
- All cavities received the new “cold EP”
- 4 out of 5 of the 2/0 cavities exceeded the HE specification by a wide margin
- 2 of 4 3/60 cavities showed excellent performance with quench fields above 30 MV/m and Q_0>4x10^{10} at 21 MV/m!

D. Gonnella, LCLS-II-HE DOE CD-3A and Status Review, 2019

Path 2: Nitrogen Infusion (Derived from N-doping)

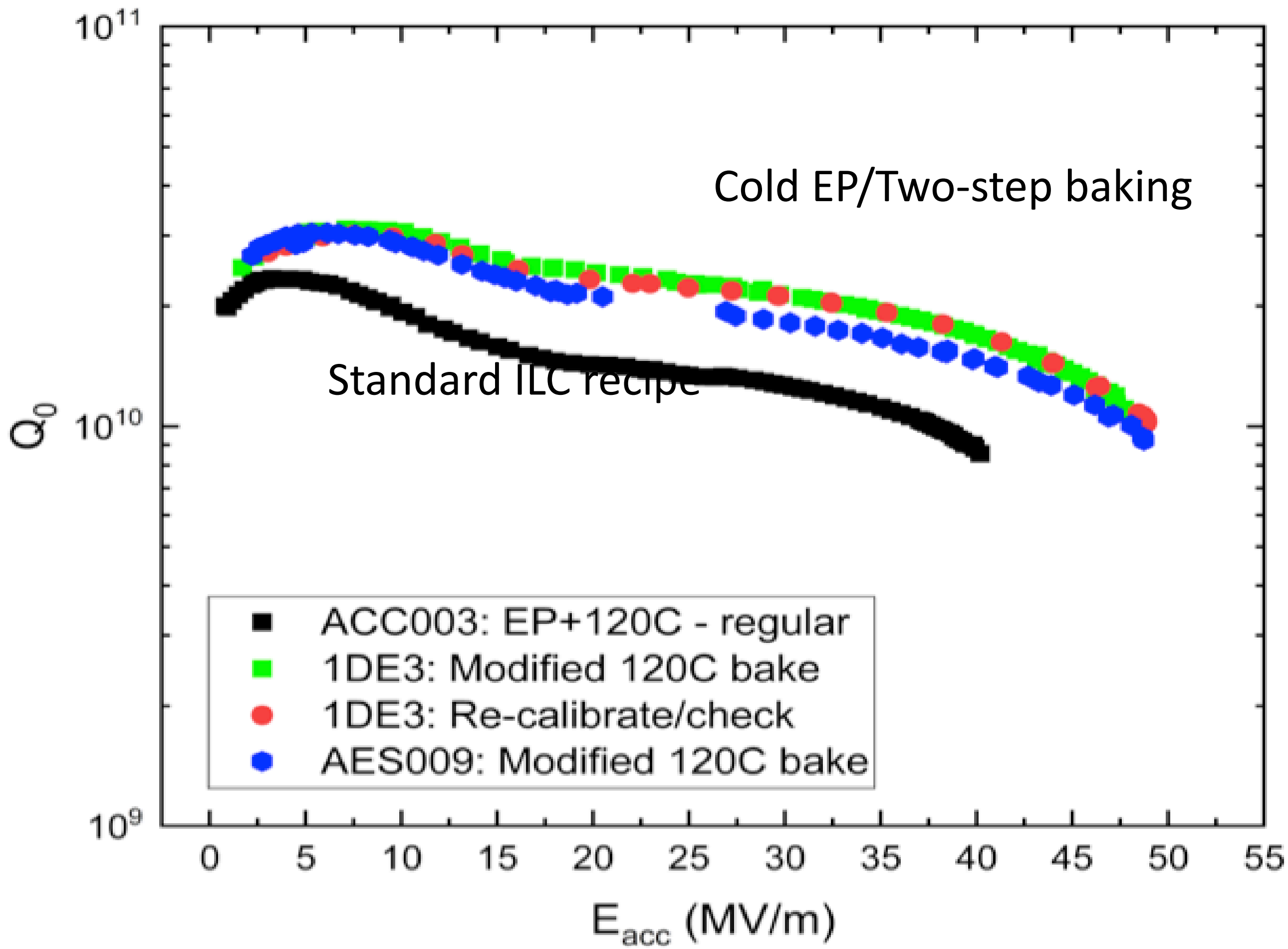


- Q above 2×10^{10} is reached at 31.5 MV/m.
- Challenge is that the infusion method is sensitive to furnace cleanliness - and may be difficult to implement on a wide scale.

