CLIC: Overview of applications using high-gradient acceleration, from photon sources to medical physics (5/5)

CERN academic training - Compact Linear Collider

Walter Wuensch,
walter.wuensch@cern.ch

Introduction

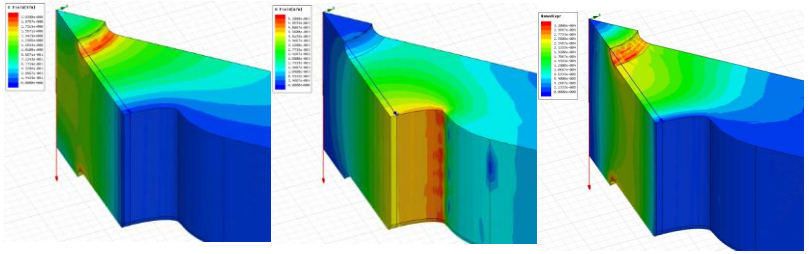
"Another reason to support fundamental science is that it produces ideas and devices that end up being useful in entirely unexpected ways and that have an impact far larger than the original investment in the research."

- You've heard this week about the physics motivation for CLIC and the technology developed for it.
- I will now describe to you some of the ways in which CLIC high-gradient and X-band technology is being used in accelerator applications outside the field of high-energy physics.
- The other theme is that the adoption of the technology is generating important contributions back to the CLIC project (we did this on purpose!).

Disclaimer

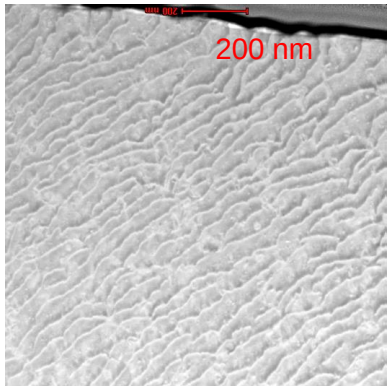
- There are many applications so presentation will often be superficial, but the idea is to give you an overview. I am happy to give you more information after the lecture.
- This presentation is not comprehensive. In particular, I will focus only on projects with which CLIC has a direct collaboration. There are more X-band and high-gradient application activities around the world which I don't have time to cover.

X-band and High-Gradient Technology: What is it?

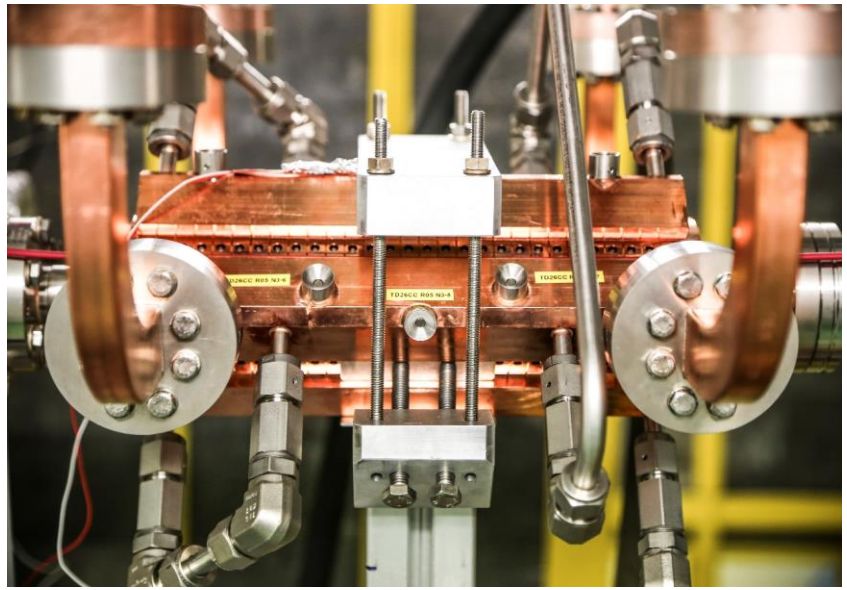


$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

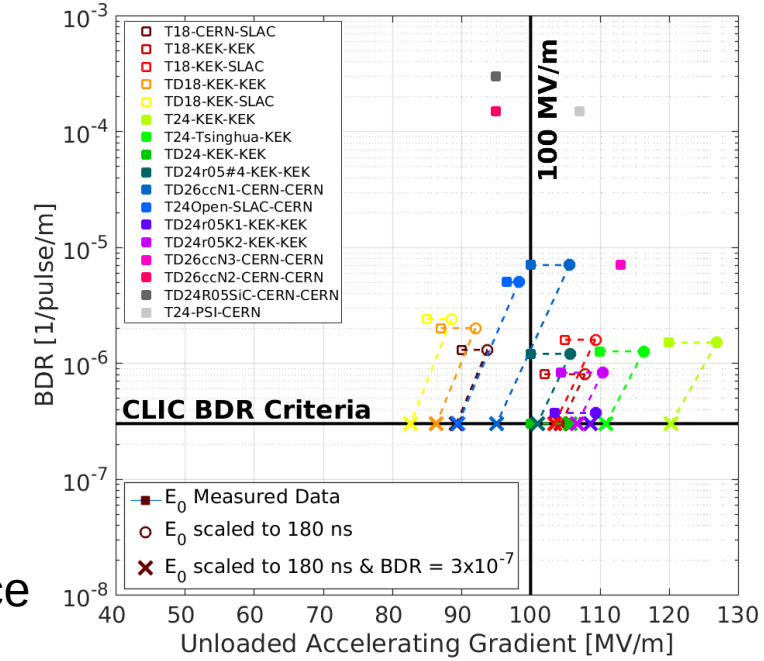
rf design methodology



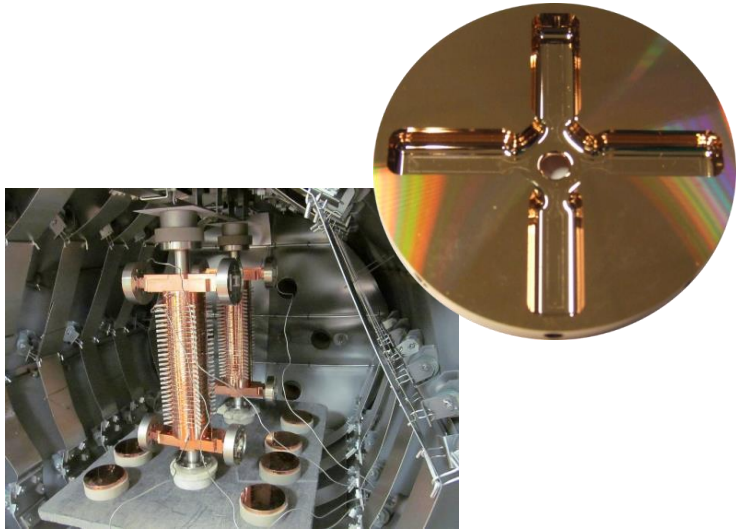
High-field dynamics



1. >100 MV/m accelerating structures



Prototype performance



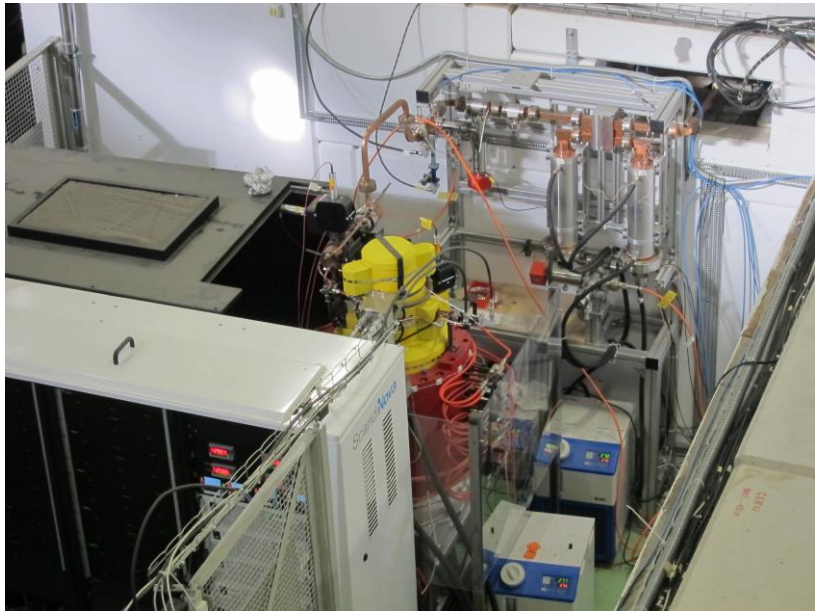
Fabrication technology

X-band and High-Gradient Technology: What is it?

Toshiba 6 MW klystron

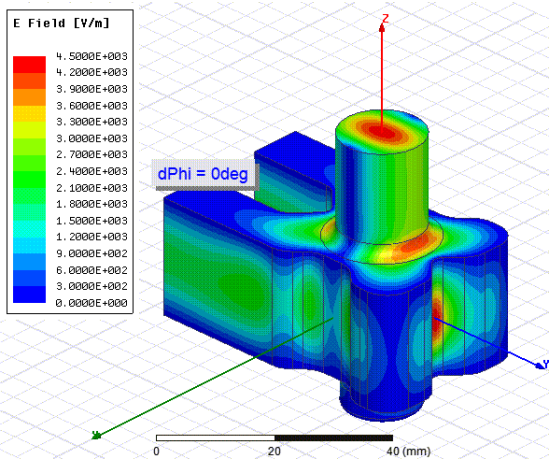
CPI 50 MW klystron

Scandinova solid state modulator



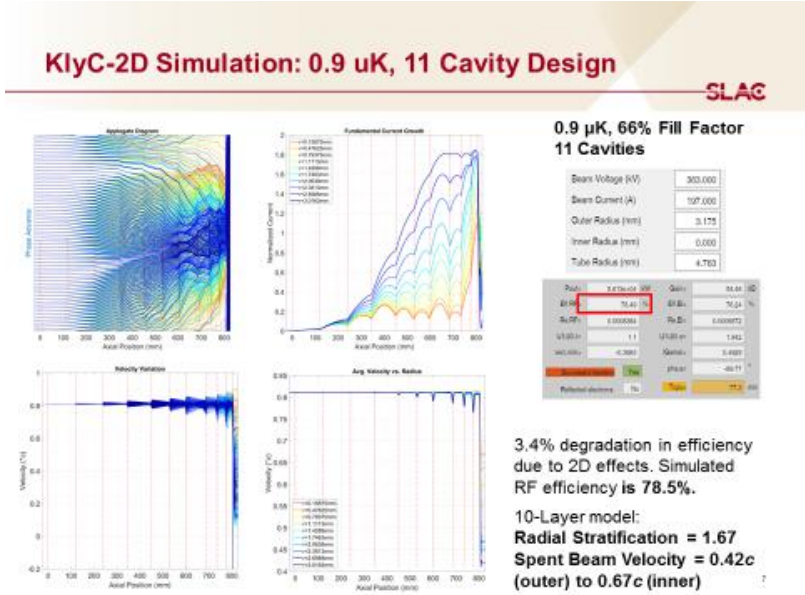
2. >150 MW 12 GHz peak power production

Pulse compressors



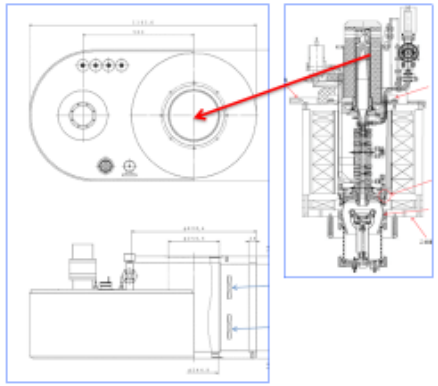
High-power waveguide components

X-band and High-Gradient Technology: What is it?

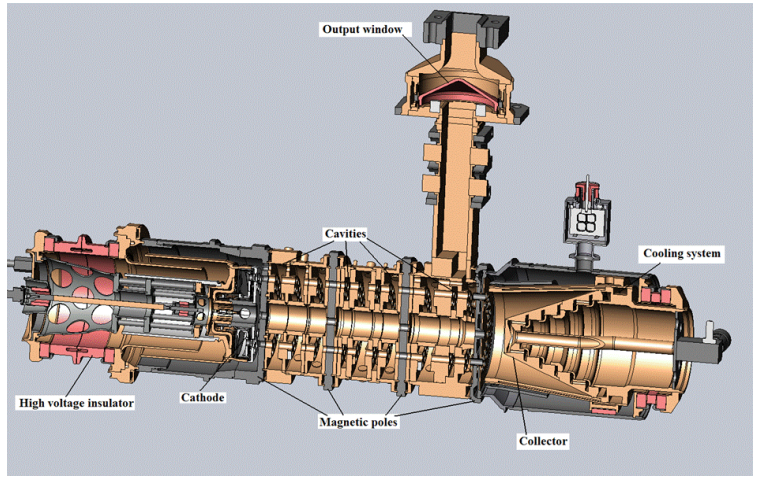


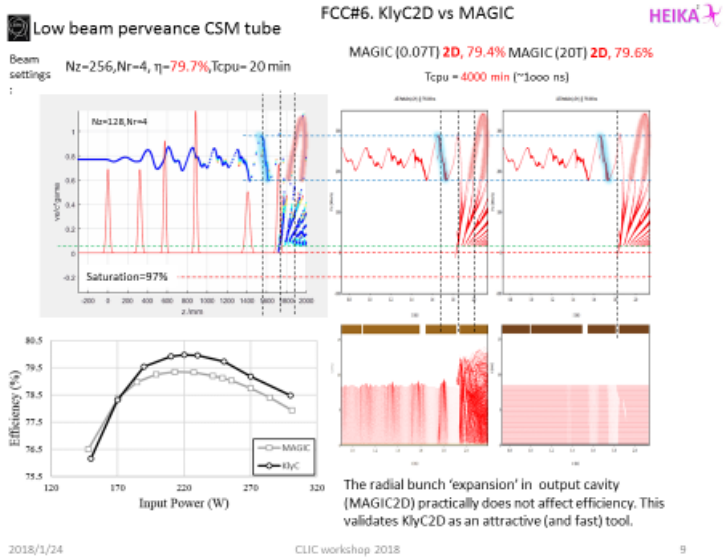
A SC Model Magnet proposed

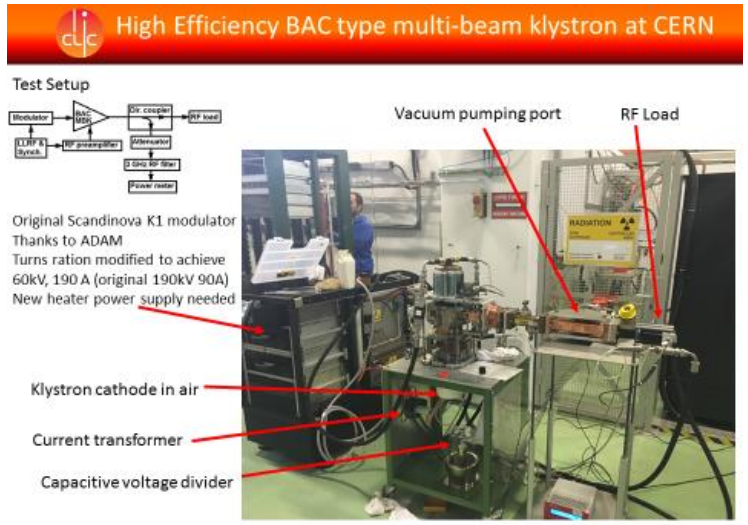
Design Parameters	
Superconductor (T-operation)	MgB_2 (@ 20 K)
Current	50 A
Central field	0.7 T
Stored energy	~ 10 kJ
Cryo-cooler applied	6.7 W @ 20 K 13.5 W @ 80 K
AC Plug Power	≤ 3 kW (< 1,5 kW/Klystron in case of a pair)



