Accelerators for EW/Higgs: Common Technology Needs

Sergey Belomestnykh
Meeting to discuss and prepare the Snowmass AF03 Report
16 December 2020

Outline of Section 2 “Common Technology Needs”

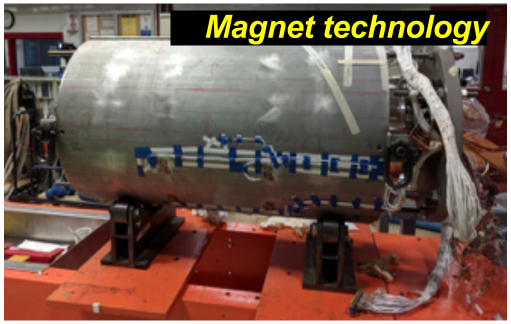
Rough structure

1. Introduction: identify common technologies for EW/Higgs machines
2. For each area provide a summary of R&D topics, their significance, challenges they address, recent results, etc.
3. Briefly describe needs of different machines

Questions for this meeting:

- What is a common technology need? E.g., identified as a key R&D by to or more projects (see matrix on the next slide)?
- Are any technologies missing? Do projects want to add key technologies for their machines?
- How are we going to organize writing?

As there is an overlap with Topical Groups AF07 (Accelerator Technology -RF, -Magnets, -Targets/Sources), we will have to coordinate closely with co-conveners of these groups



Matrix of Common Technology Needs

	SRF	NRF	RF sources	SC magnets	Conv. magnets	Special. vacuum	e sources	One-offs
C^3		X	X					
CEPC	X		X		X	X	X	
CLIC		X	X				X	
ERL FCC-ee								
FCC-ee	X		X		(?)			
LHeC/FCC-eh								
HE-LHC				X		X		
ILC	X		X				X	(nanobeams)
LHeC								
Muon collider								
$\gamma-\gamma$ **collider**				X				(FEL)

Superconducting RF

Summary for SRF

SRF R&D is:

- a key technology for CEPC
- needed to further improve existing technology for FCC-ee
- for luminosity/energy upgrades of ILC

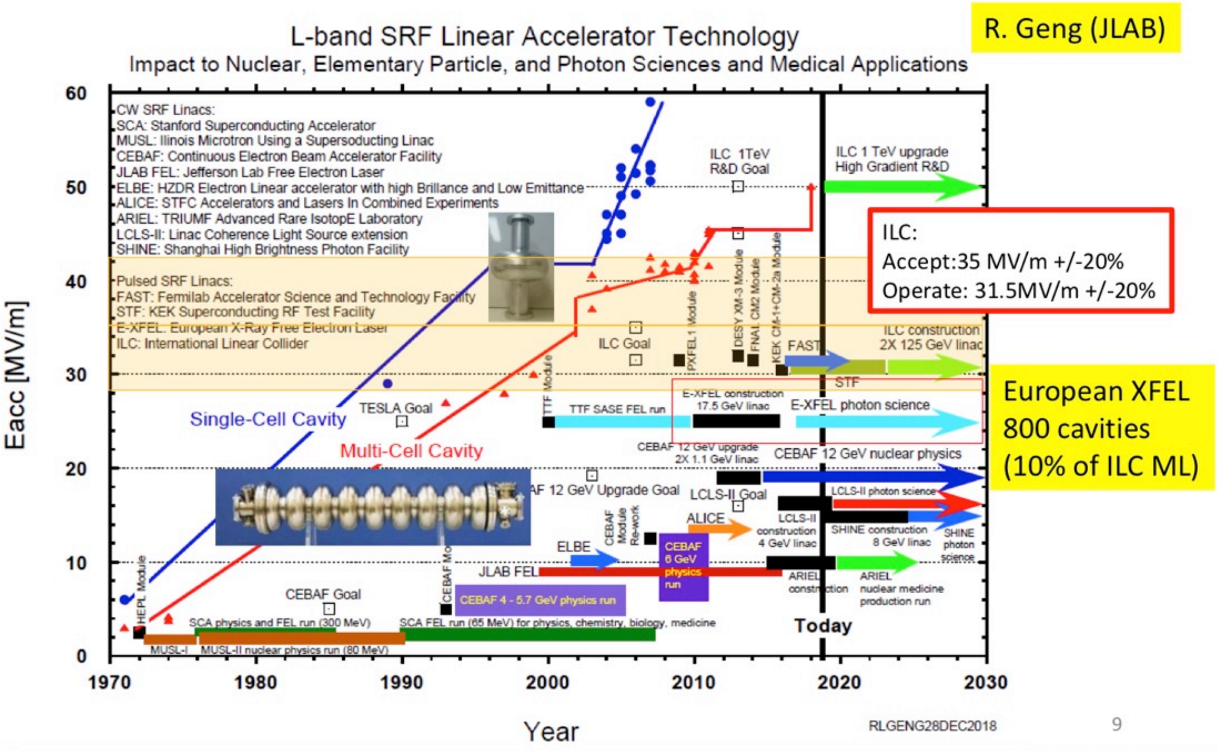
R&D areas

- Higher Q and higher gradients in CW and pulsed regimes (bulk Nb)
- Improve cavity fabrication: large-grain Nb, seamless cavities, …
- Improve Nb/Cu coating techniques
- In short- to mid-term explore new cavity shapes: QWR for FCC-ee, LSF and TW for ILC, …
- Long-term: new materials, e.g., A15 (Nb_3Sn, Vn_3Si)

AF7-RF plans to organize a mini-workshop on Cavity Performance Frontier in February 2021

SRF for ILC

- **Mature technology for the 250 GeV** baseline machine
- The machine is upgradable, **SRF R&D** is needed **for luminosity and energy upgrades**


L-band SRF Linear Accelerator Technology

Impact to Nuclear, Elementary Particle, and Photon Sciences and Medical Applications

R. Geng (JLAB)

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

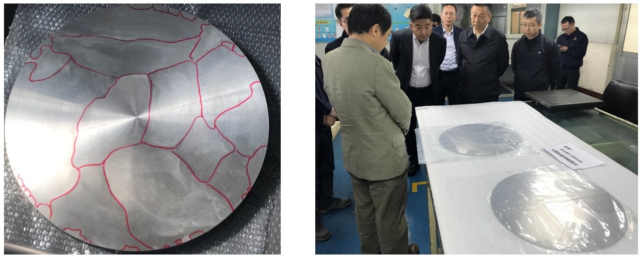
European XFEL
800 cavities
(10% of ILC ML)

SRF R&D for further Luminosity (& Energy) upgrades to ILC

- **Key areas** of further SRF development over last 5 years are **higher Q and higher gradients**
- Higher Q values with
  - Nitrogen doping
  - LCLS-II and LCLS-II-HE are benefitting from high Q nitrogen doped cavities.
- **Higher gradient (35 – 49 MV/m) at higher Q** with
  - Nitrogen infusion
  - Cold Electropolishing /Two-Step baking
- **Higher Q** values (e.g., 2×10^{10} @ 31.5 MV/m) can lead to **luminosity upgrades (x4 or x6)** via higher beam power
  - Increasing the RF pulse length (more bunches)
  - Increase the repetition rate of the pulses
- *See LOI and paper for AF3 which discuss the* ***corresponding challenges for RF power, cryogenic power, damping rings, damping time reduction, positron source, and beam dumps***
- **Energy upgrade studies** are underway for ILC to reach 3 TeV
  - Via R&D exploration underway for Gradients to 70 – 80 MV/m
  - *See LOI and paper for AF7*