For the Top Factory energy upgrade

Additional linac to raise the energy is based on a gradient of 40 MV/m at $Q = 2 \times 10^{10}$

Path 1: Cold EP/Two-step Baking of 1-cell Cavities=> Near 50 MV/m

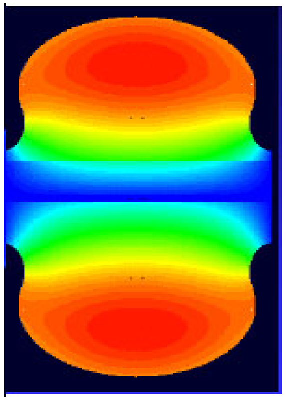


Path 2: Advanced Cavity Shapes (50 – 60 MV/m)

Re-entrant shape

60 mm aperture

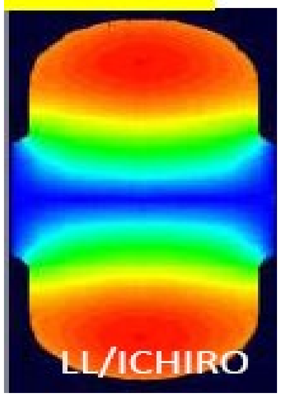
H_{pk}/E_{acc} 35.4 Oe/(MV/m) and $E_{pk}/E_{acc} = 2.28$



Low-Loss/Ichiro Shape

60 mm aperture

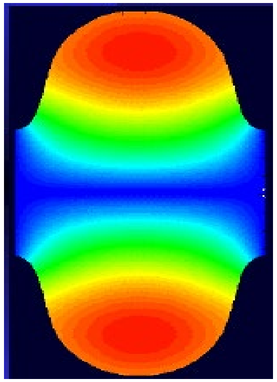
H_{pk}/E_{acc} *to 36.1* Oe/(MV/m),
Epk/Eacc = 2.36



Standard TESLA shape

60 mm aperture

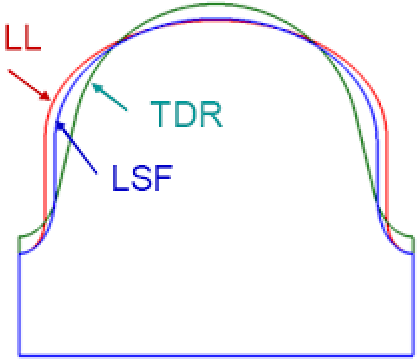
H_{pk}/E_{acc} *to 42* Oe/(MV/m), *Epk/Eacc = 2.0*



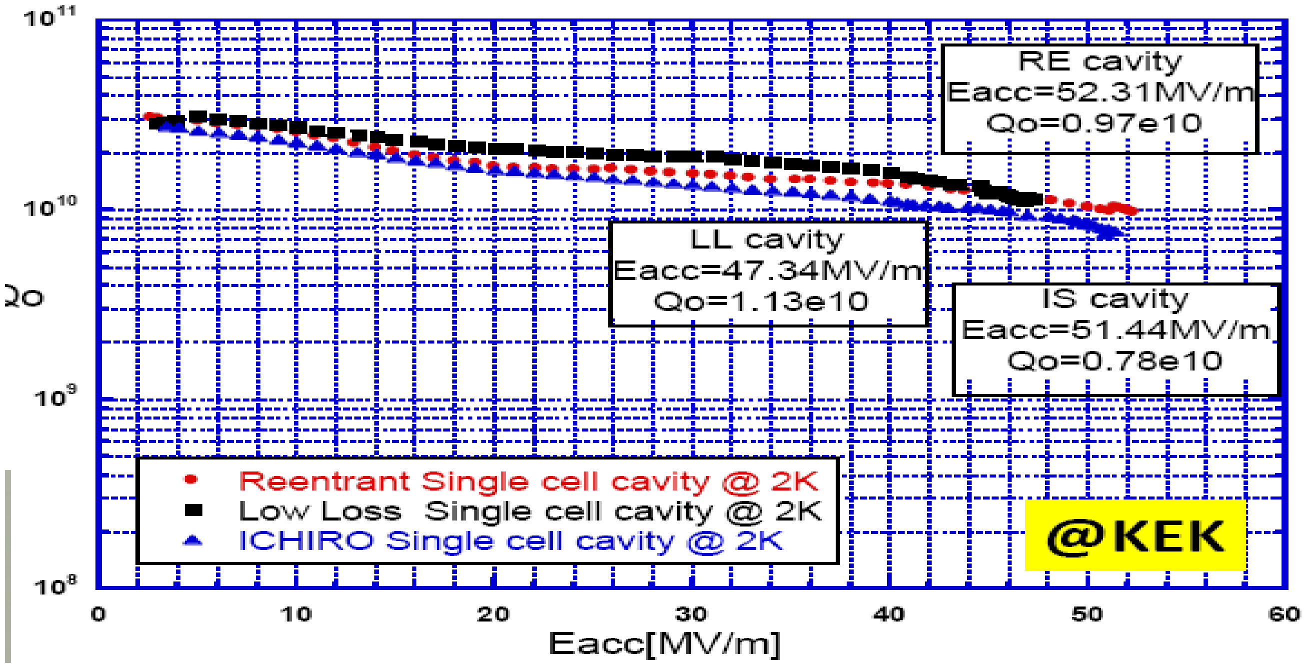
Newer:

LSF Shape

SLAC/Jlab/KEK



$H_{pk}/E_{acc} = 37.1$ Oe/(MV/m)
$E_{pk}/E_{acc} = 1.98$



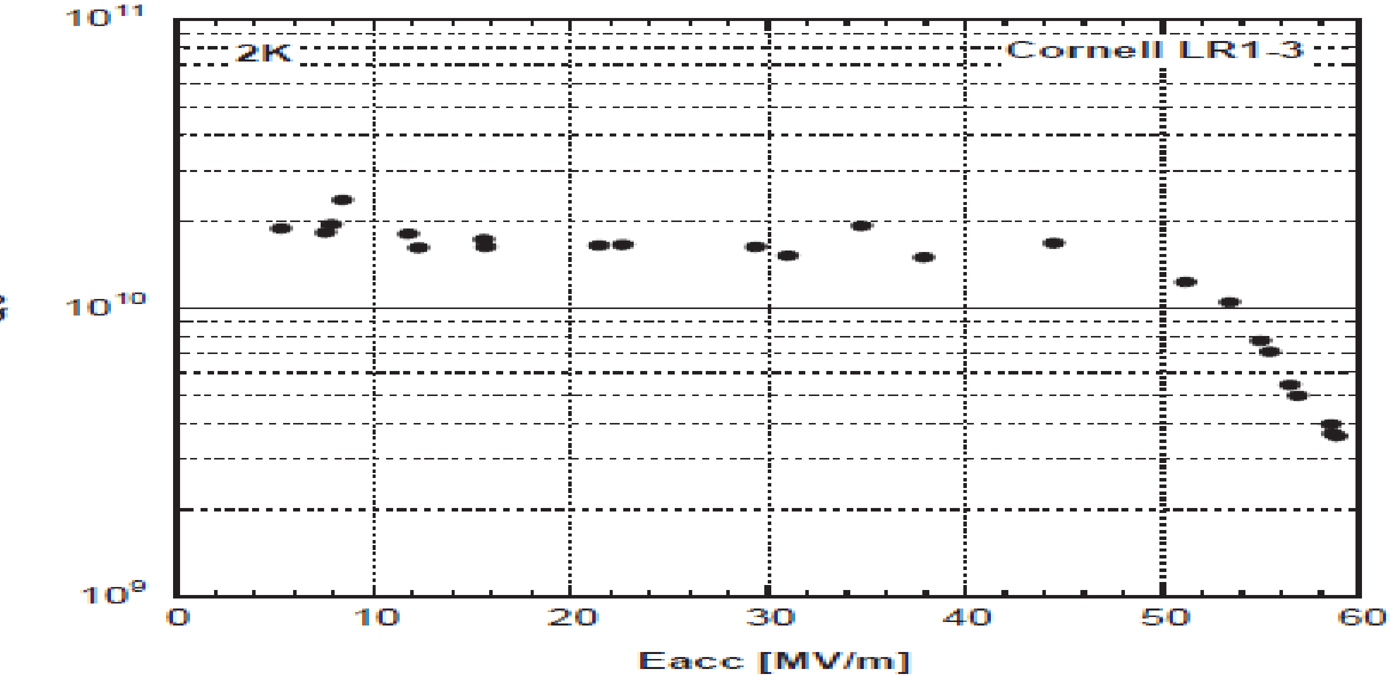
KEK Results

Low Loss

Ichiro

Re-entrant – 70 mm

52 MV/m



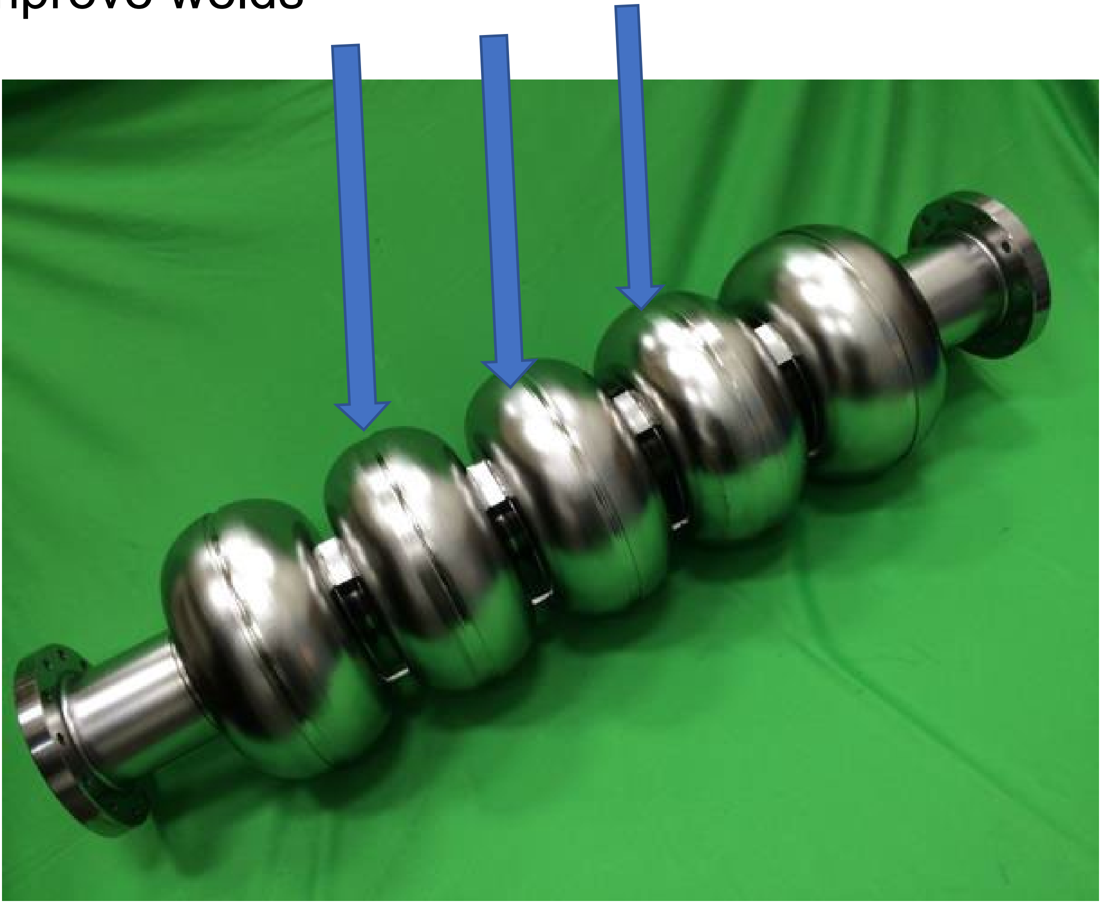
Cornell Results

Re-entrant 60 mm

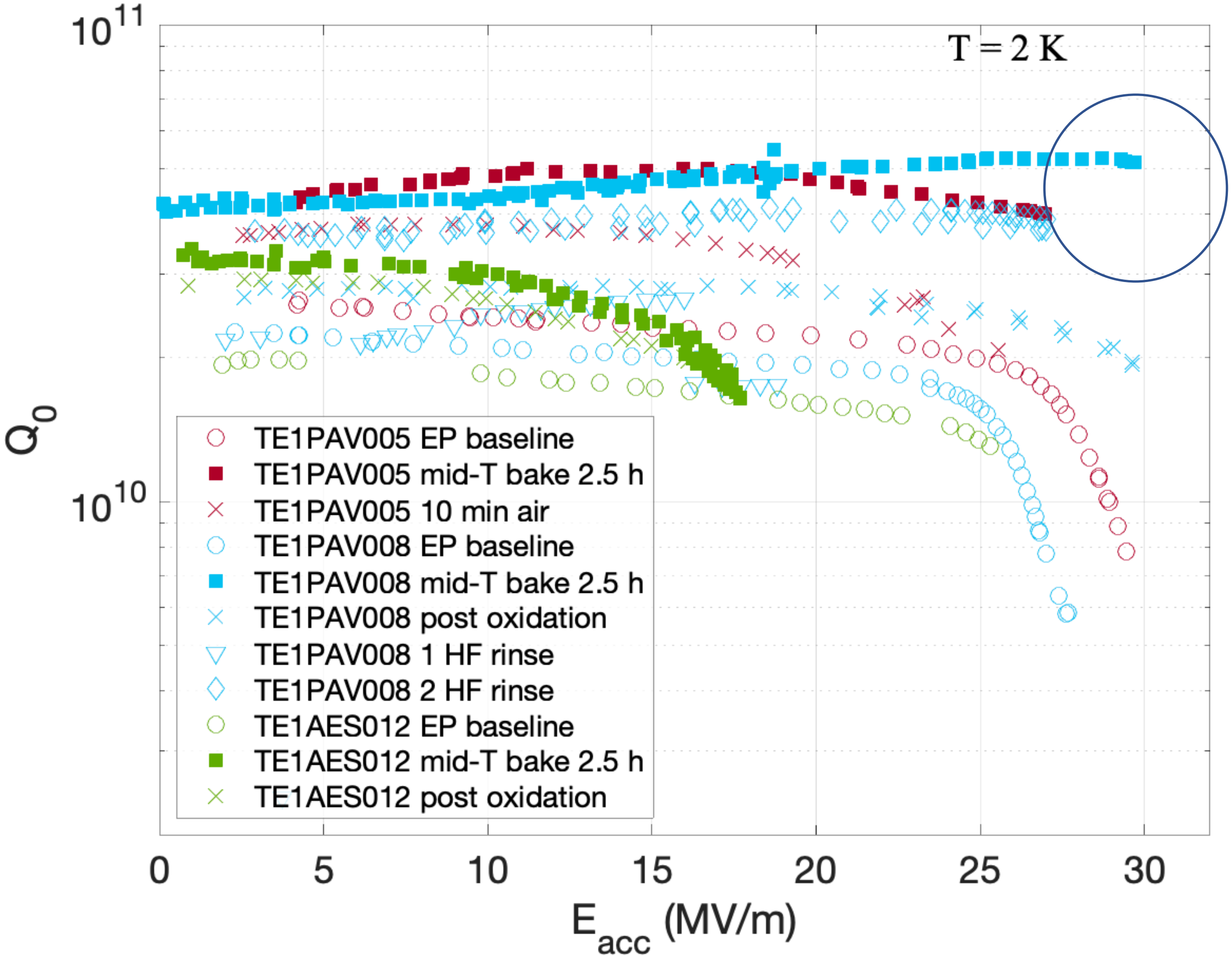
59 MV/m

LSF Shape

- 50 MV/m in 3 mid-cells in the 5-cell cavity LSF5 _ JLAB/KEK
- Need to improve welds



Teaser: Mid-T (300 C) Baking
=> Oxide Free Cavity
Q = 5×10^{10} at 30 MV/m



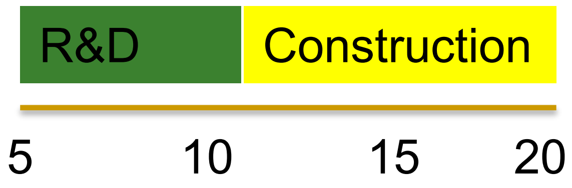
Final Remarks

- R&D on high Q can lead to higher luminosities
- R&D on high Gradients will lower cost of Top Factory, and subsequent energy upgrades
- In later talk, I will present other paths to higher gradients for ILC energy upgrades.