A. Yamamoto -180124 12

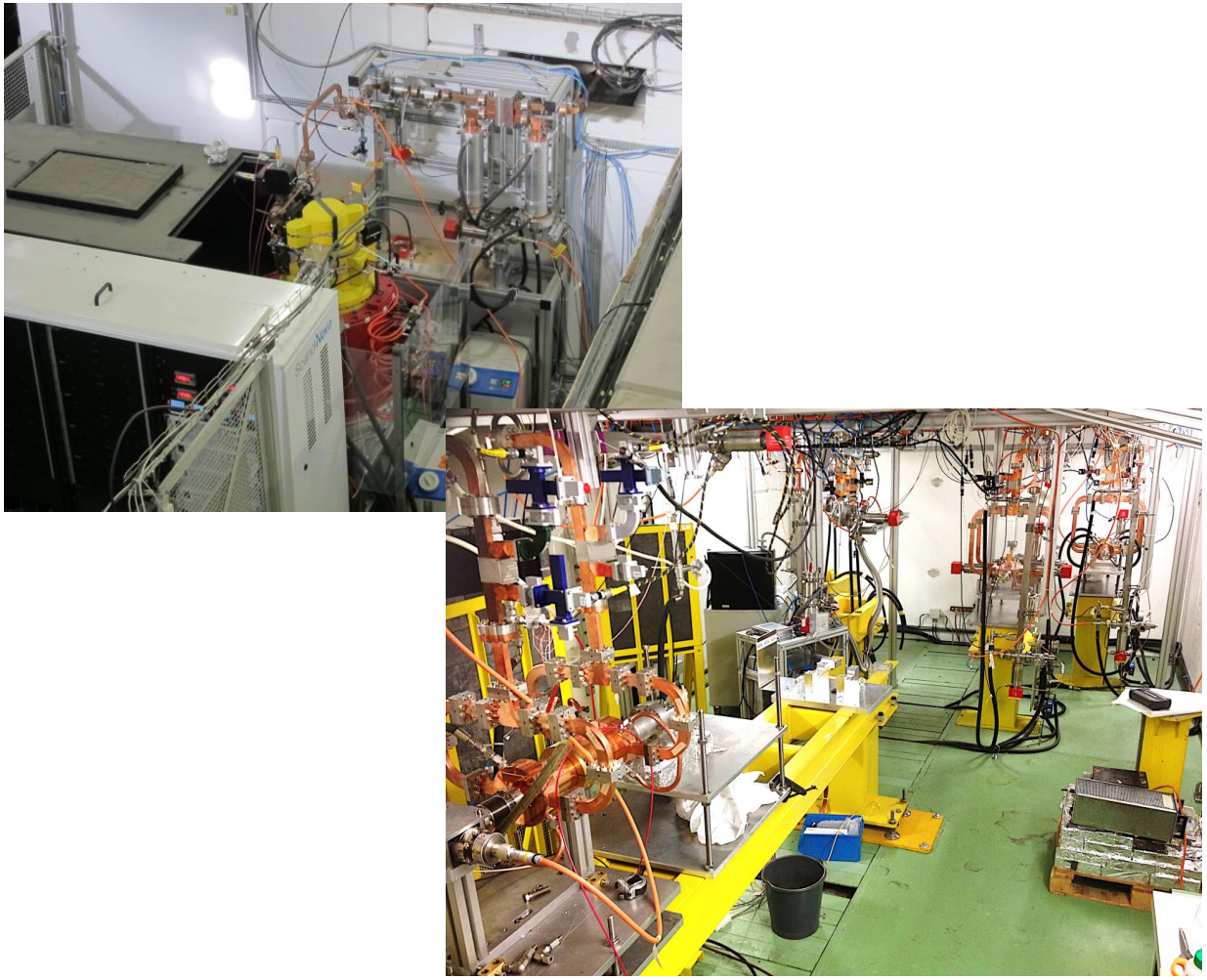




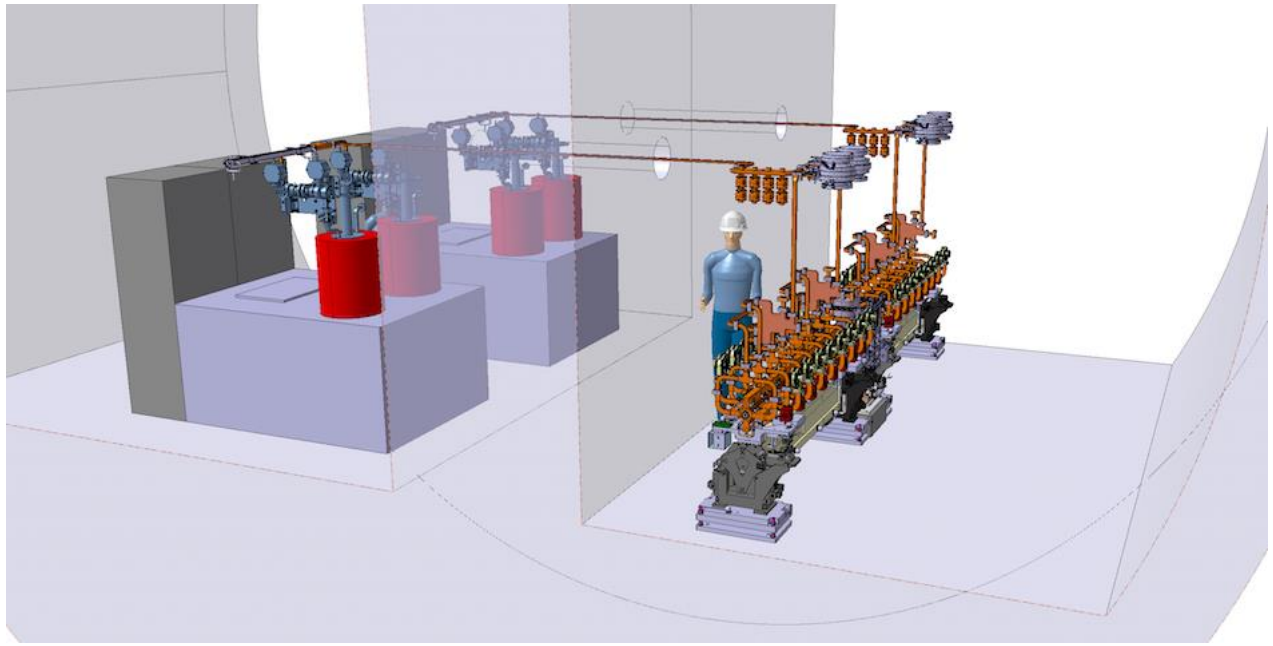


3. High-efficiency klystrons

From test stand to integrated linac

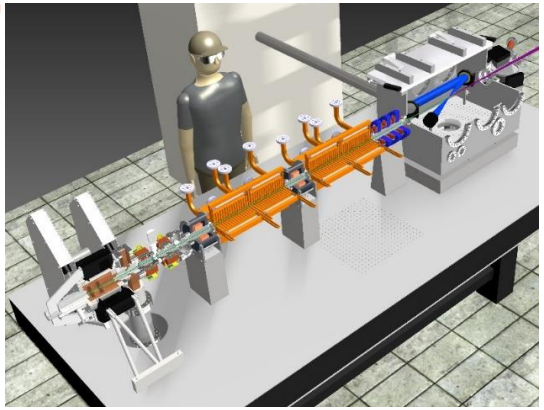


CLIC high-gradient test stand

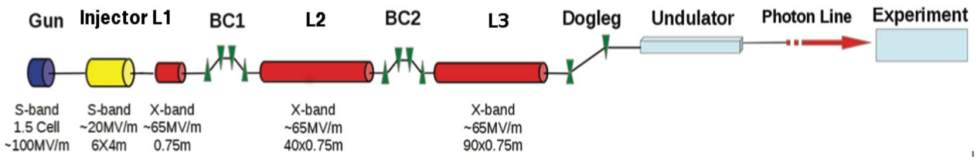


Klystron-based CLIC tunnel layout

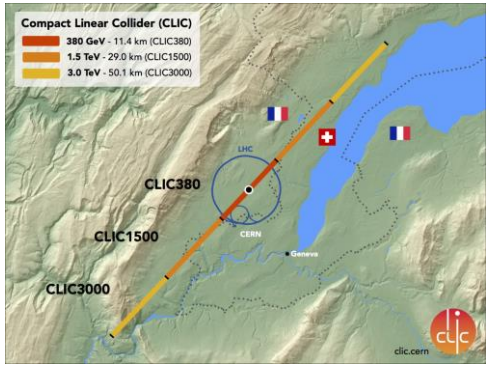
Applications overview



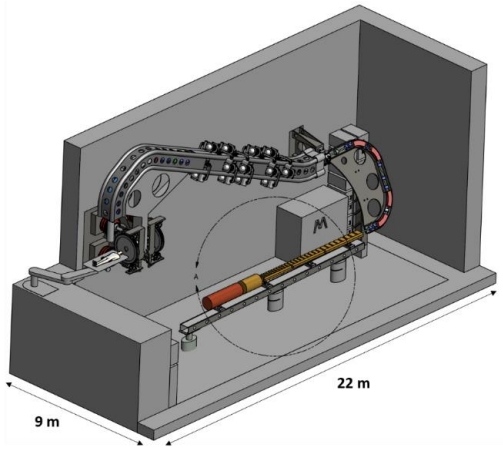
Inverse Compton Source



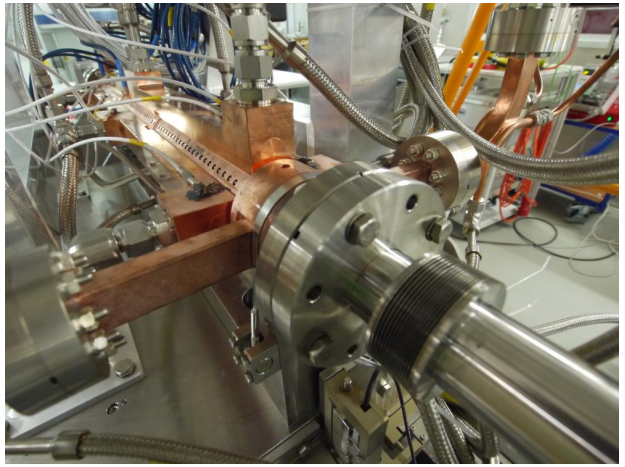
XFEL



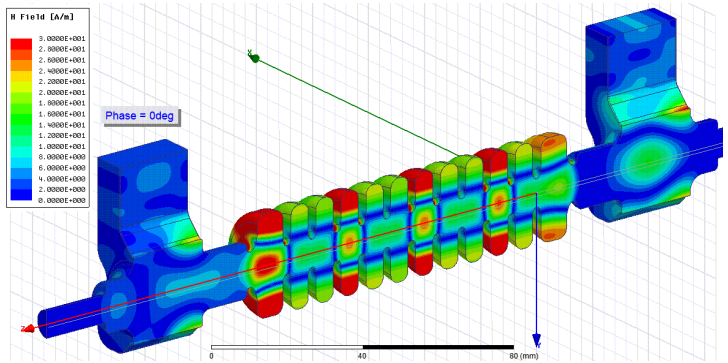
Linear collider



Medical applications



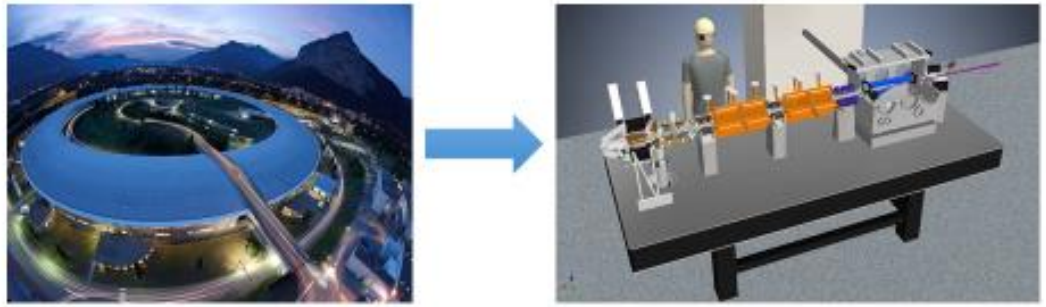
Energy spread linearizer



Deflector for short bunch diagnostics

Smart*Light – compact X-ray source

Inverse Compton Scattering X-ray source



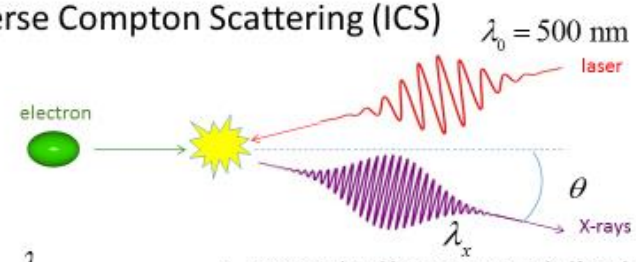
Jom Luiten, Peter Mutsaers, Xavier Stragier

Interreg Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

TU/e Technische Universiteit Eindhoven University of Technology

- Laboratory room scale highly monochromatic X-ray source.
- Alternative to synchrotron light source beam line, less brilliance but local facility.