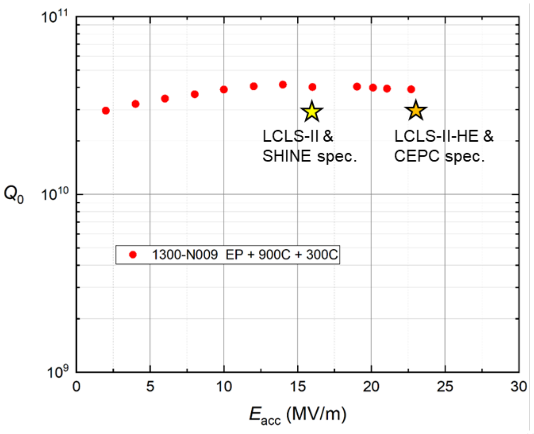
650 MHz SRF system R&D for CEPC

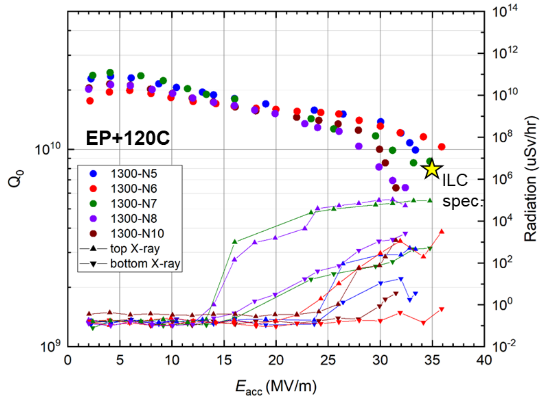
- **Challenges**:
  - Achieving 20 MV/m with $Q_0 > 1.5 \times 10^{10}$ in long term operation of 240 2-cell 650 MHz cavities
  - Developing robust and variable high power (> 300 kW CW) input couplers that are design compatible with cavity clean assembly and low heat load
  - Developing efficient and economical damping of the HOM power with minimal dynamic cryogenic heat load
- The cavities shall demonstrate $Q_0 > 4\times10^{10}$ at 22 MV/m during vertical acceptance test. *Achieved $Q_0 = 6\times10^{10}$ at 22 MV/m with BCP and nitrogen infusion in June 2020.*
- R&D to reach high Q with nitrogen doping or other technology
- **Alternative option** to increase luminosity at Z-pole is developing a single cell 650 MHz cavity design. This would require operating cavities with $Q_0 = 3\times10^{10}$ at 40 MV/m in Higgs mode (5×10^{10} at 42 MV/m in vertical testing) – **very ambitious goal**.
- R&D on large-grain Nb cavities
- Possibly thin-film caoting

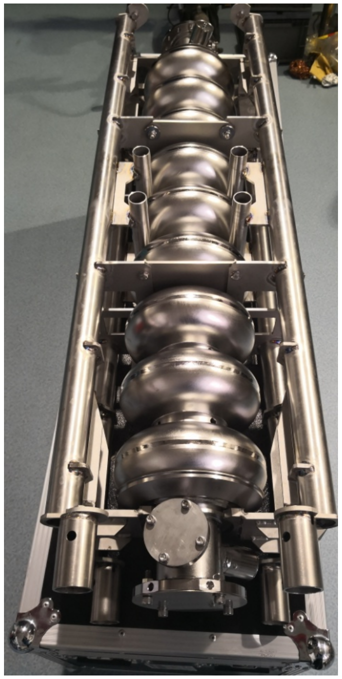


Large grain Nb sheets made by OTIC

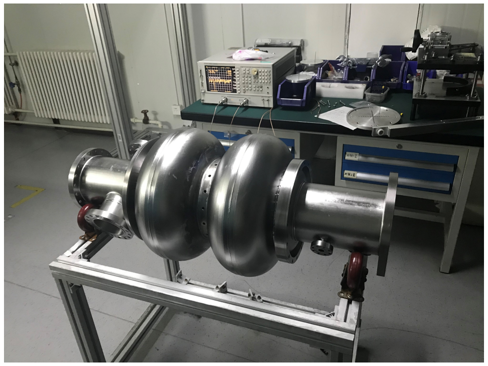
CEPC SRF R&D cavity testing results



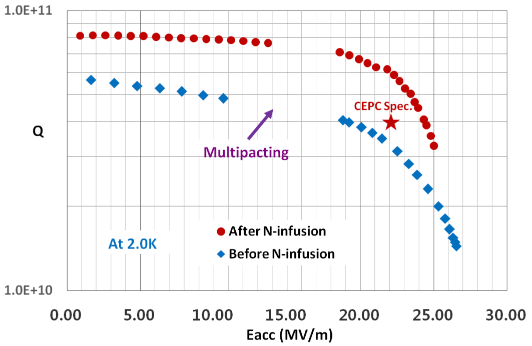




Booster 1.3 GHz 9 cell cavity



Collider ring 650 MHz 2-cell cavity



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

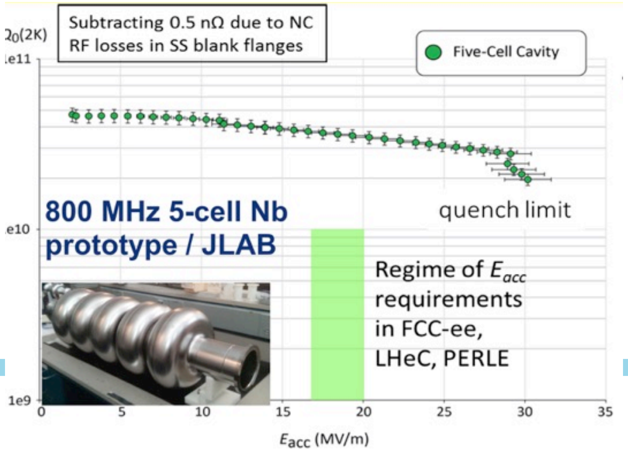
SRF for FCC-ee

Per 2019 FCC-ee CDR, the SRF system is based on the **technology practically available today**:

- 400 MHz Nb/Cu 1 to 4 cell cavities operating at 10 MV/m
- 800 MHz 4-cell cavities with accelerating gradient of 20 MV/m
- New fundamental RF power couplers operating up to 1 MW CW and adjustable Q_{ext}. A back-up option: 2 couplers at 0.5 MW.

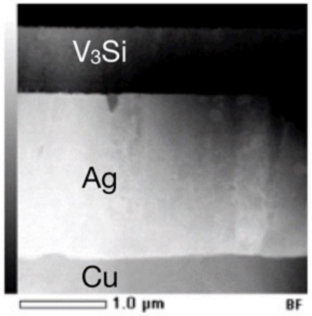
However, there is **room for improvement** in several areas. **5-10 years outlook**:

- Parallel development of cavities, cryomodules, power and HOM coupler
- 400 MHz Nb/Cu cavities
- Seamless cavity fabrication
- Better coating techniques
- 800 MHz bulk Nb cavities
- Alternative cavity shapes



SRF R&D topics for FCC-ee

- Coating technologies
    - HIPIMS coating produces much dense layers in all orientations
- Cu substrate fabrication
    - Transfer seamless cavity fabrication technology from HIE-ISOLDE cavities to 400 MHz elliptical cavities
    - Test in preparation of a 1.3 GHz seamless cavity with HIPIMS coating
- Coating materials
    - Alternative materials: sputtering A15 compounds onto copper substrate. Promising results with intermediate Ta layer to avoid intermixing of Cu and Nb_3Sn. Vn_3Si – more stable, promising results with intermediate Ag layer.
    - Long-term effort
- Cavity shapes
    - Alternative shapes are under considerations: QWR or HWR may be small enough at 400 MHz for bulk Nb fabrication, have good HOM spectrum; wide-open quasi-waveguide crab cavities.