Technical Maturity

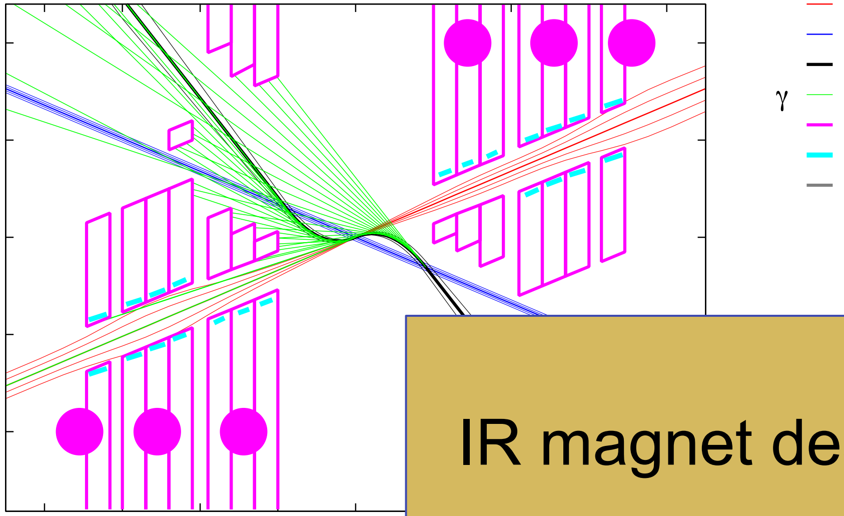
1- Significant R&D required
2– Some R&D in a few key areas required
3 – Shovel ready

- Overall Technical Maturity: SRF = 2; IR quads = 2
- Critical Technologies and TRL level
  - SRF linacs with high Q_0 for CW operation
  - Superconducting asymmetric IR quadrupole magnets
  - High current source
- Technically limited timeline

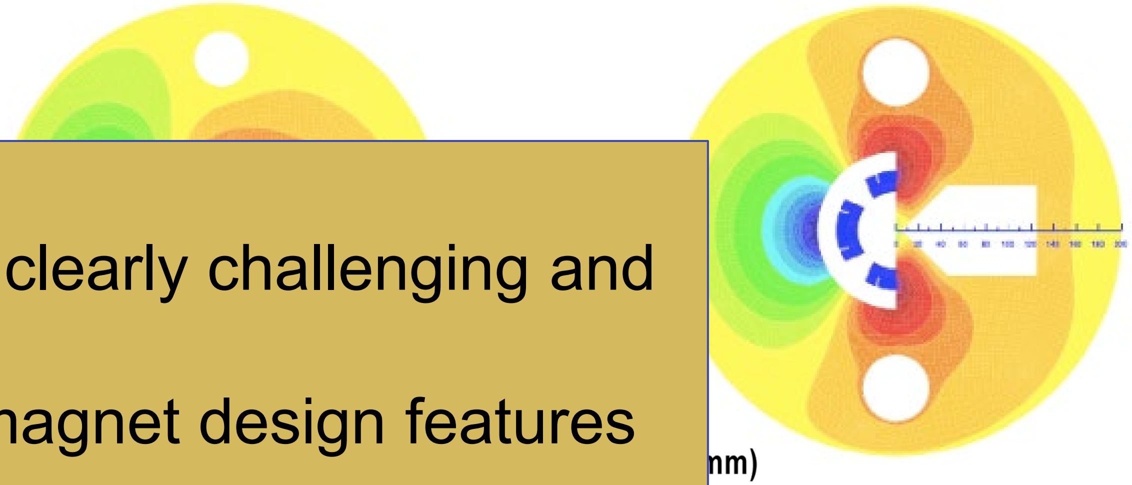


(Modify as appropriate)

Asymmetric IR Design: Challenge Triplet Magnets & SR



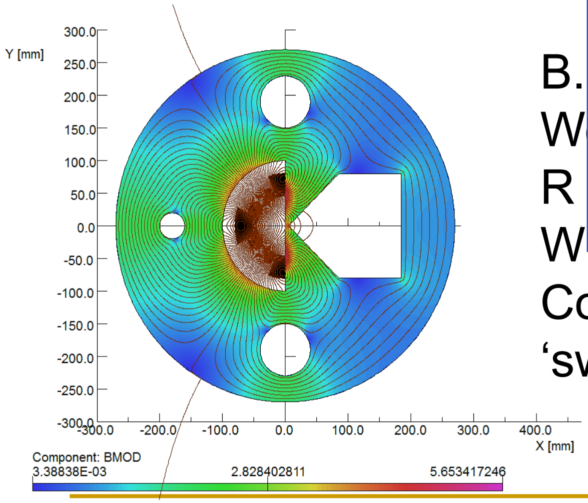
S. Russenschuck in CDR 2012
CDR parameter: R = 23mm; 250T/m SA [6-7T] &
R = 46mm; 145 T/m HQ [6-7T]