Inverse Compton Scattering (ICS)

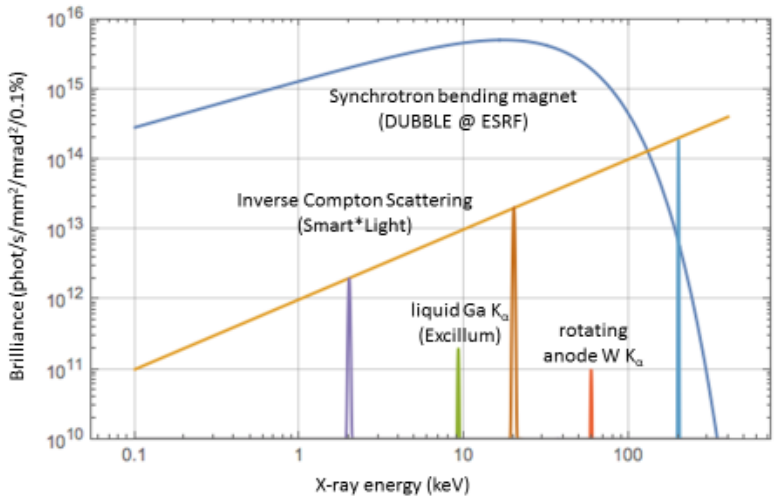


$$\lambda_x = \frac{\lambda_0}{4\gamma^2}(1+\gamma^2\theta^2)$$

- X-rays emitted in narrow cone, half angle γ^{-1}
- X-ray energy dependent on emission angle
- 1% energy spread if $\theta < 0.1\,\gamma^{-1}$

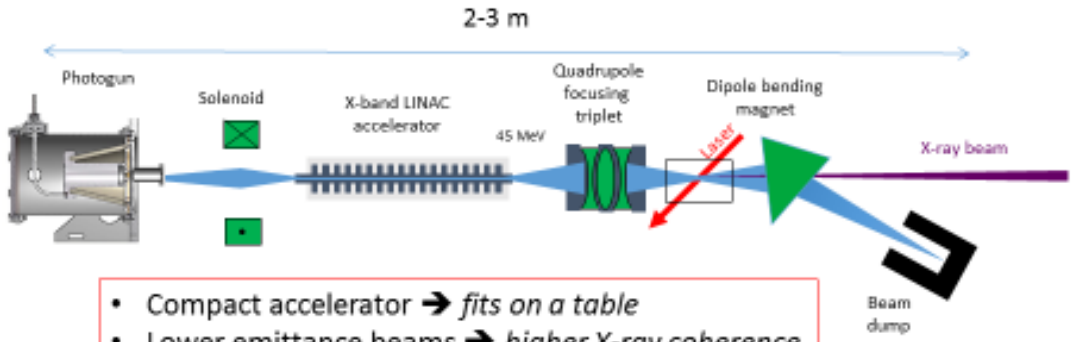
Electron energy	Lorentz factor γ	X-ray wavelength	X-ray energy	Half cone angle 1% energy spread
5 MeV	11	10 Å	1.2 keV	9.0 mrad
20 MeV	40	0.78 Å	16 keV	2.5 mrad
50 MeV	99	0.13 Å	95 keV	1.0 mrad

Brilliance

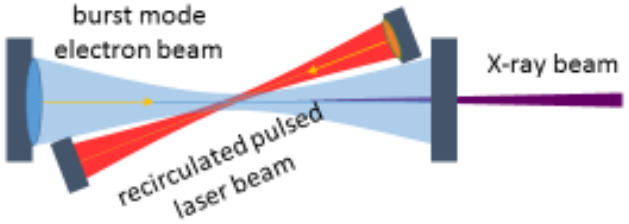


Smart*Light – compact X-ray source

X-band LINAC-based ICS sources: why?



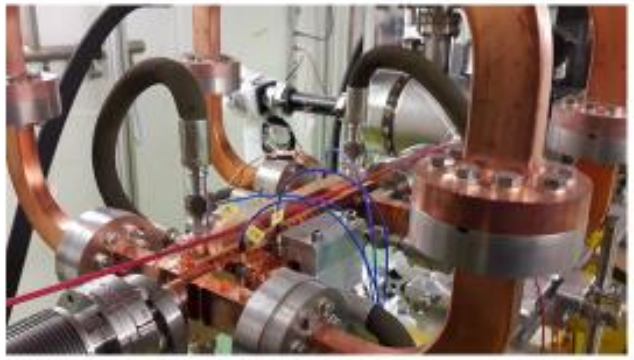
- Compact accelerator ➔ *fits on a table*
- Lower emittance beams ➔ *higher X-ray coherence*
- Easier alignment, *fast change of X-ray energy*

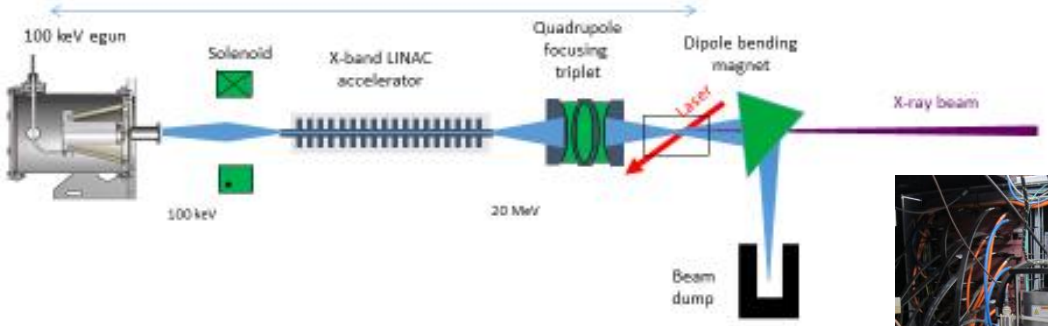


ICS X-ray source - Planning

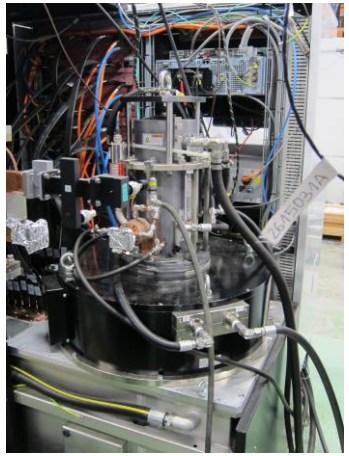
Phase 1 (+/- 2 years)
(20 MeV e⁻ / 20 keV x-rays)

- Infrastructure in bunker
- 100 keV electron egun
- Accelerator sections + focusing
- Xband infrastructure
- Laser
- Beam dump (radiation issues)
- Control + safety system

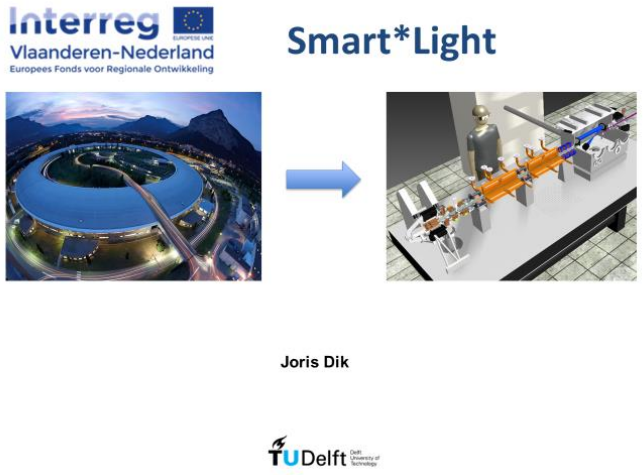


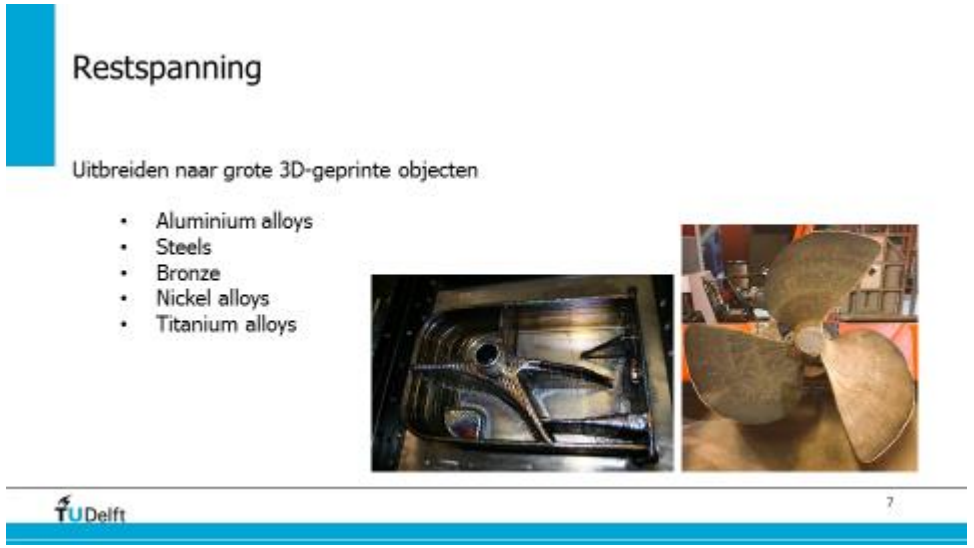


Based on 6 MW Toshiba klystron



Smart*Light –Users, Artists to Engineers





Smart*Light recently held kick-off and users meeting.

TTX at Tsinghua University

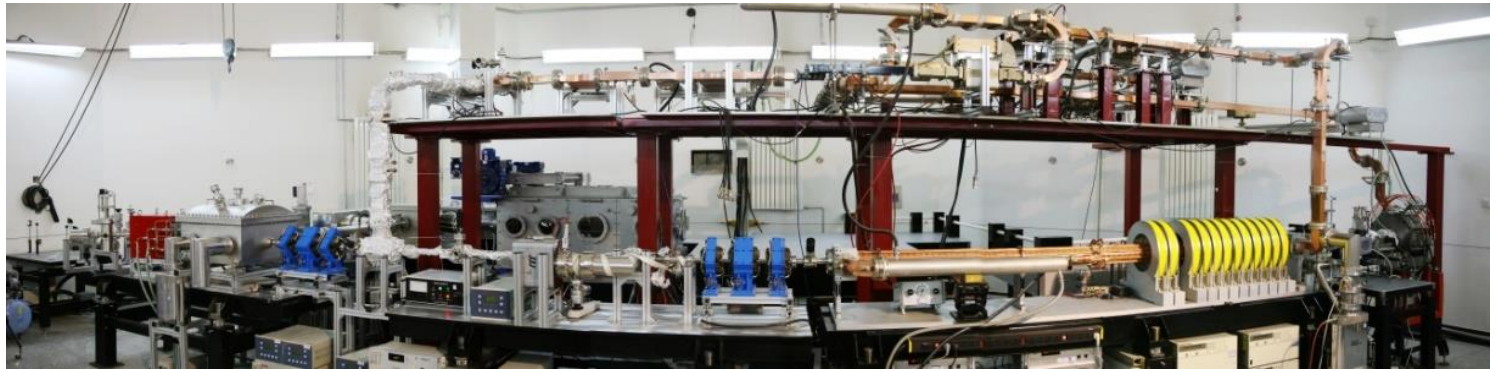
Thomson Scattering X-ray Source at Tsinghua University