Normal conducting RF

Summary for NRF

Two LC proposals based on NRF: Cool Copper Collider (C^3) and CLIC:

- **C^3**: **new NRF structure** with internal manifolds distributing the RF to each cell, cooled to ~80 K.

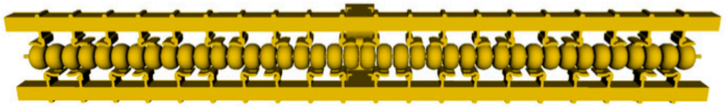
- **CLIC**: **mature technology** for X-band structures

- Synergy with other applications

AF7-RF plans to organize a mini-workshop on Cavity Performance Frontier in February 2021

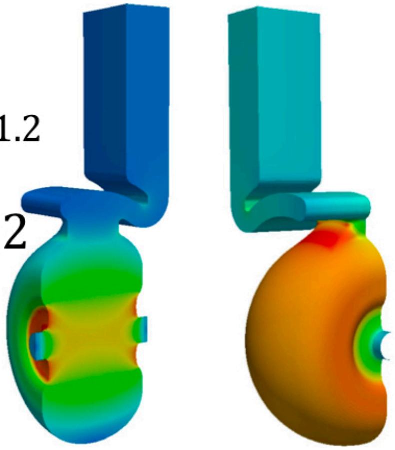
NRF for C^3: first meter-scale prototype at C-band

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



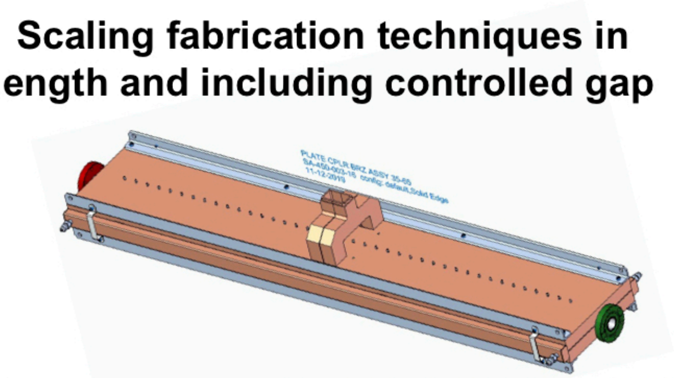
$$\frac{\mathrm{H_{peak}}}{\mathrm{H_{unperturbed}}} = 1.2$$

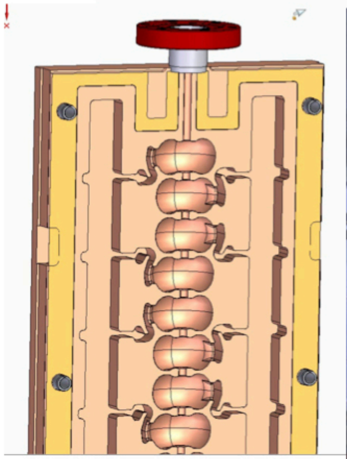
$$\frac{\mathrm{E_{peak}}}{\mathrm{E_{acc}}} = 2.22$$

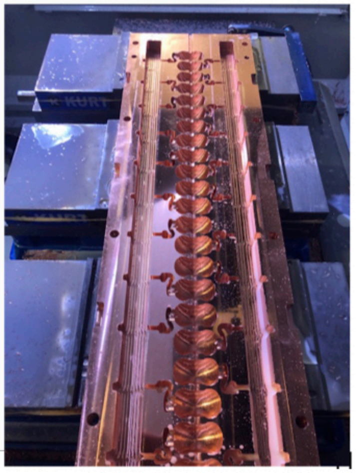


S. Tantawi, and Z. Li

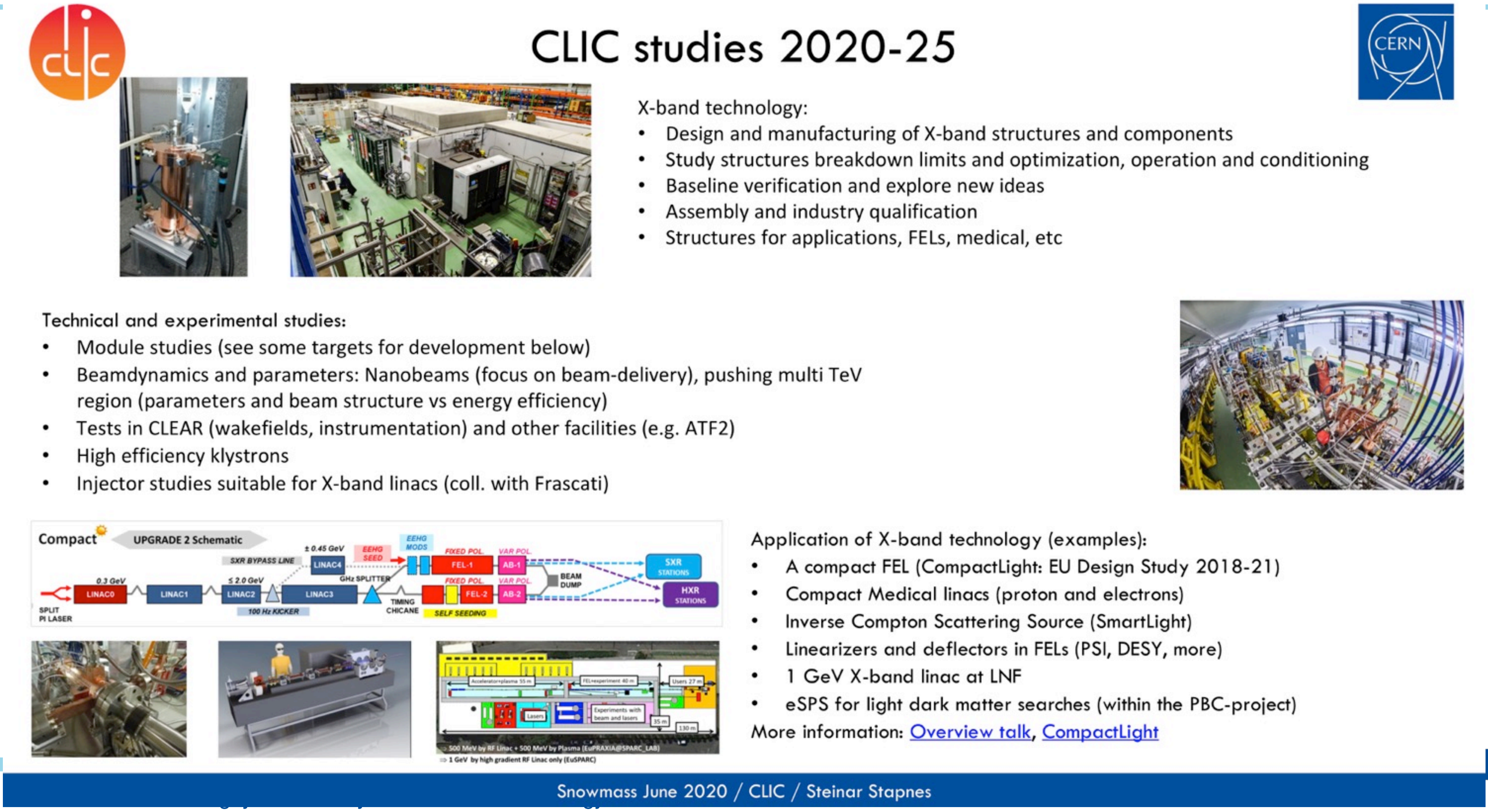
Scaling fabrication techniques in length and including controlled gap







NRF for CLIC



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)