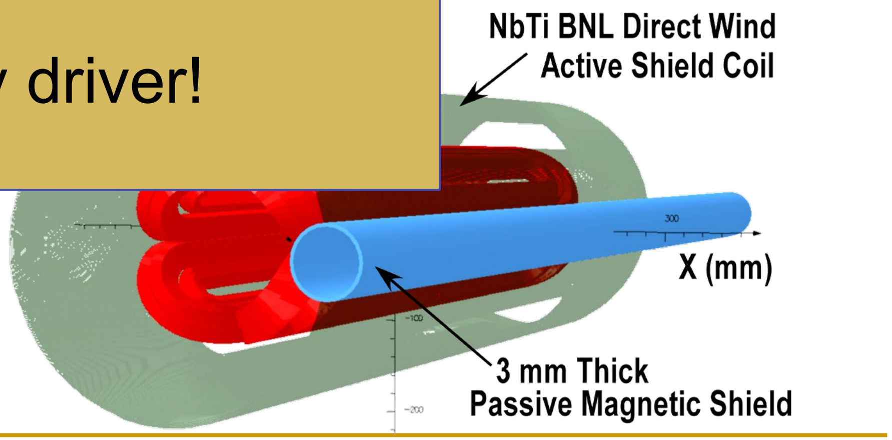
IR magnet design is clearly challenging and

requires novel SC magnet design features

➔ Excellent technology driver!



B.
W
R
With an active coil for field
Compensation ➔
'sweetspot'



SRF Frequency Choice: Why not ILC or ESS technology?

- Review of the SC RF frequency:

-HL-LHC bunch spacing requires bunch spacing with multiples of 25ns (40.079 MHz)

Frequency choice: *h* * 40.079 MHz

h=18: 721 MHz or h=33: 1.323GHz

SPL & ESS: 704.42 MHz; ILC & XFEL: 1.3 GHz

Existing technologies do not quite match that requirement (20MHz)!

➔ Look at a design optimization for LHeC specific needs!!!

Technology Status

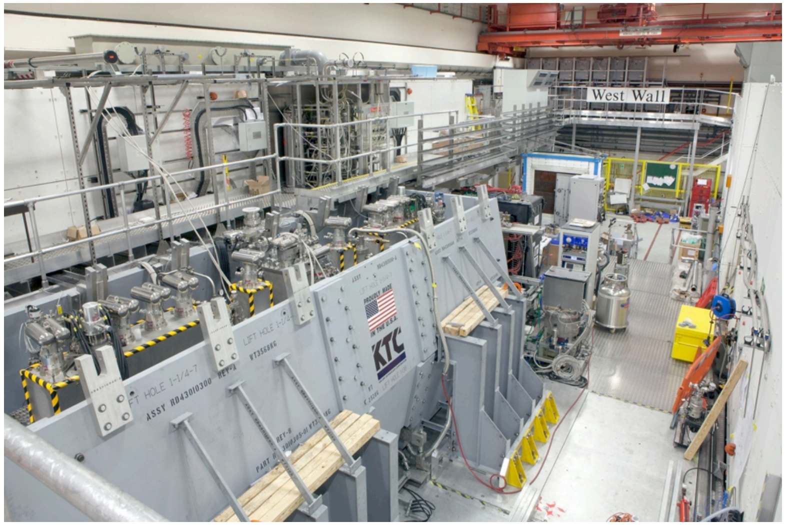
Many components have been developed and tested

More is needed

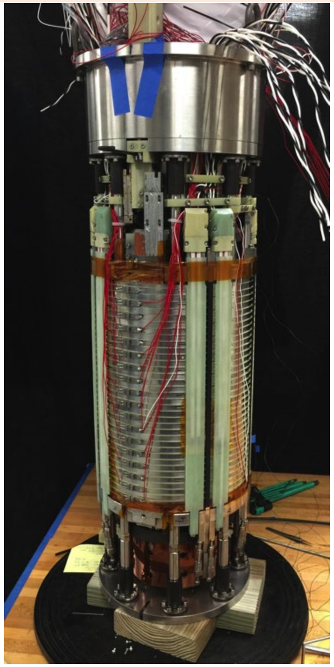
- production targets, fast-ramping magnets and energy recovery power converters, robust high field collider magnets, efficient shielding, efficient cooling, normal and superconducting RF, …

- Facility to integrate
    - addresses the more “subtle” issues (e.g. full width of technologies, but also safety, …)

MICE
(UK)