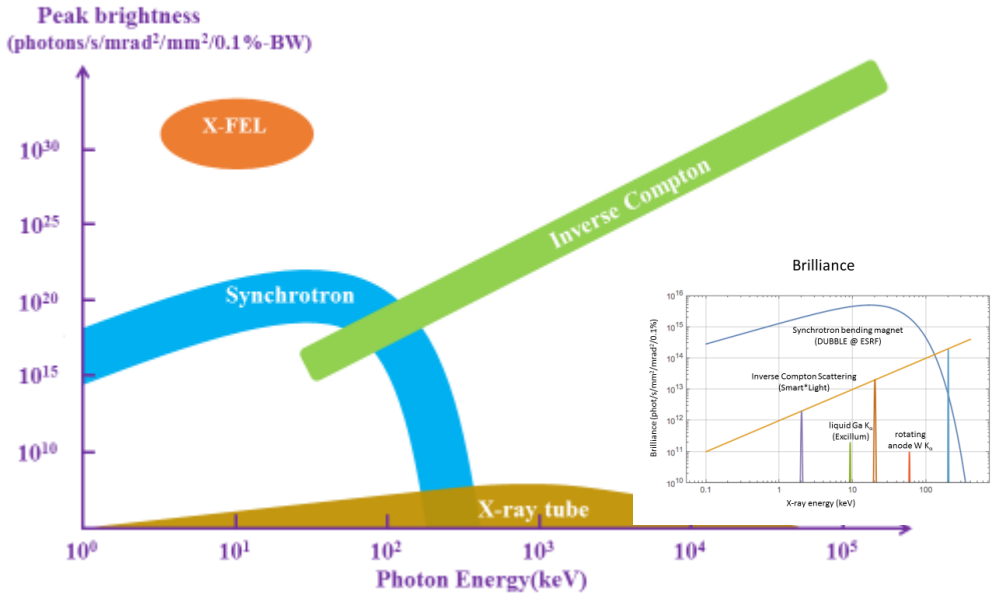
Jiaru Shi

2017.6.13

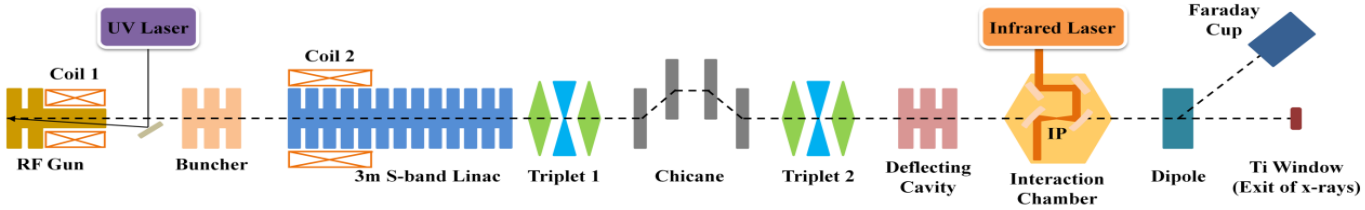
For the TTX team

X/γ-ray source



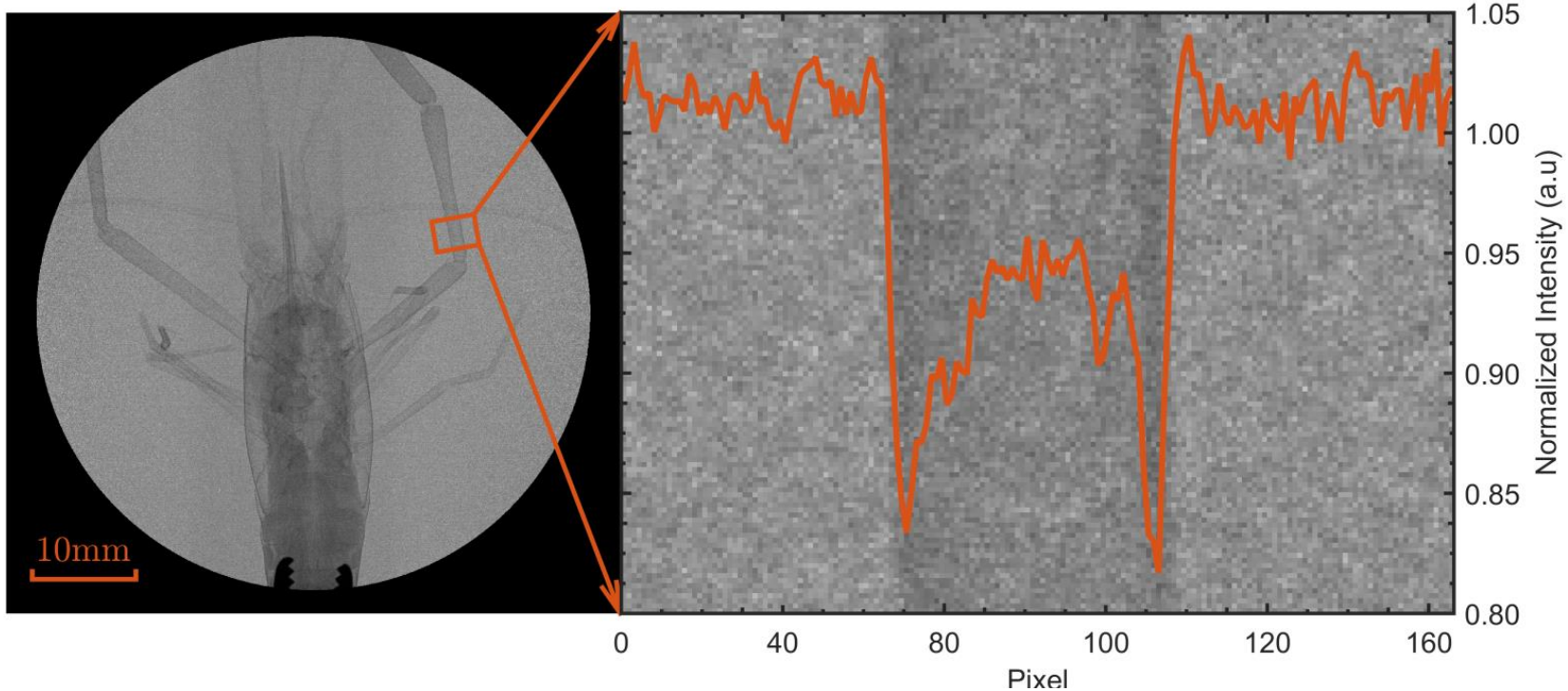


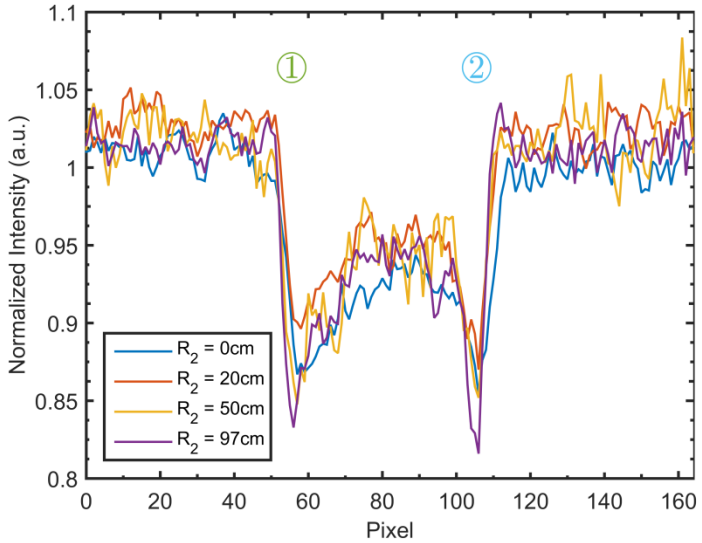
Existing facility with 3 m S-band linac, 45 MeV