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

Snowmass June 2020 / CLIC / Steinar Stapnes

RF sources

Summary for RF sources

- There is a need to develop **high-efficiency** (>80%) **MW-class klystrons** for CW (to compensate SR losses in circular machines) and pulsed (to deliver high accelerating gradients) applications. Using modern concepts is promising.
- **Magnetrons** can be procured for less than $1/W, but there are significant challenges, e.g., short lifetime, need of advanced control and feedback techniques, waveguide or cavity combiners.
- **SSA**'s are still less efficient than klystrons and magnetrons, however new developments are promising (GaN-based modules, Class F, …)

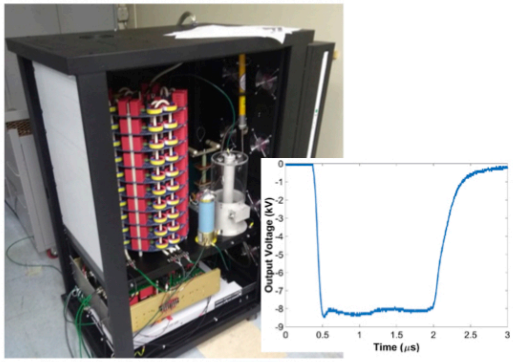
- Synergy with many other applications

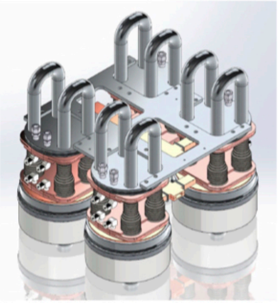
- *To those interested in this technology, I recommend attending AF7-RF mini-workshop on RF Systems and Sources tomorrow, 12/17/2020 at https://indico.fnal.gov/event/46775/overview (registration required)*

RF sources for C^3

- 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

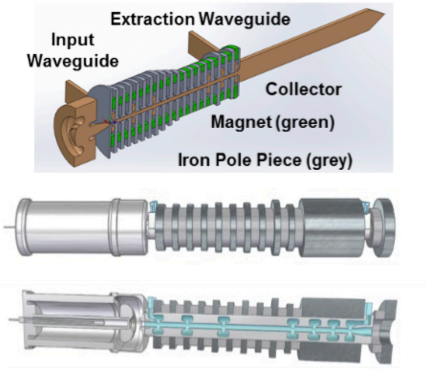
Low-cost “Digikey Catalog” Marx Modulator



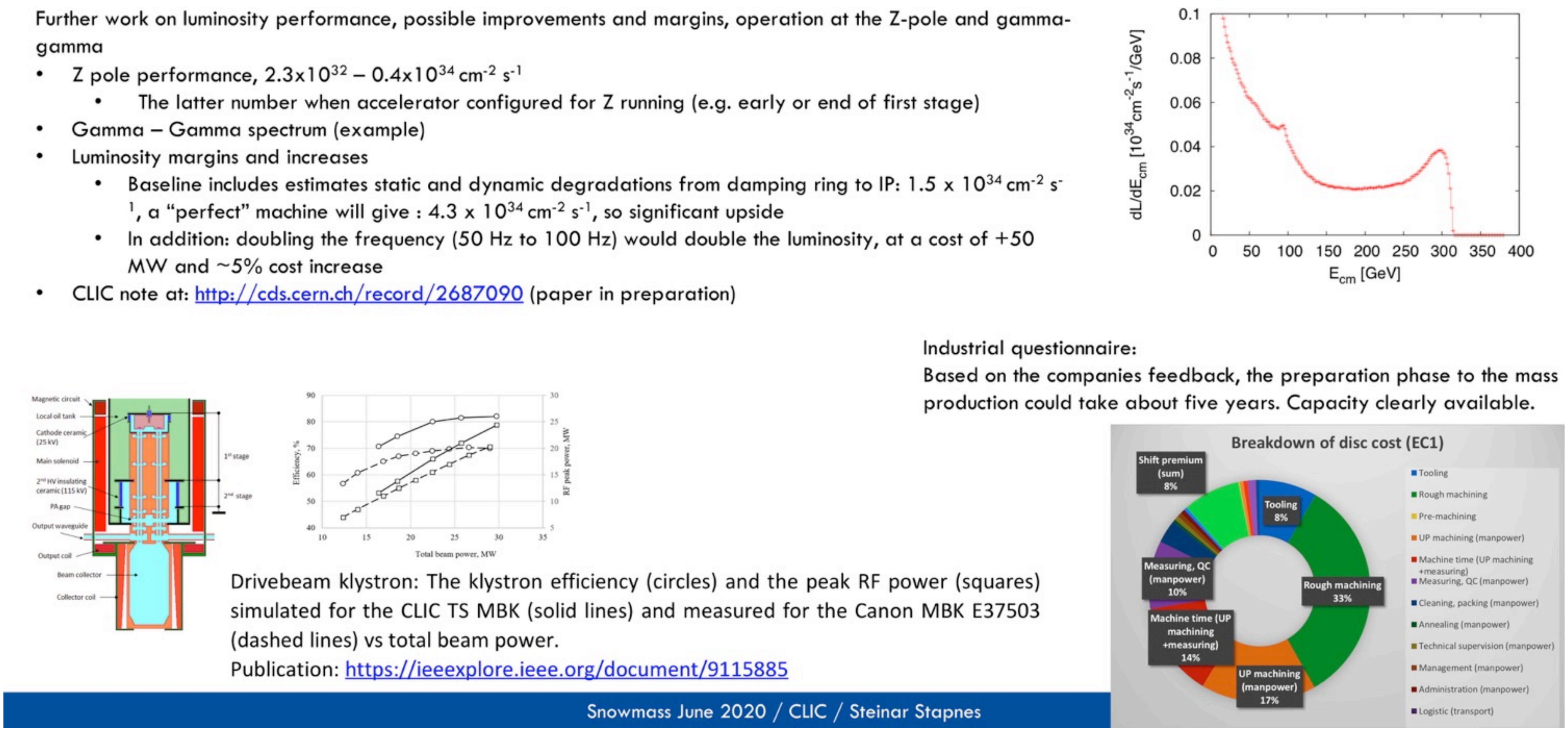


Modular Klystron Array operating at extremely low voltages

Integrated Pole Pieces/
Long Period Halback Arrays



RF sources for CLIC



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

- Z pole performance, $2.3 \times 10^{32} - 0.4 \times 10^{34}$ 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: 1.5×10^{34} cm^{-2} s^{-1}, a "perfect" machine will give : 4.3×10^{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

Breakdown of disc cost (EC1)

Snowmass June 2020 / CLIC / Steinar Stapnes

RF sources for CEPC: 650 MHz high-efficiency klystron

Facility: CEPC high power and high efficiency test facility (lab) at IHEP

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
- 2020 - 2021 : Fabricate 2nd high efficiency klystron & test
- 2021 - 2022 : Fabricate 3rd high efficiency klystron & test

Reached

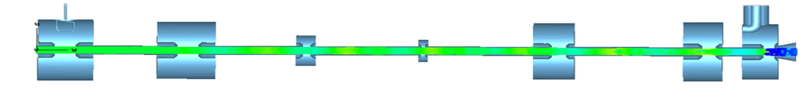
Parameters	Conventional efficiency	**High efficiency**
Centre frequency (MHz)	650+/-0.5	**650+/-0.5**
Output power (kW)	800	**800**
Beam voltage (kV)	80	**-**
Beam current (A)	16	**-**
Efficiency (%)	~ 65	**> 80**

Goal

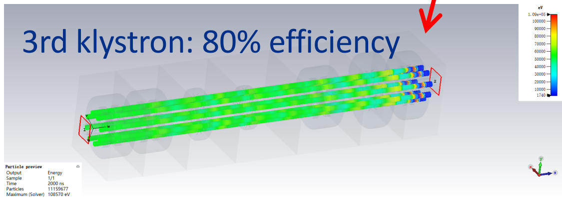
1st klystron: 62% efficiency

On March 10, 2020 the first CEPC 650 MHz klystron output power has reached pulsed power of 800 kW (400 kW CW due to test load limitation), efficiency 62% and bandwidth >+-0.5 MHz.