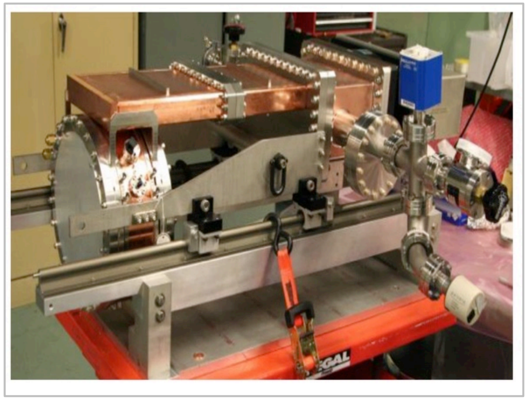


FNAL
Breakthrough in HTS cables



NHFML
32 T solenoid with low-temperature HTS

MuCool: >50 MV/m in 5 T field

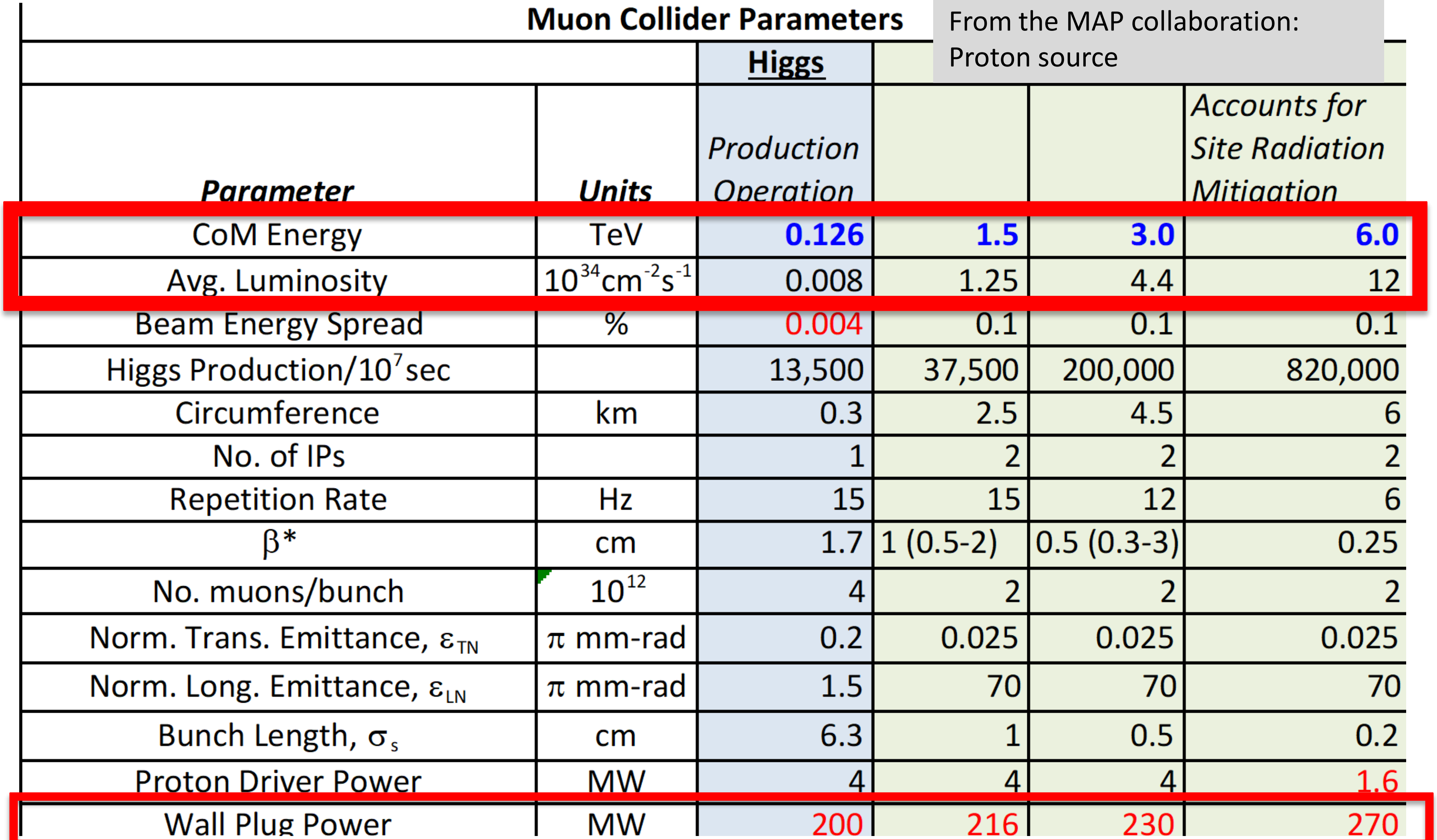


FNAL
12 T/s HTS
0.6 T max

Mark Palmer

Target Parameter Examples

From the MAP collaboration:
Proton source

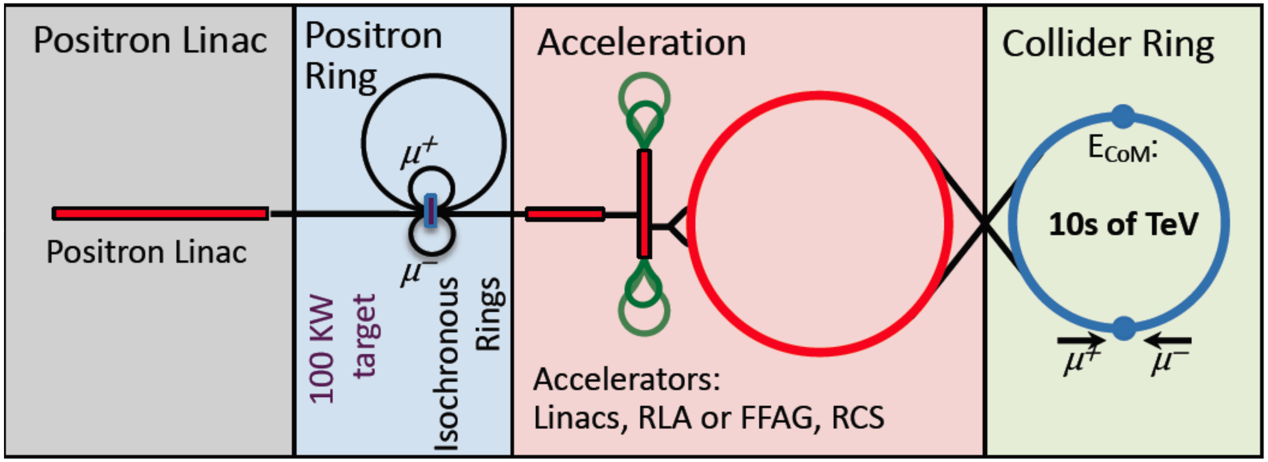


Muon Collider Parameters

		Higgs			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

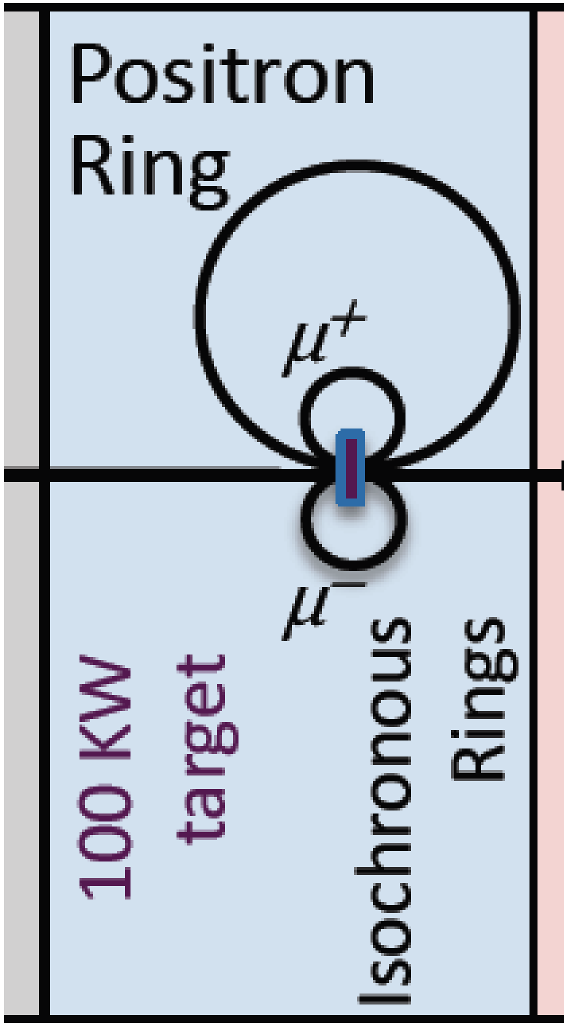
Even at 6 TeV above target luminosity with reasonable power consumption
But have to confirm power consumption estimates

The LEMMA Scheme



From the LEMMA team: Positron-driven source (M. Antonelli et al.)

45 GeV positrons to produce muon pairs
Accumulate muons from several passages



Low emittance muon beam
no cooling required, much less radiation

But large positron current and production needed O(10^{17}/s)
Target is challenging

Currently, do not reach luminosity goal
More work is needed to conclude

Proposed Scope

- “In the first period, in time for the next European Strategy for Particle Physics Update, the study aims to establish whether the investment into a full CDR and a demonstrator is justified. It will provide a baseline concept, well-supported performance expectations and assess the associated key risk as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.”

- Benchmark region around O(3 TeV), L = O(10^{34} $cm^{-2}s^{-1}$)
  - Well above higgs factory energy
  - Should focus on technologies ready in 10-20 years
  - MAP did work on this range