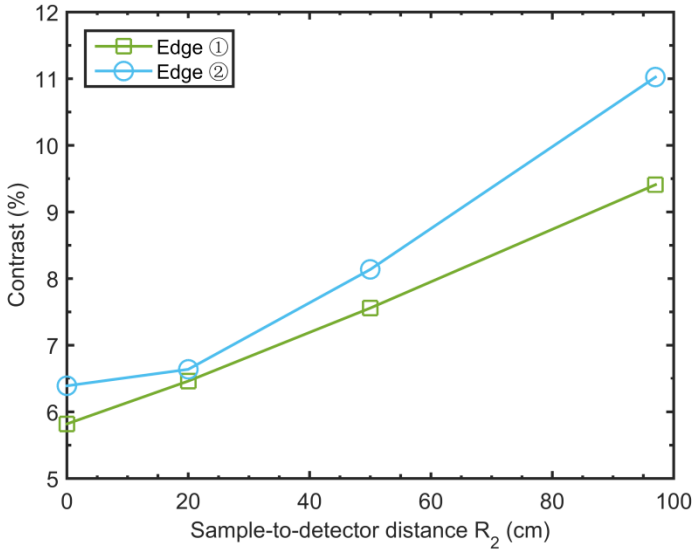


X-ray phase contrast image

Z. Chi

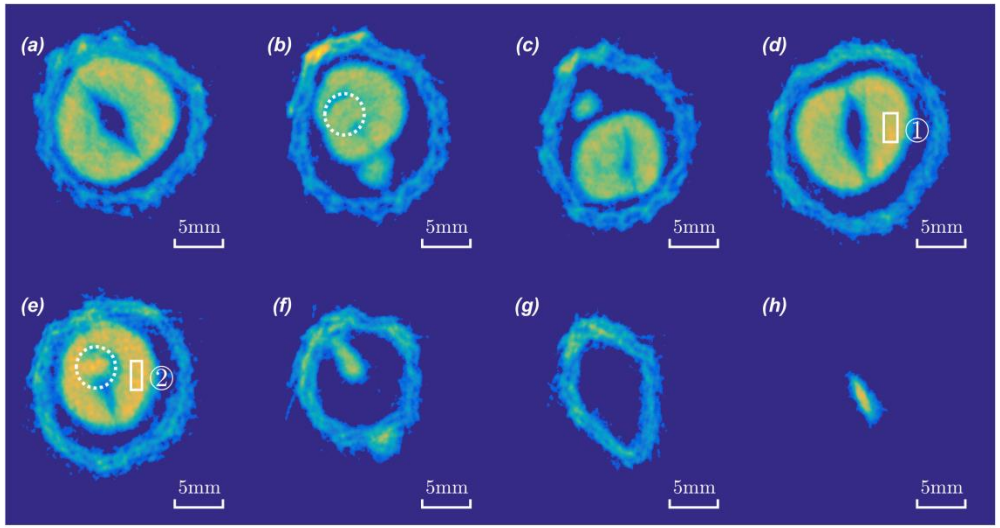


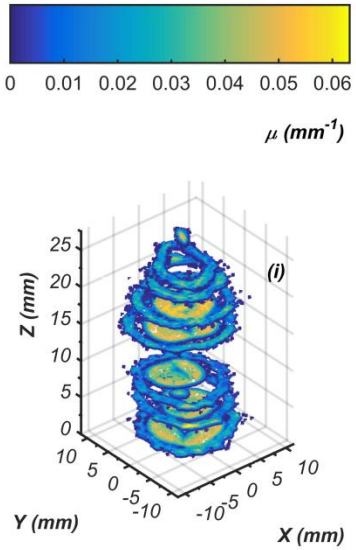




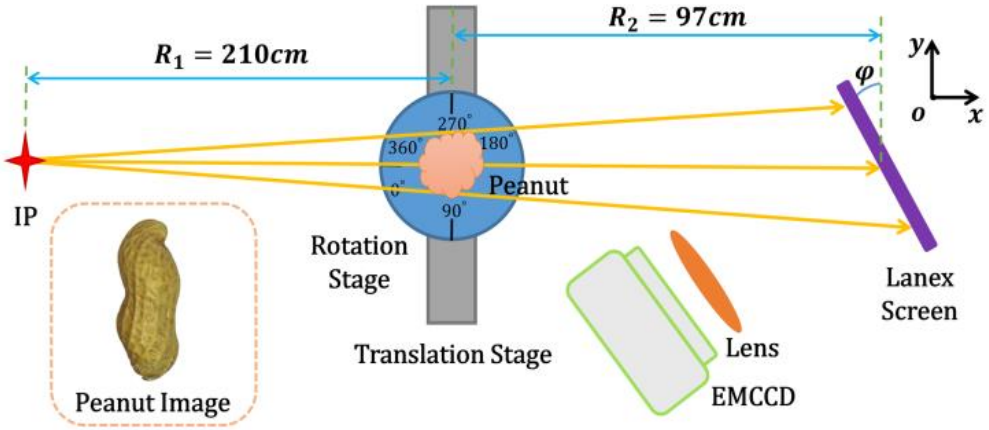
X-ray CT

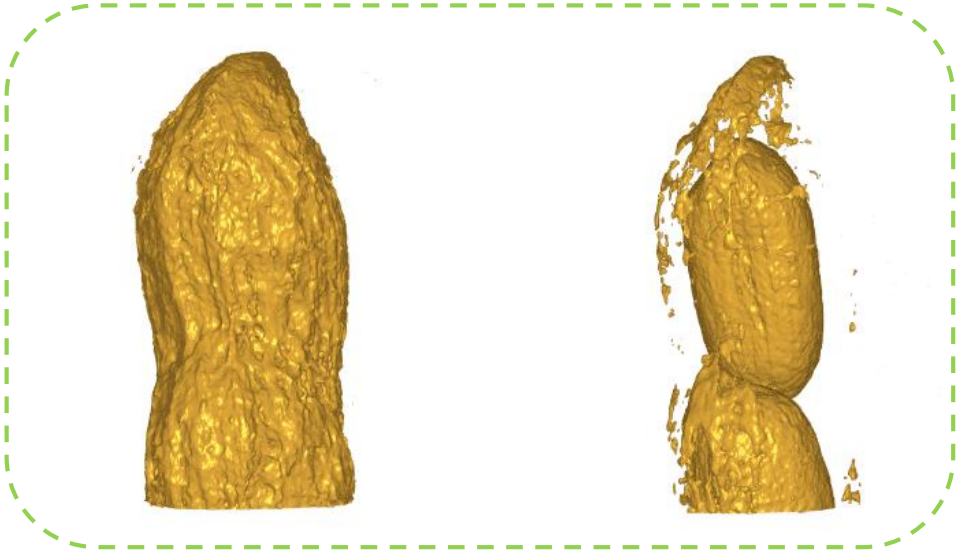
Z. Chi



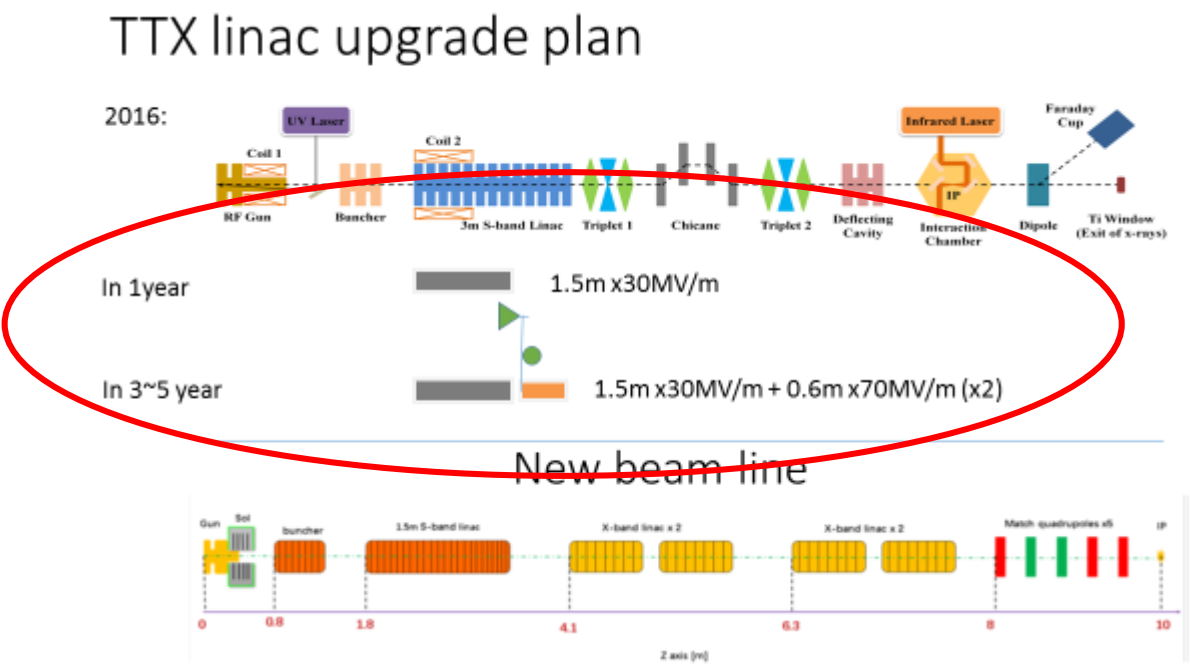


Peanut





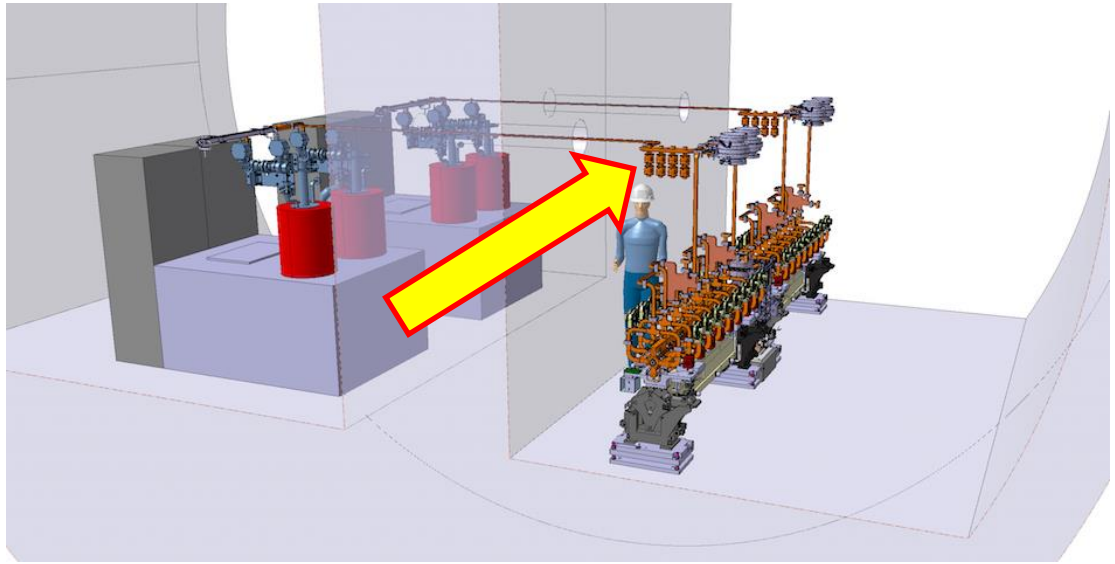
TTX upgrade plans

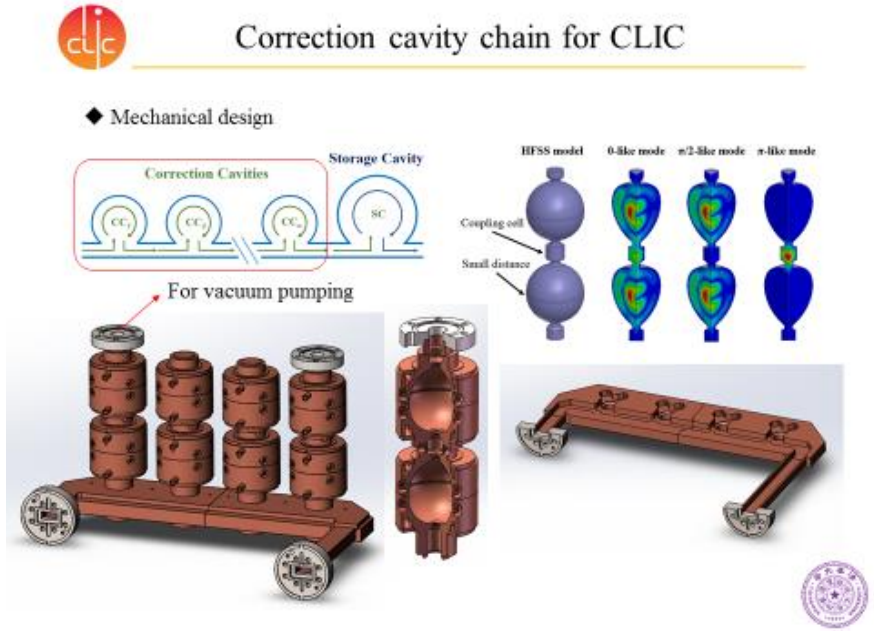


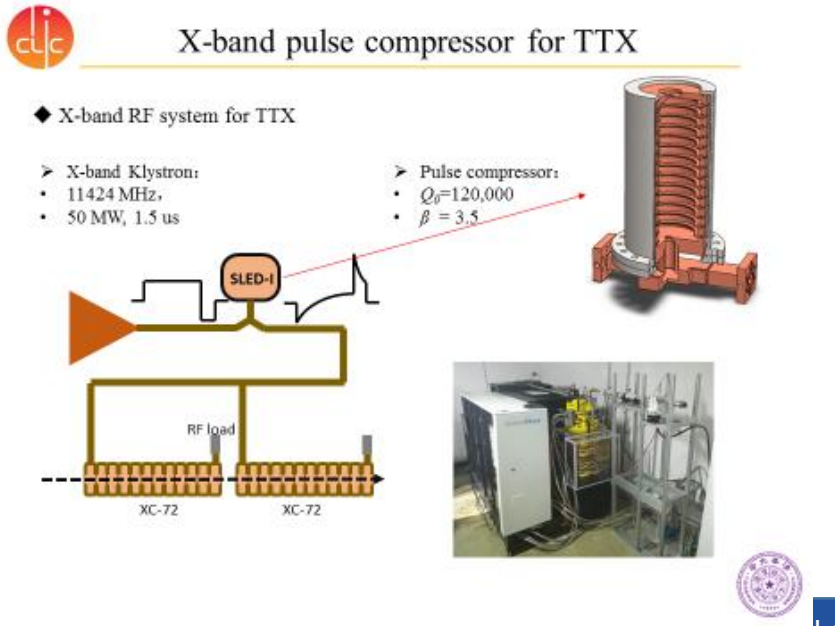
Progressively higher energy through increasing gradient and implementation of X-band.

50 MW CPI klystron, Scandinova modulator being commissioned in Tsinghua.

TTX – the intellectual return path







ELI-NP – Large-scale inverse Compton Source

D. Alesini

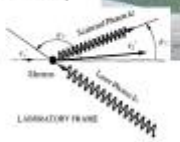
ELI-NP GAMMA BEAM SYSTEM

⇒ Advanced **source of Gamma-ray photons** in construction in Magurele (Bucharest, **Romania**) in the context of the **ELI-NP** Research Infrastructure by the "EuroGammaS" Association (composed by the INFN, the "Association leader", the University of Rome "La Sapienza", the CNRS, ACP S.A.S., Alsyom S.A.S., Comeb Srl, ScandiNova Systems AB);

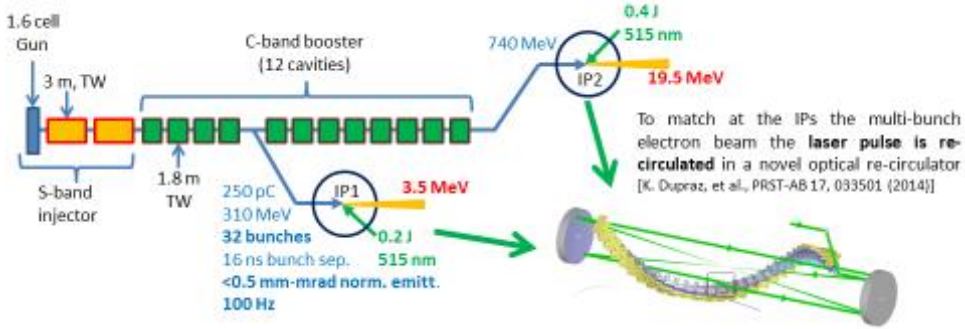
⇒ The photons will be generated by **Compton back-scattering** in the collision between a high quality electron beam and a high power laser;

⇒ The machine is expected to achieve:

- **energy of the gamma photons tunable** 0.2-19.5 MeV
- **narrow bandwidth** (<0.5%)
- **high spectral density** (>10^4 photons/sec/eV)



[TDR ELI-NP GBS arXiv:1407.3669]
[A. Giribono, MOVA016]



To match at the IPs the multi-bunch electron beam the **laser pulse is re-circulated** in a novel optical re-circulator [K. Dupraz, et al., PRST-AB 17, 033501 (2014)]

ELI-NP LINAC

The ELI-NP LINAC operates:

⇒ at **100 Hz**

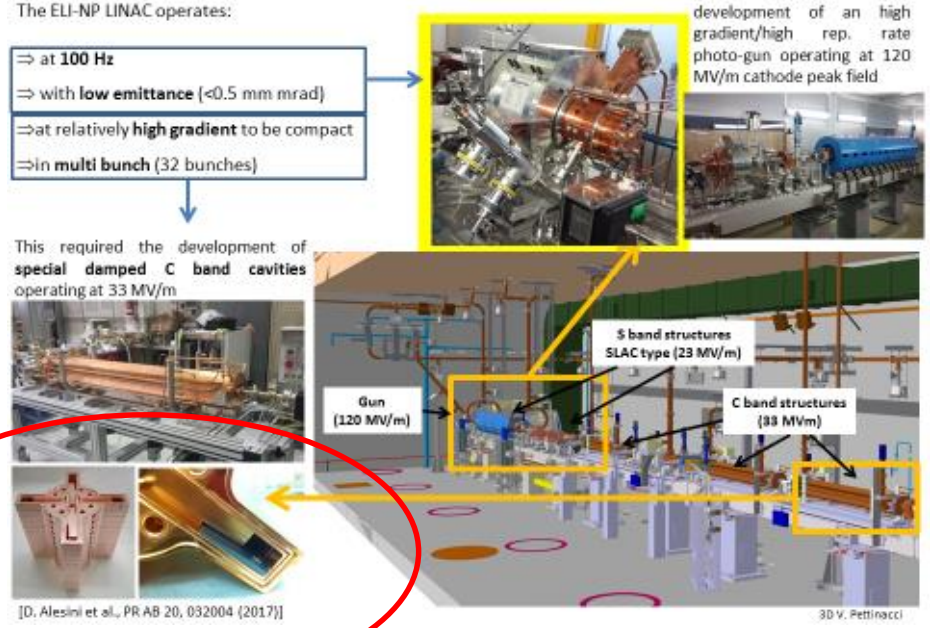
⇒ with **low emittance** (<0.5 mm mrad)

⇒at relatively **high gradient** to be compact

⇒in **multi bunch** (32 bunches)

This required the development of **special damped C band cavities** operating at 33 MV/m

This required the development of an high gradient/high rep. rate photo-gun operating at 120 MV/m cathode peak field

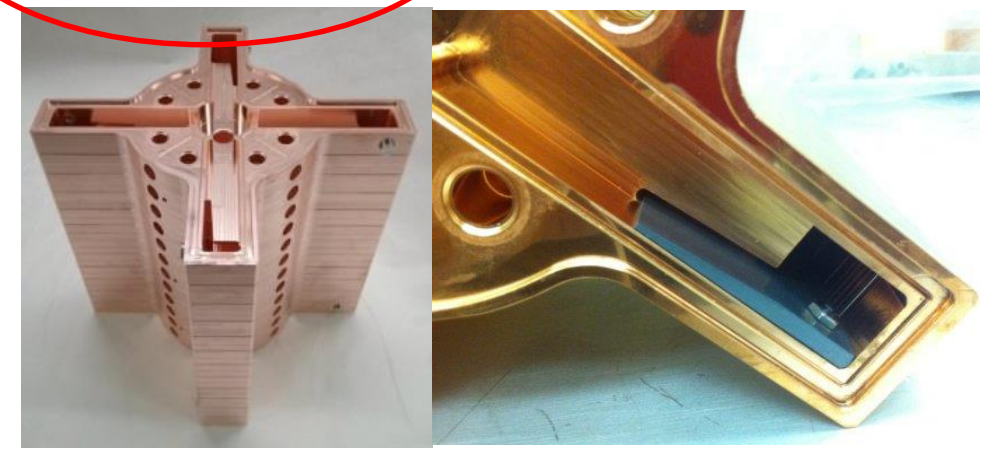


[D. Alesini et al., PR AB 20, 032004 (2017)]

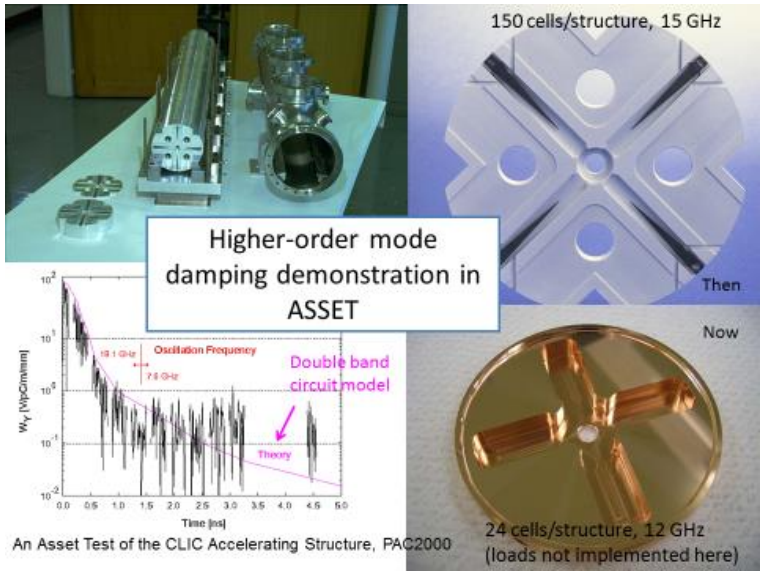
3D V. Pettinacci

CLIC disk

Higher-order-mode damping for stability of high current beam developed by CLIC

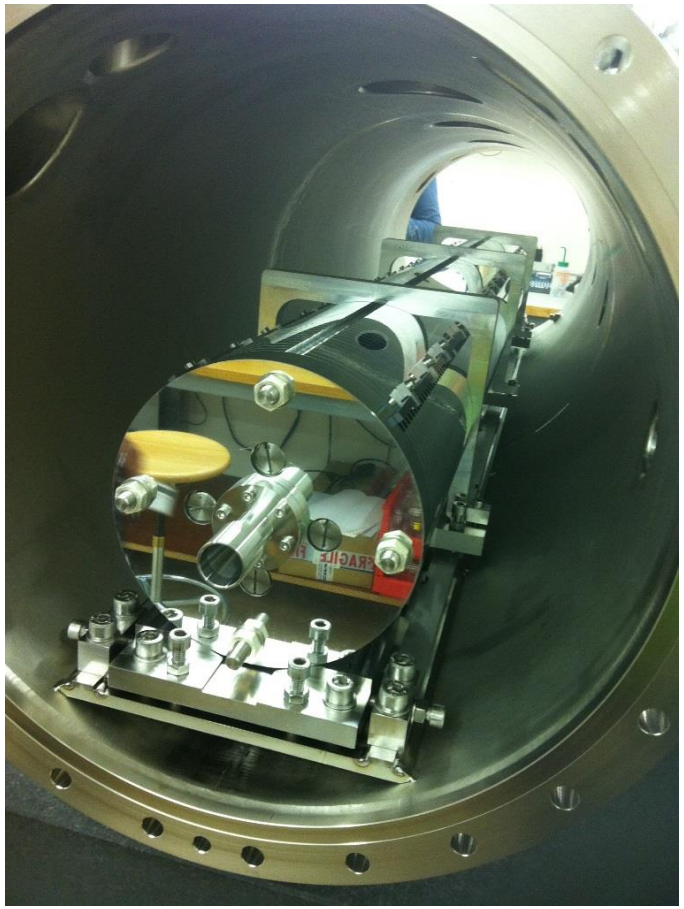


HOM suppression developed by CLIC



Direct beam measurement in 1999.