2nd klystron: 77% efficiency



3rd klystron: 80% efficiency



SC magnets

SC magnets summary

- **16 T SC dipoles** for HE-LHC
- **Magnets for scSPS** – HE-LHC injector options
- **SC undulators** for a $\gamma-\gamma$ collider (*see LOI*)

- *Need to explore synergy with AF7-Magnets*

SC magnets for HE-LHC (integration aspects)

Working hypothesis: no major CE modifications on tunnel and caverns

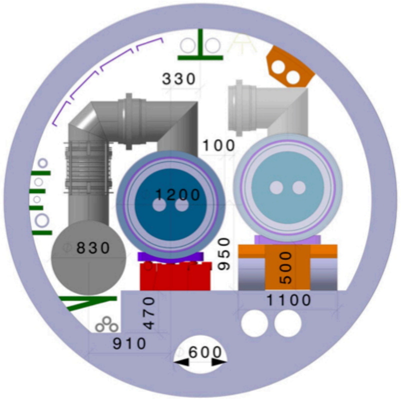
- similar geometry and layout as LHC machine and experiments
- **maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **classical cryostat design gives ~1500 mm diameter!**

Strategy:

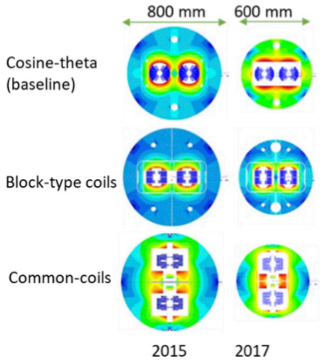
- **allow stray-field and/or cryostat as return-yoke**
- **optimization of inter-beam distance (compact)**

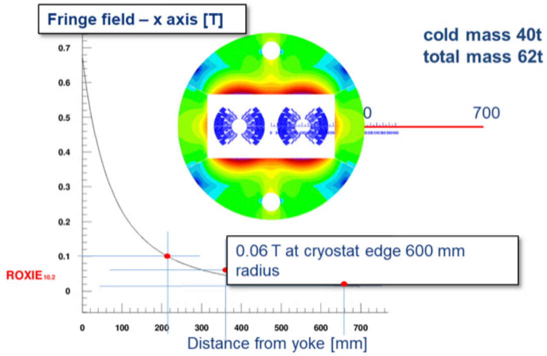
→ smaller diameter also relevant for FCC-hh cost

LHC tunnel diameter 3.8 m



16 T cryo-dipole integration approach





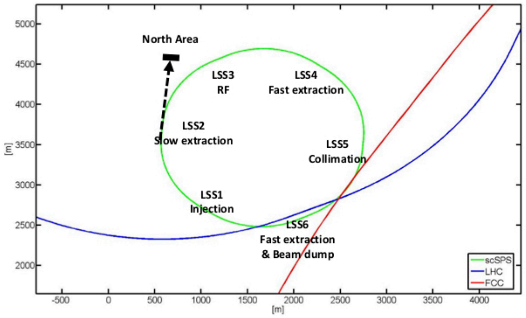
2018: intrabeam distance → 250 mm (194 mm for LHC)

cold mass 40t
total mass 62t

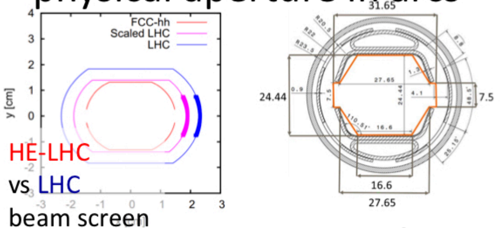
QRL Φ830 mm (LHC 650)
MB Φ1200 mm (LHC 1106)

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

HE-LHC injector options

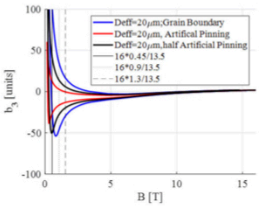


physical aperture in arcs



HE-LHC
vs LHC
beam screen

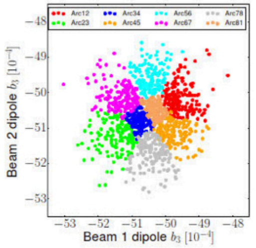
magnet field quality:
effective filament size **20 µm**, APCs,
with **50% pinning efficiency**, **interbeam distance →250 mm**,
and **magnet sorting**
(+ **dipole bending**)



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



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

Conventional magnets

Conventional magnets summary

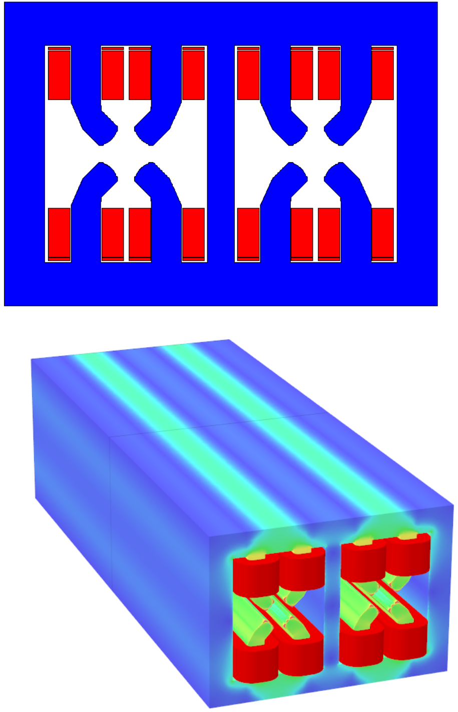
- CEPC: Collider dual aperture dipole magnets and **dual aperture quadrupoles**, high-precision booster dipole magnet

- *Need to explore synergy with AF7-Magnets*

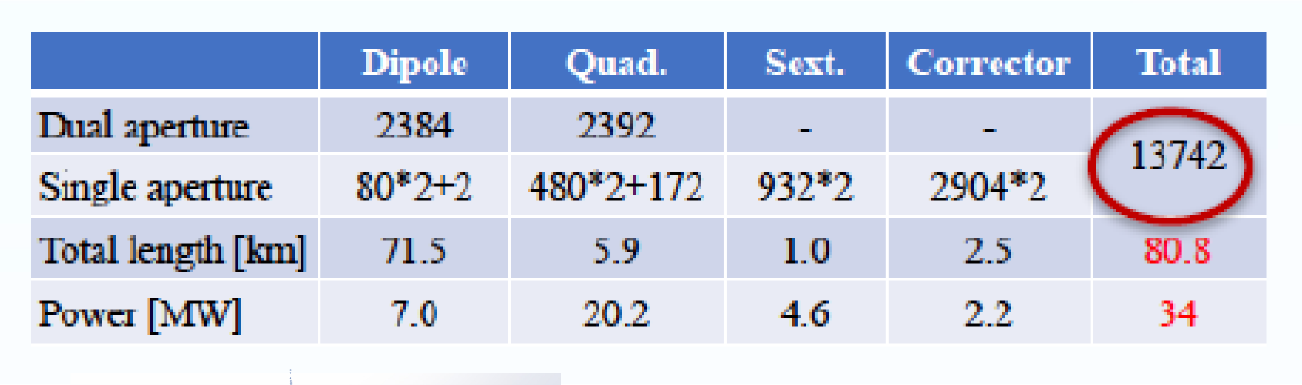
CEPC collider ring dual aperture quadrupole (key R&D item)