- Benchmark region 10+ TeV, L = O(10^{35} $cm^{-2}s^{-1}$)
  - New territory, beyond what CLIC can do
  - Need to fully understand physics needs
  - Need to address a number of additional challenges

- Exploration of synergies
  - Neutrino factory
    - potential useful application, would be large-scale demonstrator
  - Higgs factory
    - more mature options exist currently, but we can come back if no one is moving forward

Tentative Target Parameters?

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Note:
Based on extrapolation CLIC @ 14 TeV would need 130 MW beam power for L = 28 x 10^{34} cm^{-2}s^{-1} of which 1/3 is within 1% around nominal energy

Additional benefits for muon collider less initial state radiation and smaller beam energy spread

2 IPs in each case
Single bunch
Luminosity decays exponentially

Note: The study will have to verify that these parameters can be met

Initial Key Issues

- Neutrino radiation
  - known to need mitigation for 10+ TeV
  - explore mitigation methods

- MDI and background conditions

- Cost and power drivers
  - fast ramping magnet systems
  - collider ring magnets
  - RF systems

- Beam quality
  - Muon source, two options, define baseline and alternative, improve performance
    - Improvement of cooling channel for proton-driven scheme appears possible because hardware performance is better than initially assumed
  - Preservation of beam quality

- Define demonstration programme for implementation in second half of the decade
  - test facility and components