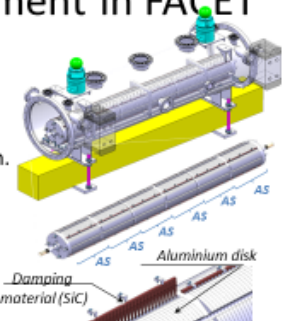
Recent experiment done at SLAC

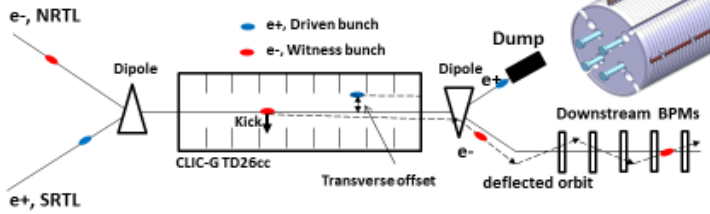


Outstanding agreement between simulation and experiment

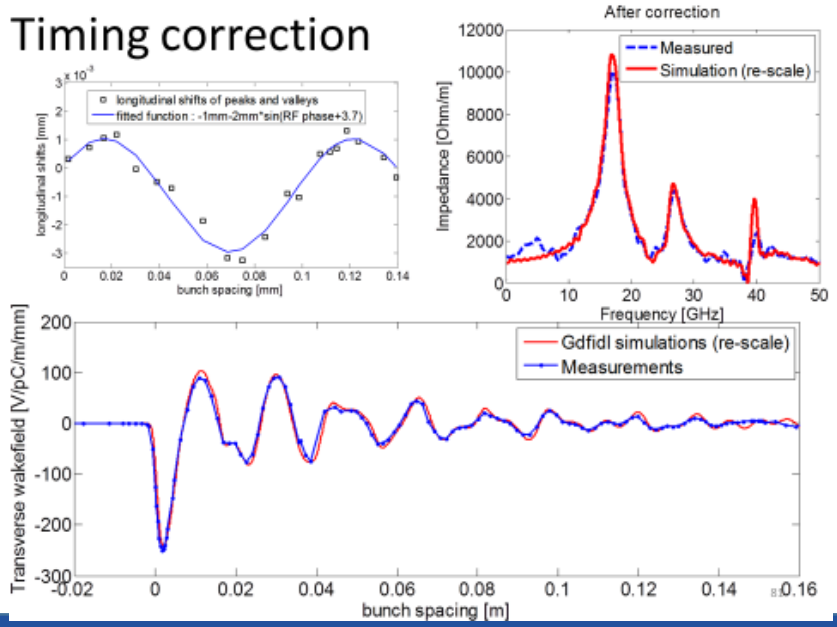
Direct wakefield measurement in FACET

- Prototype structure are made of aluminium disks and SiC loads (clamped together by bolts).
- 6 full structures, active length = 1.38m
- FACET provides 3nC, 1.19GeV electron and positron.
- RMS bunch length is near 0.7mm.
- Maximum orbit deflection of e- due to peak transverse wake kick (1mm e+ offset): 5mm, BPM resolution: 50um





Timing correction

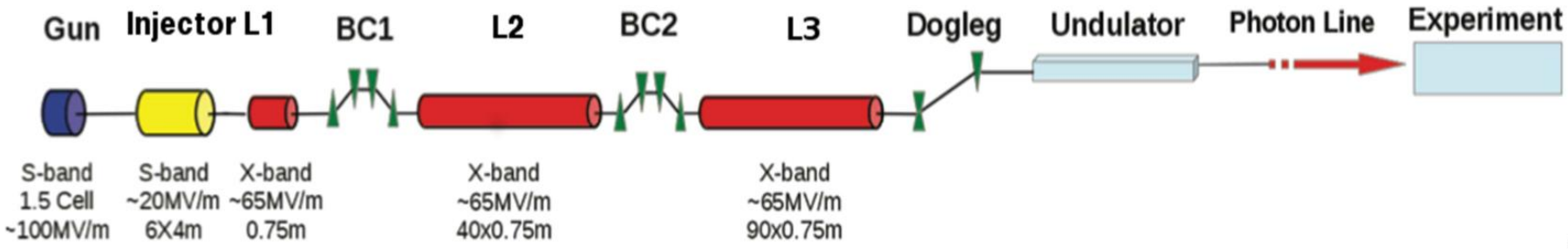


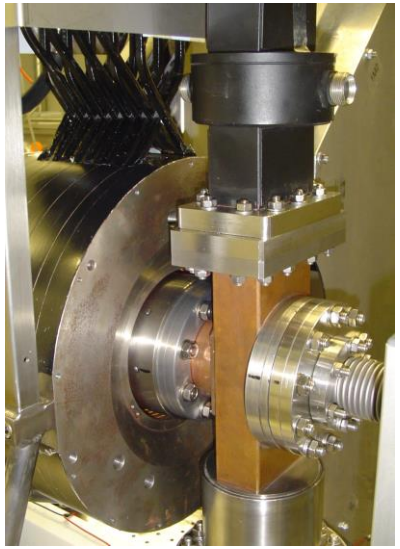
Free electron laser

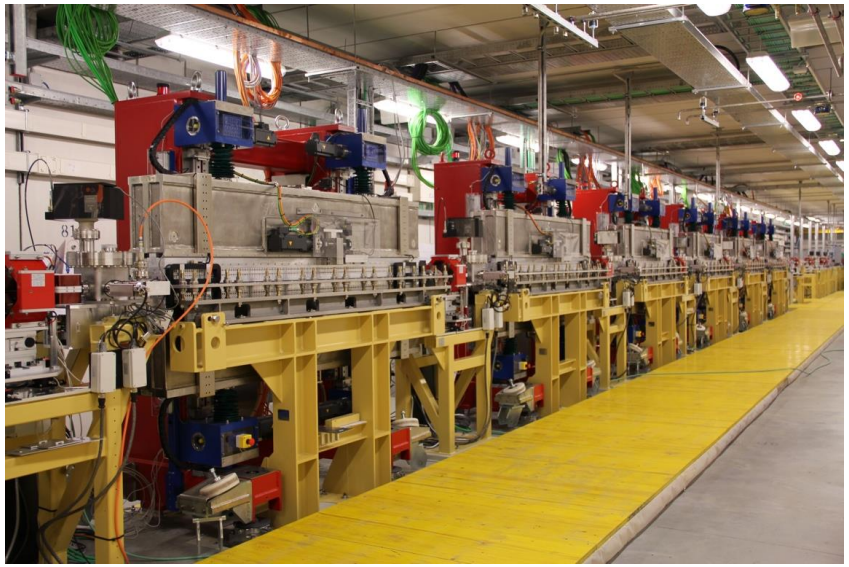
EU funded design study for next generation compact and low cost XFEL.

Compact

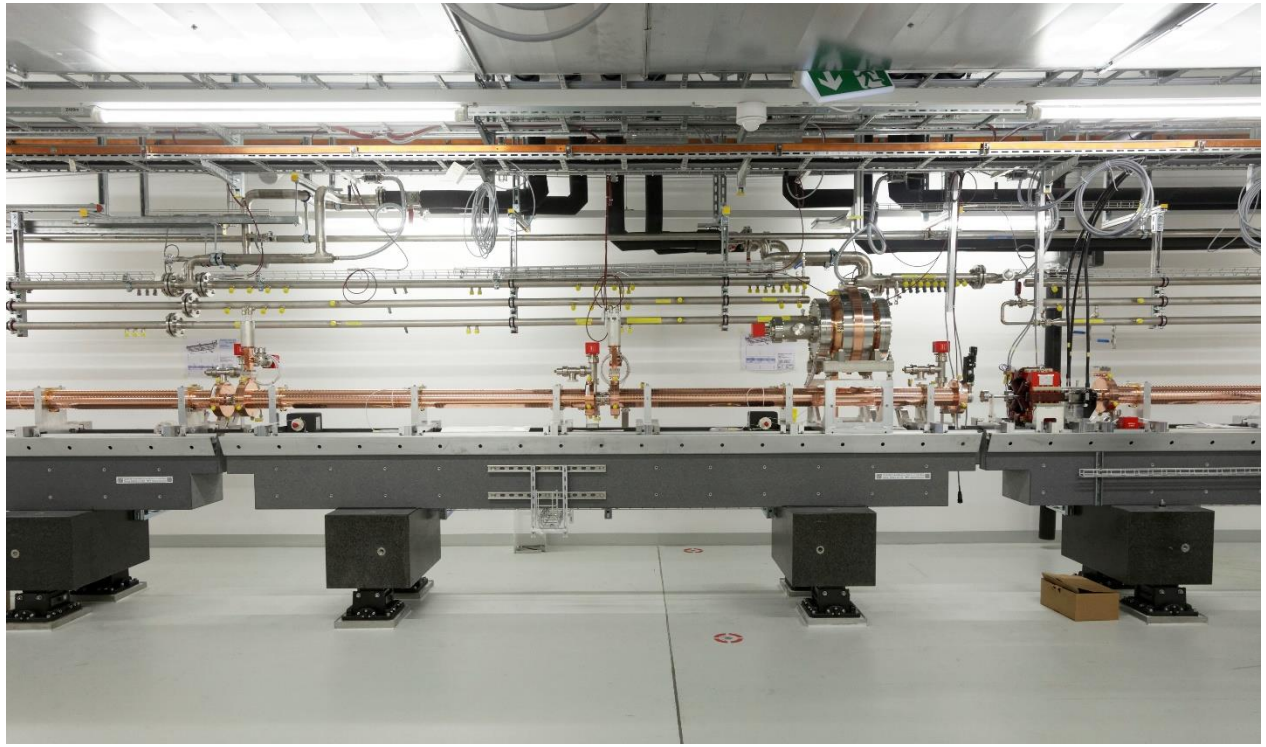
Bring together technology advances in key accelerator systems for XFEL

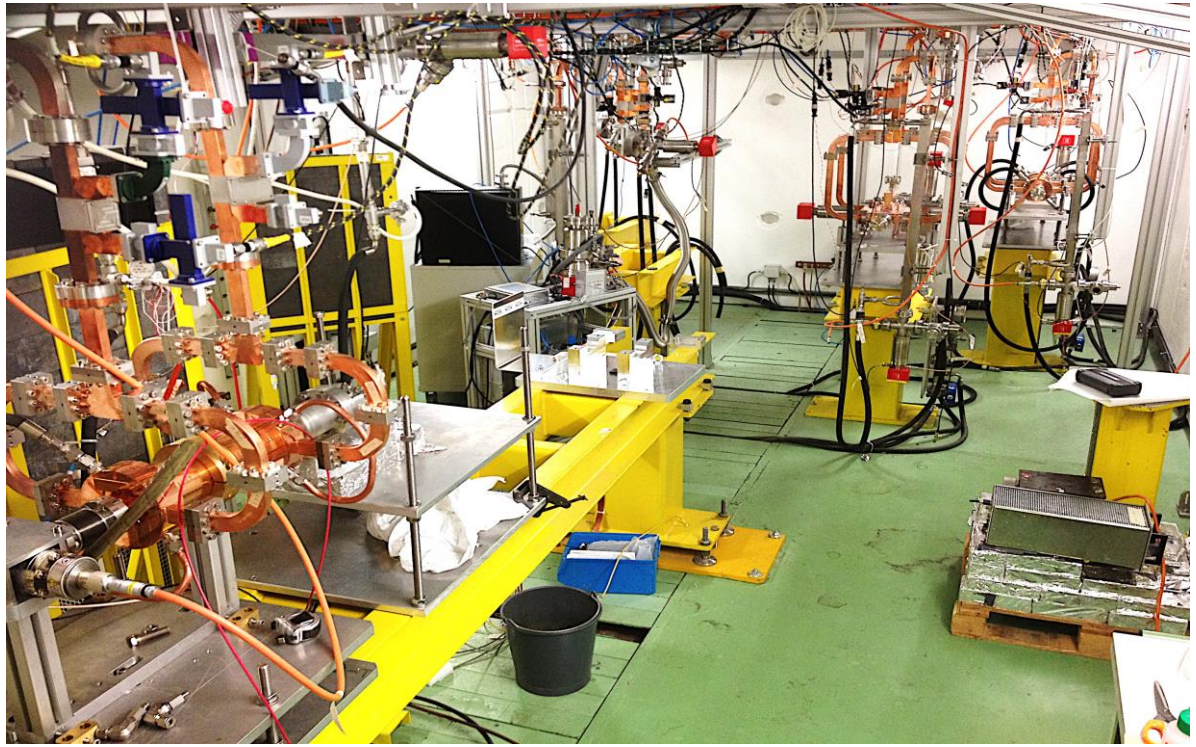






Compact





SwissFEL C-band linac:
Approximately 30 MV/m

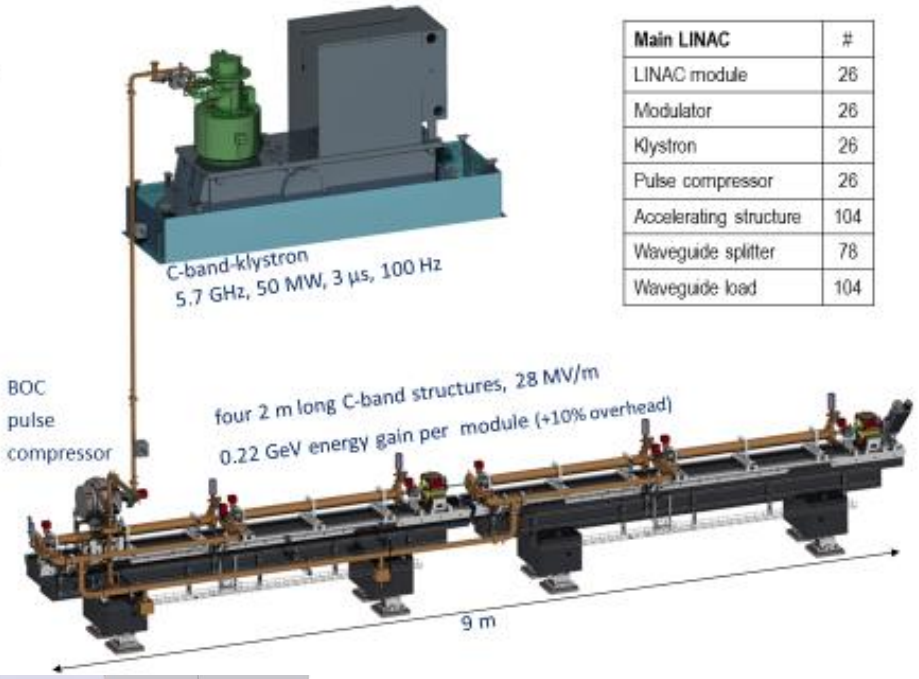
CLIC prototypes:
Over 100 MV/m

SwissFEL

- Recent implementation of a large-scale normal-conducting linac – 5.8 GeV, over 100 accelerating structures.
- Strong linear collider technology heritage and with implementation many important lessons have been learned.

SwissFEL rf unit

C-band linac modules



Main LINAC	#
LINAC module	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structure	104
Waveguide splitter	78
Waveguide load	104

Installation of last Linac girder: Sept. 13, 2016

Solid-state modulators for C-band linac

Two prototypes were tested at PSI for evaluation of the series.