Dual aperture quadrupole

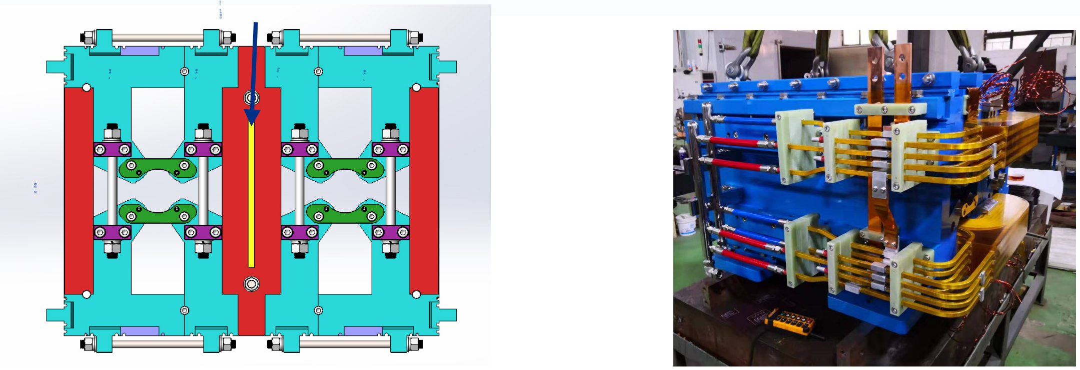
New design



Might be common technology with FCC-ee



	Dipole	Quad.	Sext.	Corrector	Total
Dual aperture	2384	2392	-	-	13742
Single aperture	80*2+2	480*2+172	932*2	2904*2	
Total length [km]	71.5	5.9	1.0	2.5	80.8
Power [MW]	7.0	20.2	4.6	2.2	34



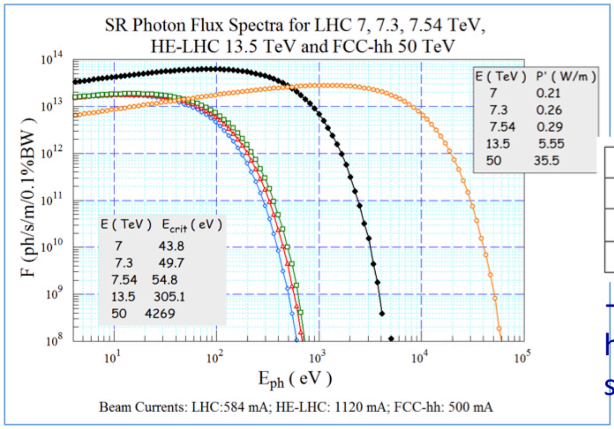
The first dual aperture quadrupole model - not yet working - new design underway

Specialized vacuum

Specialized vacuum summary

- HE-LHC challenges: **SR handling** and **collision debris**
- CEPC, although is not identified as critical R&D

Specialized vacuum for HE-LHC (SR handling)



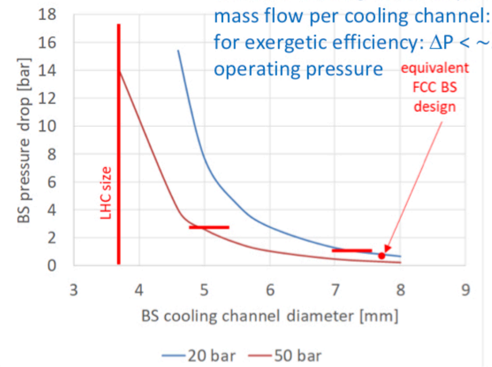
HE-LHC photon flux per meter = 5.4x LHC (7 TeV) and 1.8x FCC-hh (50 TeV)

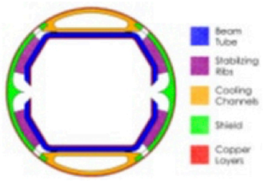
parameter	LHC	HE-LHC	FCC-hh
linear SR power [W/m]	0.25	5.5	35
linear photon flux [10^{16} photons/m/s]	5	27	15
critical photon energy [eV]	44	320	4300

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

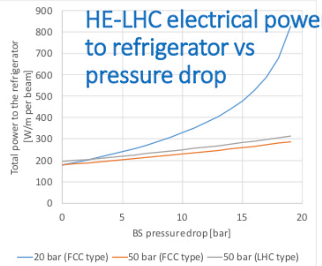
HE-LHC beam-screen pressure drop

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





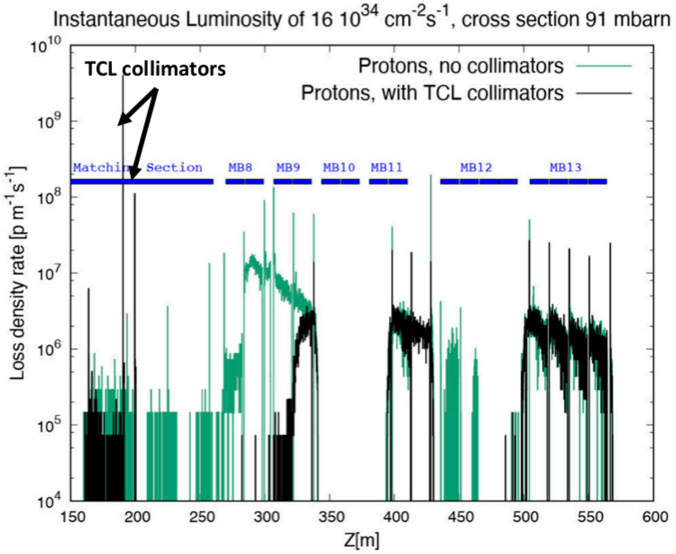
FCC-hh BS compatible w 20 bar operating pressure


HE-LHC electrical power to refrigerator vs pressure drop

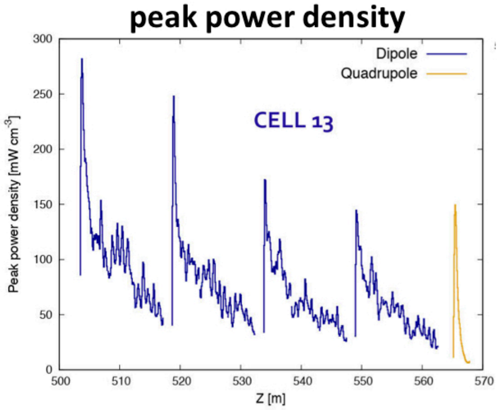
BS type	Operating Pressure [bar]	DP [bar] BS (+ CV)	Power to ref. [W/m/beam]	Operation cost (10 y) [MCHF]	Distribution cost
LHC-type beam screen	20	N/A	N/A	N/A	N/A
	50	14 (+3)	300	52	+
FCC-type beam screen	20	0.8 (+1)	200	35	-
	50	0.3 (+1)	184	32	+

Specialized vacuum for HE-LHC (collision debris)

- ❑ 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)