50 MW / 3µs RF, 370kV / 344A / <20 ppm voltage stability pulse to pulse @ 100 Hz

AMPEGON

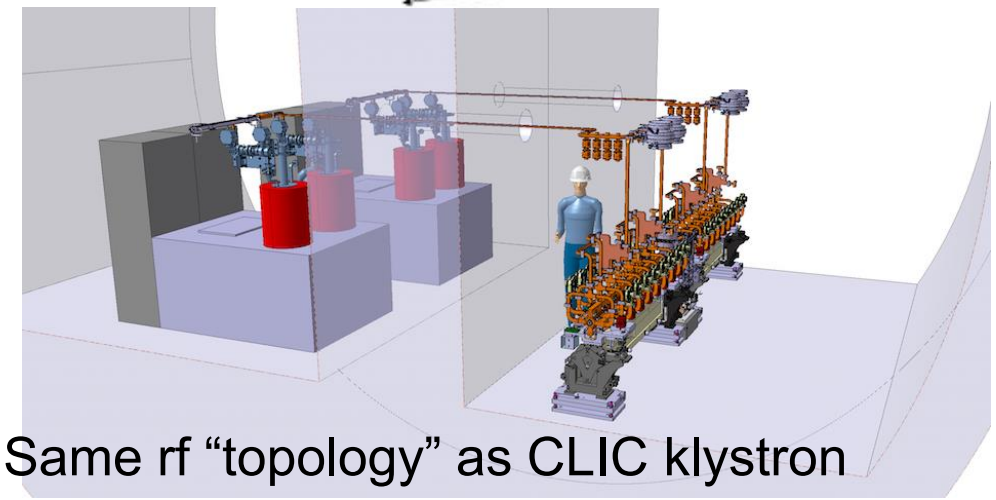
Type-µ modulator prot. for PSI C-band

- 13 modulators (Linac 1, Linac 2)
- Installation planned from Nov. 2016 – June 2017

ScandiNova

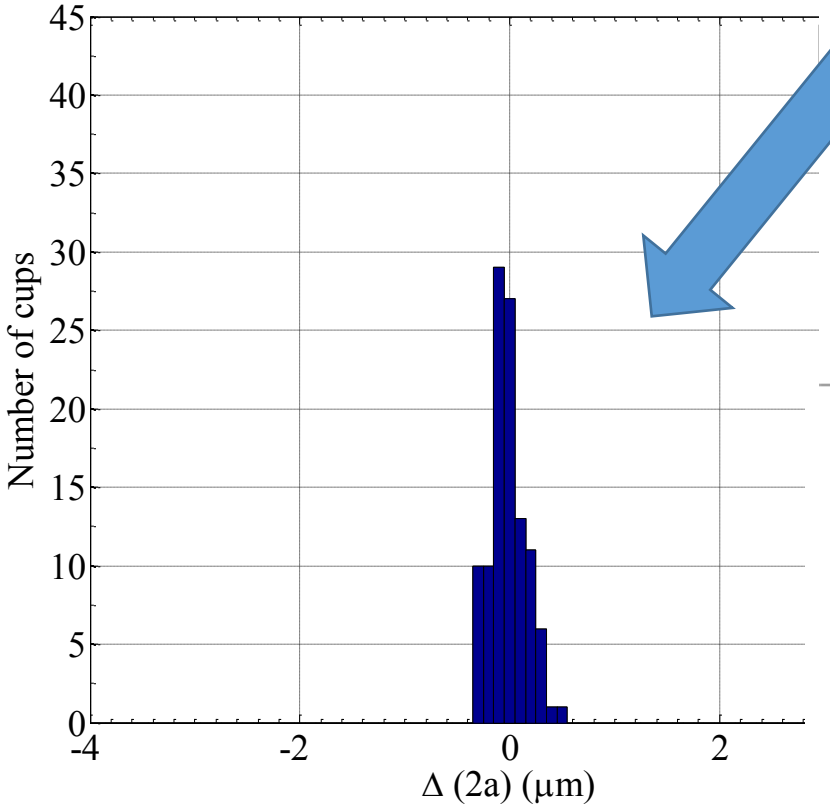
K2-3 proto. for PSI C-band

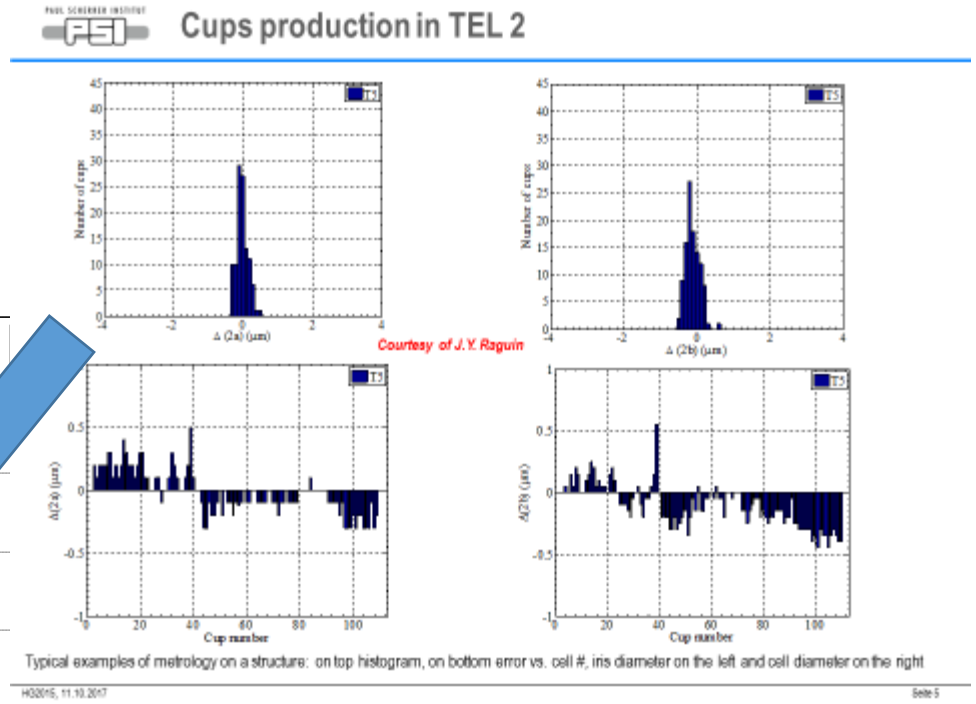
- 13 modulators (Linac 3)
- Installation planned from March 2016 – Sep. 2017

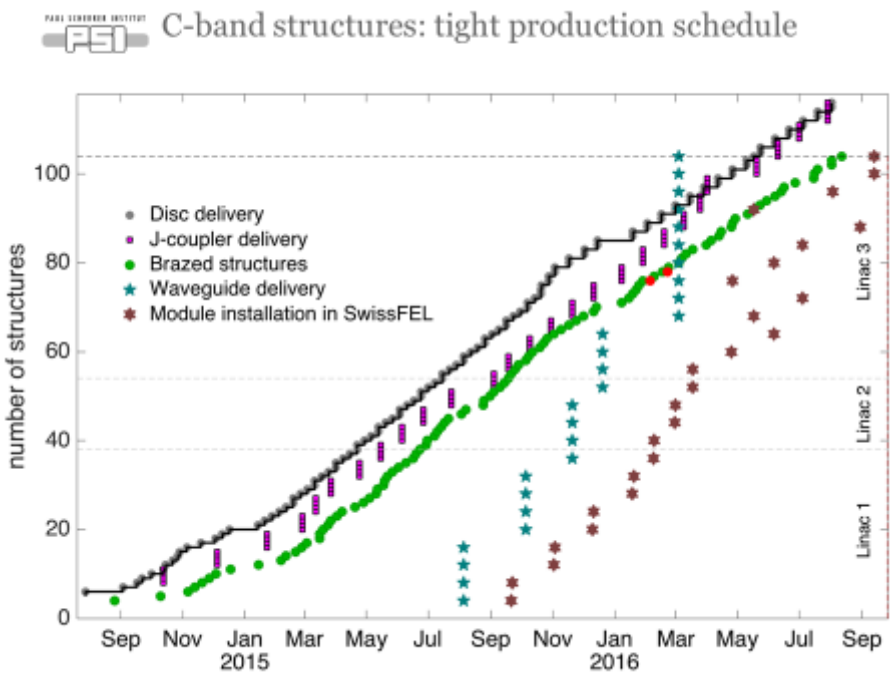


Same rf “topology” as CLIC klystron

SwissFEL micron tolerances

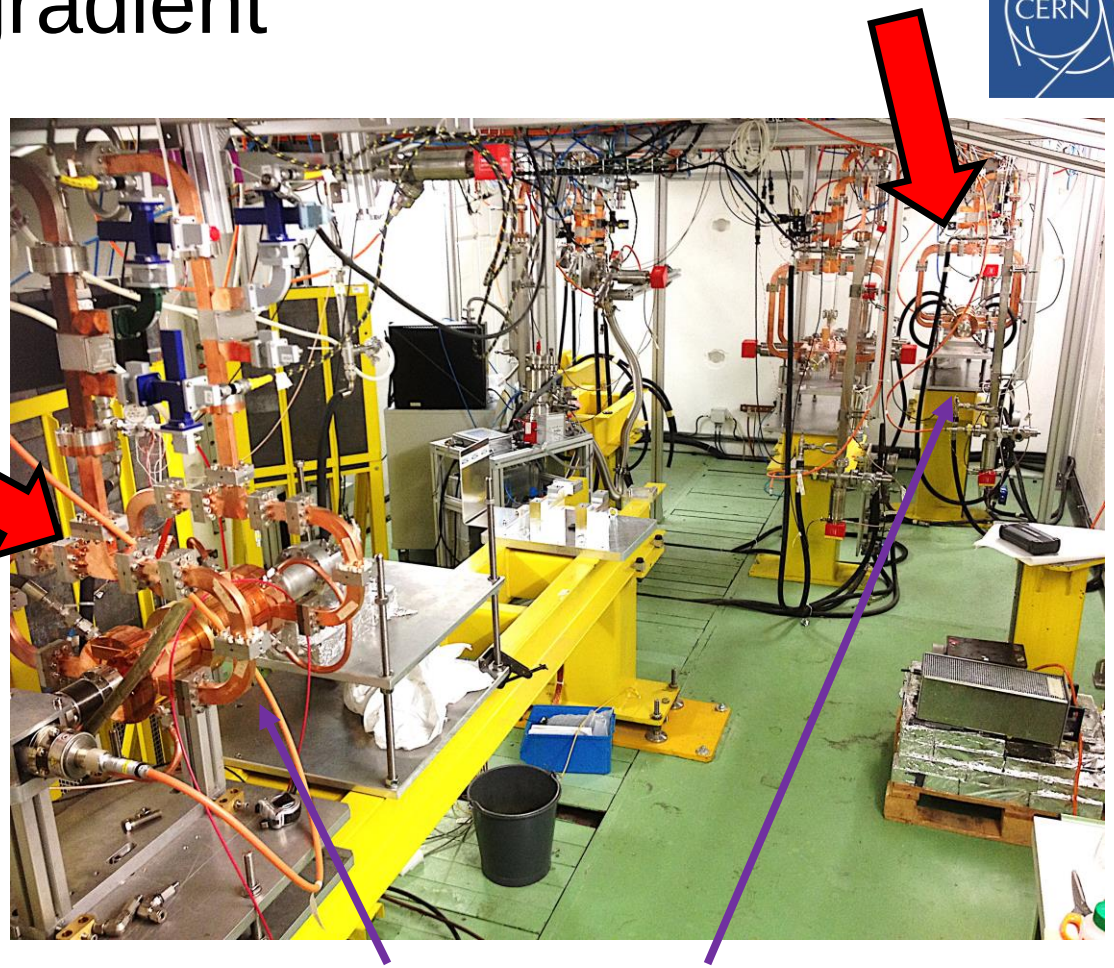






Sub-micron precision achieved in production!

SwissFEL gradient



Gradient only limited by C-band power source

Two PSI-built X-band structures installed in Xboxes – both operating over 115 MV/m.

High-gradient upgrade at FERMI, XFEL in Trieste

Elettra Sincrotrone Trieste

First prototype high gradient S-band section

GOALS

- Higher energy (1.8 GeV), 50 Hz even at high energy
- Higher peak current
- Low breakdown rate (< 1×10^{-8} bpp/m)

PRESENT LINAC ENERGY
1.5 GeV @ 10 Hz

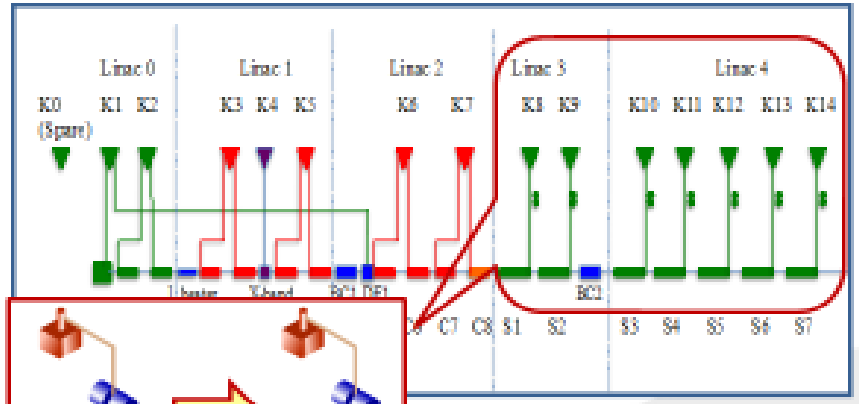
→

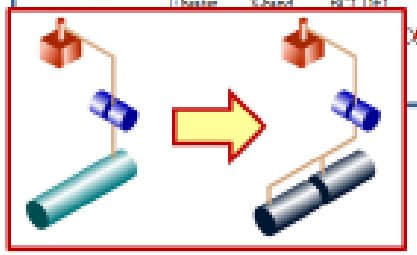
TARGET LINAC ENERGY
1.8 GeV @ 50 Hz

CONSTRAINTS

- Available space
- Active acceleration length is fixed

Linac Layout





SOLUTION
High Gradient Structures (**30 MV/m**) for replacing BTW ones

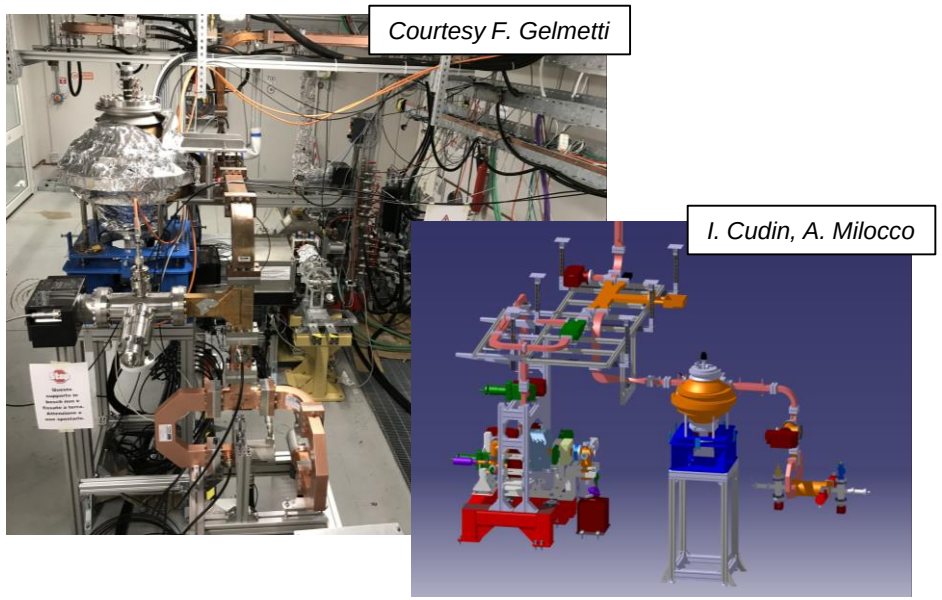
SAC–MAC Joint Meeting – 21 February 2018

Ref. C. Serpico

First prototype high gradient S-band section

A first (short) prototype is being built in collaboration with PSI.