Electron sources

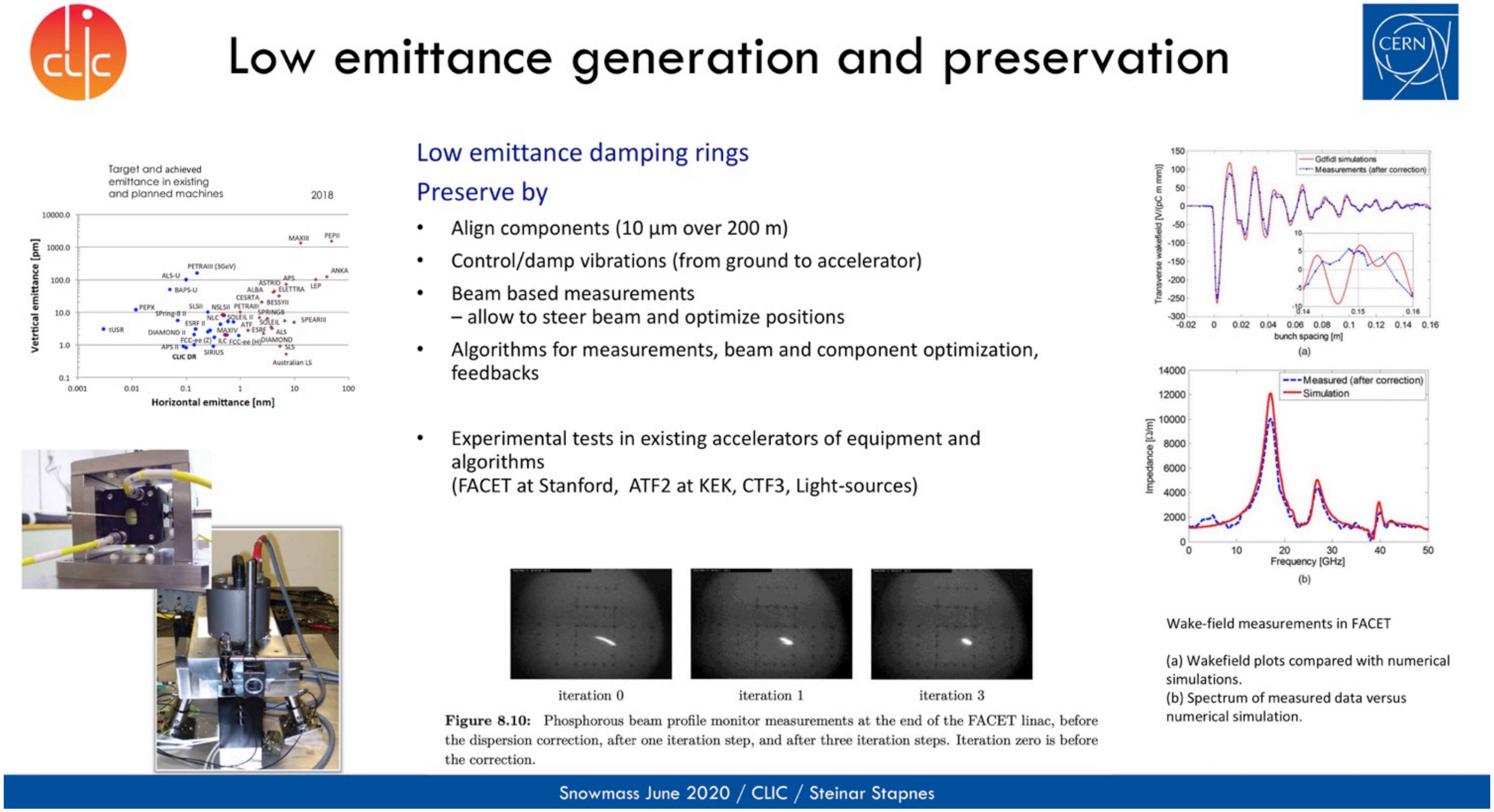
Electron sources summary

- This is a common topic for many projects covering not only electron guns, but also injectors and damping rings
- New designs are being pursued at various labs
- For ILC, demonstrations at CESR (Cornell) have established confidence in the ILC damping ring parameters, but some R&D will be needed for upgrades

- Synergy with FELs and other machines

- *Need to explore overlap with AF7-Targets/Sources*

Electron sources for CLIC



Low emittance generation and preservation

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)

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

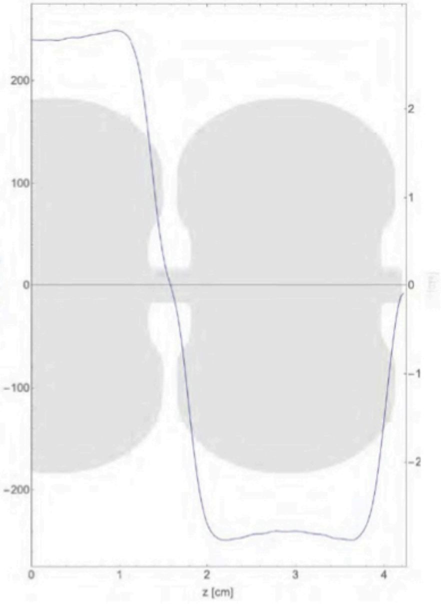
(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

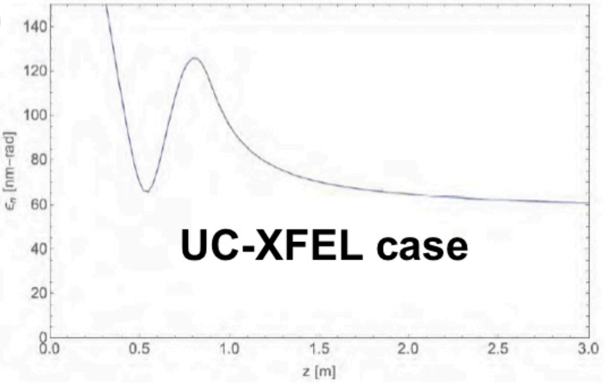
Snowmass June 2020 / CLIC / Steinar Stapnes

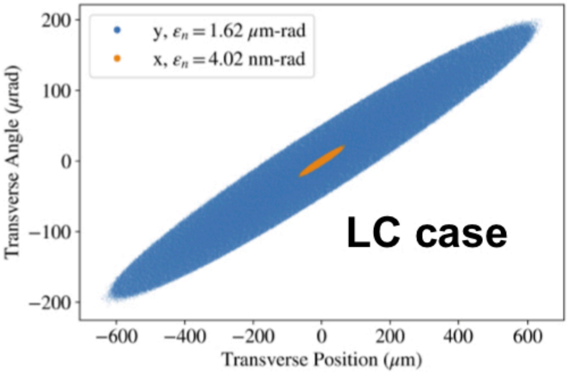
Ultra-high brightness photoinjector

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

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





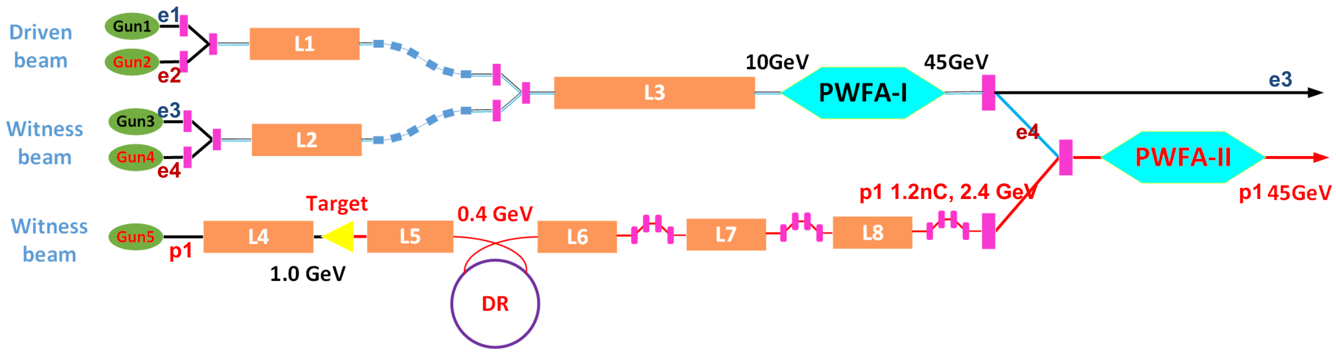


Emittance: <**55 nm**
(400 nm in LCLS inj.)
Peak current 20 A.
Enabling element
of ultra-compact XFEL
J. Rosenzweig et al., *New Journal of Physics* (Oct. 2020)

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

James Rosenzweig

Plasma injector: an alternative for CEPC



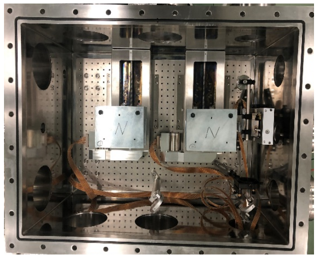
	e1/e3 Before PWFA-I	e3 After PWFA-I	e2/e4 Before PWFA-I	e4 After PWFA-I	p1 Before PWFA-II	p1 After PWFA-II	Booster Requirement
Energy (GeV)	10/10	45.5	10/10	45.5	2.4	45.5	45.5
Bunch Charge (nC)	5.8/0.84	1	15/4.5	>3	1.2	1	0.78
Bunch length (ps)	2/0.257	<1	3/0.7	<1	0.07	<1	<10
Energy Spread	~/0.2%	~1%	~/0.2%	1%	0.2%	~1%	0.2%
E_{normal} (μm·rad)	<20*/<100	~100	<50*/<100	~100	<50	~100	<800
Bunch Size (μm)	3.87/8.65	<20	30/20	<20	20	<20	<2000

The plasma accelerator performance has been checked numerically with the real linac beam quality, and it almost reached the design goal, but need experimental verfication

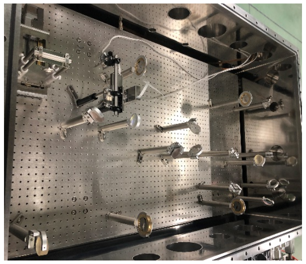
CEPC Plasma injector experimental platform

Facilities: Shanghai S-XFEL facility for electron acceleration and FACET-II at SLAC for positron

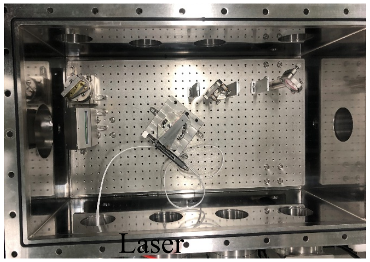
- Plasma experimental station: preliminary set up on Shanghai Soft XFEL facility
  Vacuum system: installation & testing preparation (to e tested in 2021)
  - Light path
  - Beam diagnostic system



Beam test room



main room



Laser compressor

One-offs

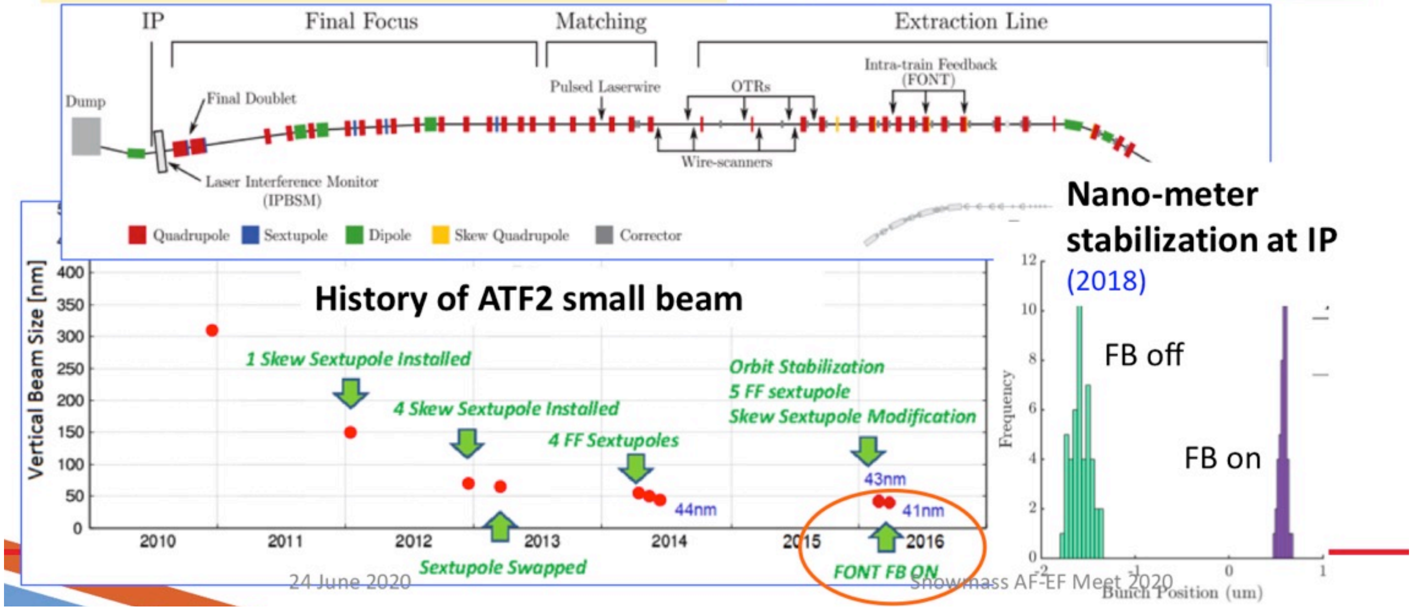
Nanobeams for ILC

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)

FELs for $\gamma\gamma$

XFEL $\gamma\gamma$ Colliders Provide a Unique Physics Environment

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

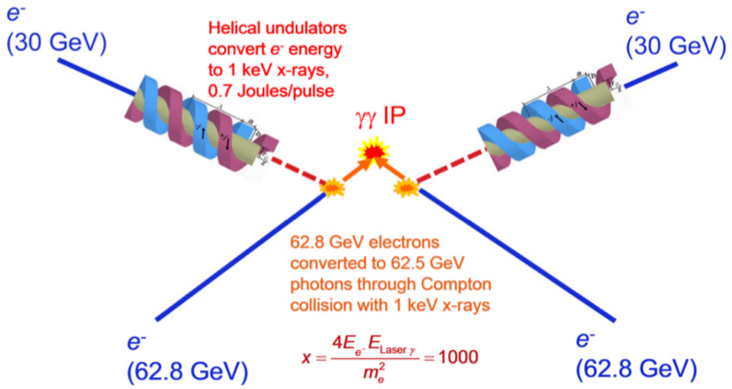
  n.b. Γ_{tot} @ $\gamma\gamma \equiv \sigma(ZH)$ @ e^+e^-

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

- $\gamma\gamma$ 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 $\gamma\gamma$ 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)

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

e^- (30 GeV)

$\gamma\gamma$ IP

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

e^- (62.8 GeV)

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

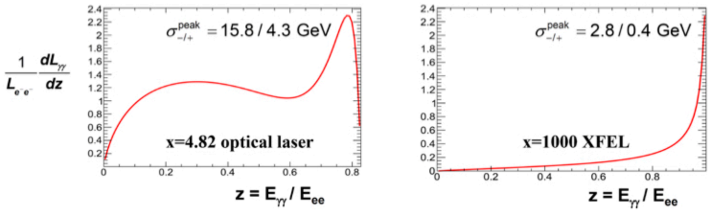
e^- (62.8 GeV)

Low emittance RF gun $\Rightarrow$ 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%.



Timothy Barklow

Cryogenics?

Summary for Cryogenics

- Most of the projects will need large cryogenic systems.
- Should we include anything in our report? Or the projects will rely solely on industry?

- *See LOI* **SNOWMASS21-AF7_AF0-166** *on Accelerator and Quantum Detector Cryogenics R&D*

Thank you!