Test Facility @ Elettra



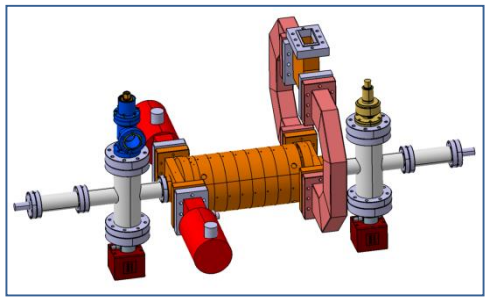
Courtesy F. Gelmetti

I. Cudin, A. Milocco

The Test Facility has been upgraded and the new RF components conditioned to 42 MW and 4.2 µs pulse width.

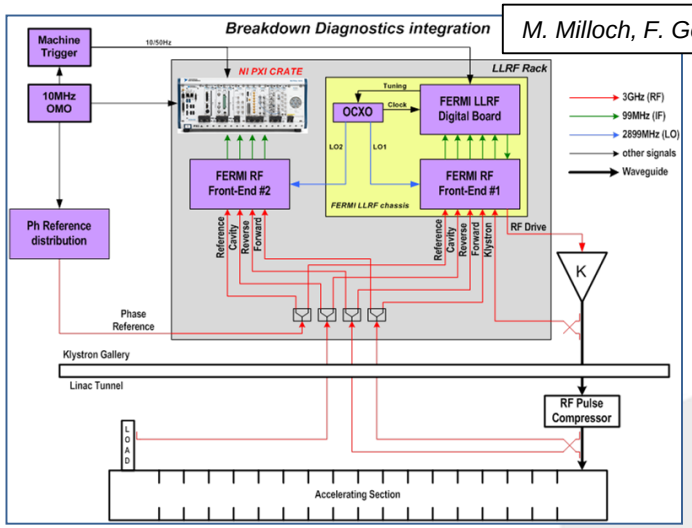
Prototype's RF conditioning up to **50 MV/m** will be possible

PSI Prototype



Test Facility Diagnostic

CERN-like breakdown diagnostic is being developed at Elettra.

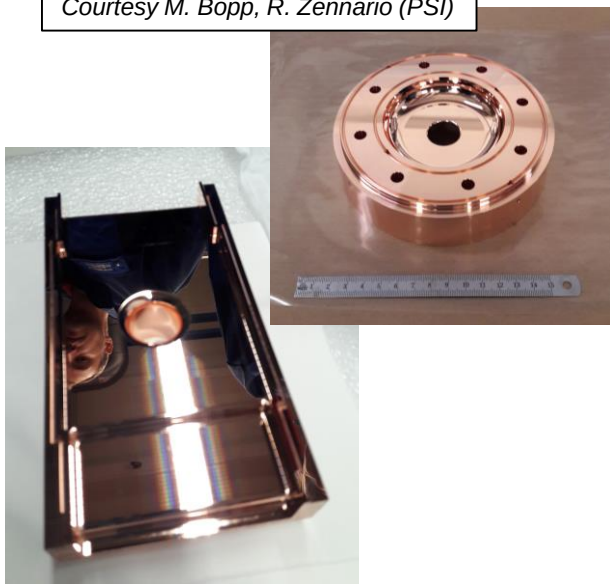


M. Milloch, F. Gelmetti

First prototype high gradient S-band section

- Short prototype of high gradient S-band section under realization at PSI. It is constructed following the recipe of the SwissFEL C-band structures.
- The prototype will be brazed by week 10 (9th of march). RF measurements in March.
- The prototype will be installed in the cavity test facility in the FERMI linac tunnel in April.
- High RF Power test at Elettra between May and August 2018 with the goal to demonstrate gradients as high as 30 MV/m at low breakdown rates (< 1×10^{-8} bpp/m).

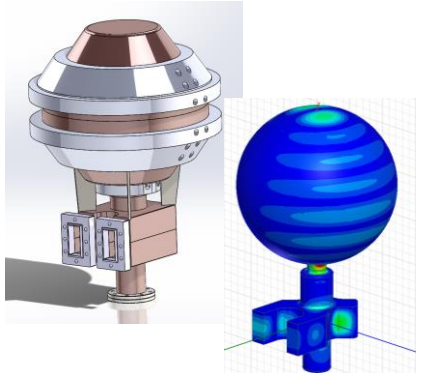
Courtesy M. Bopp, R. Zennario (PSI)



Regular Cell and Input Coupler at PSI. All components are almost ready for brazing

Meanwhile.....

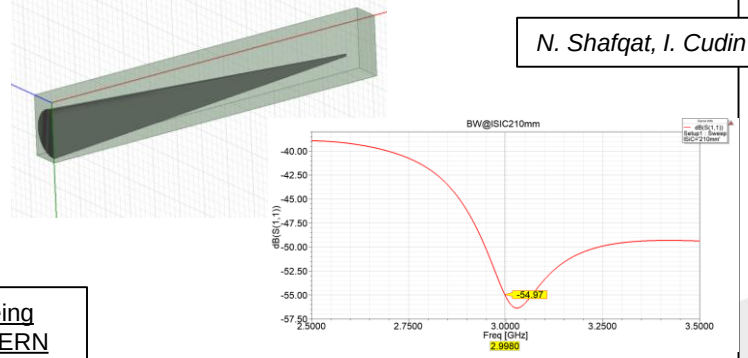
Compact Pulse Compressor based on a single-spherical cavity*



	Value	Units
Dimensions	660 x 460	mm
Op. Mode	TE113	
Q0	145000	
Beta	7	

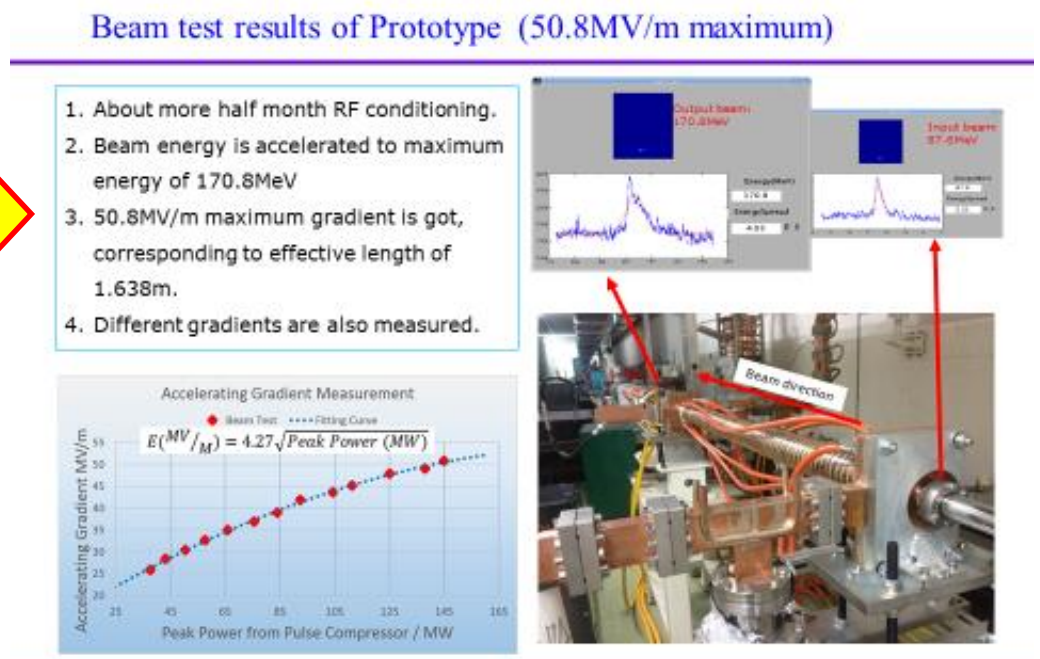
Compact S-Band Load Based on CeraSiC or EkaSiC absorbers*

N. Shafqat, I. Cudin

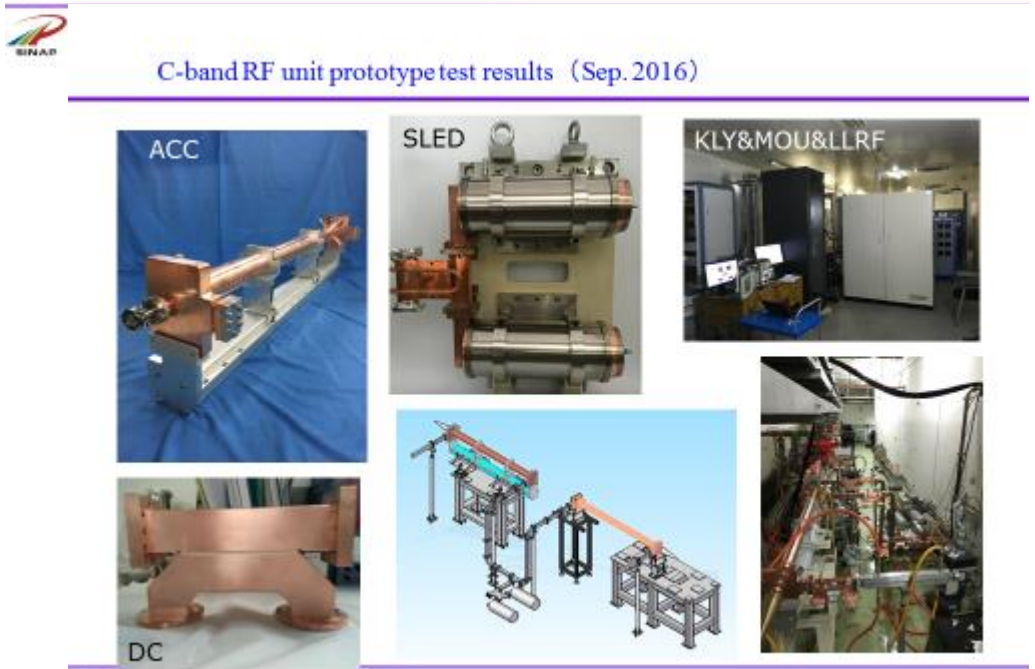


*Waveguide components are being developed in collaboration with CERN

SINAP XFEL



We will return to the X-band infrastructure later in lecture.



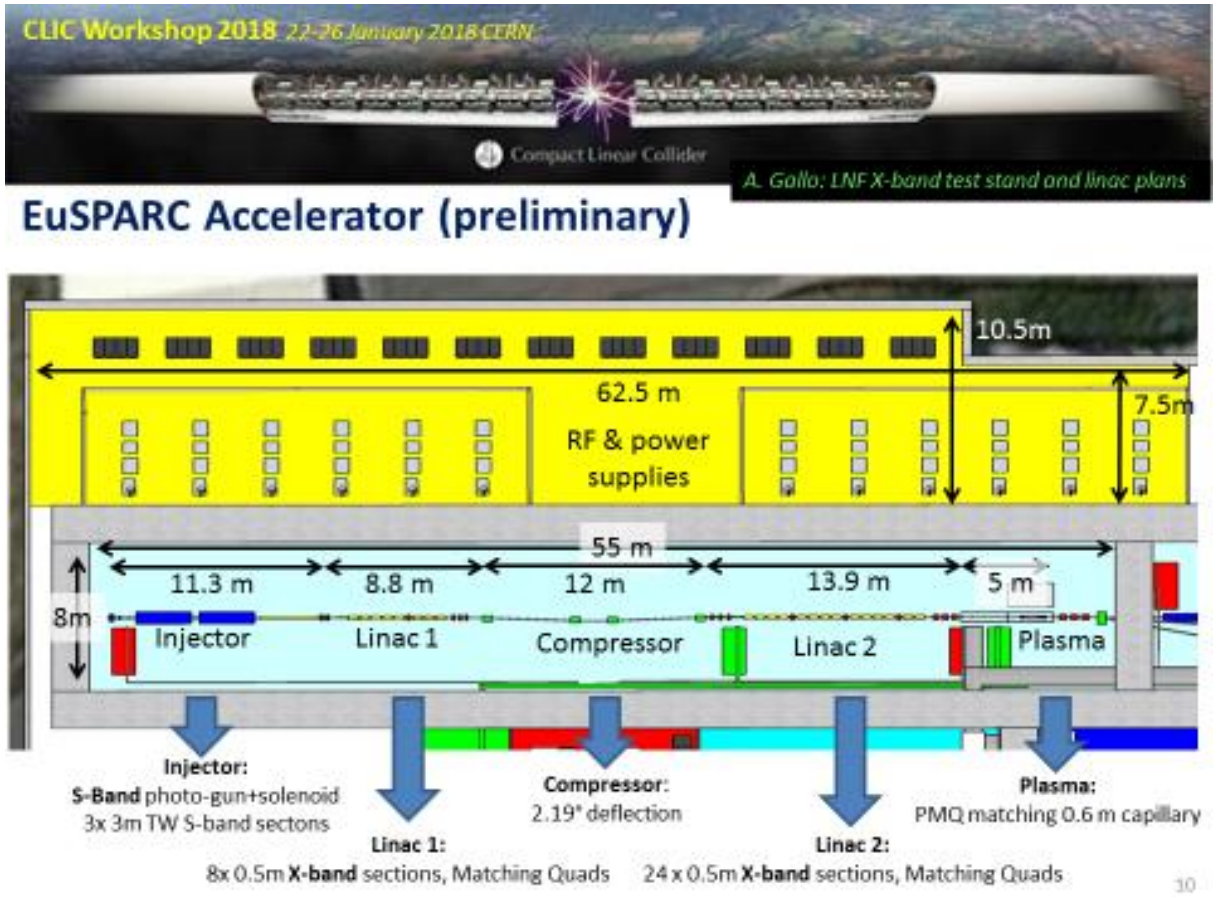
EuSPARC – electron linac facility for XFEL and plasma acceleration research

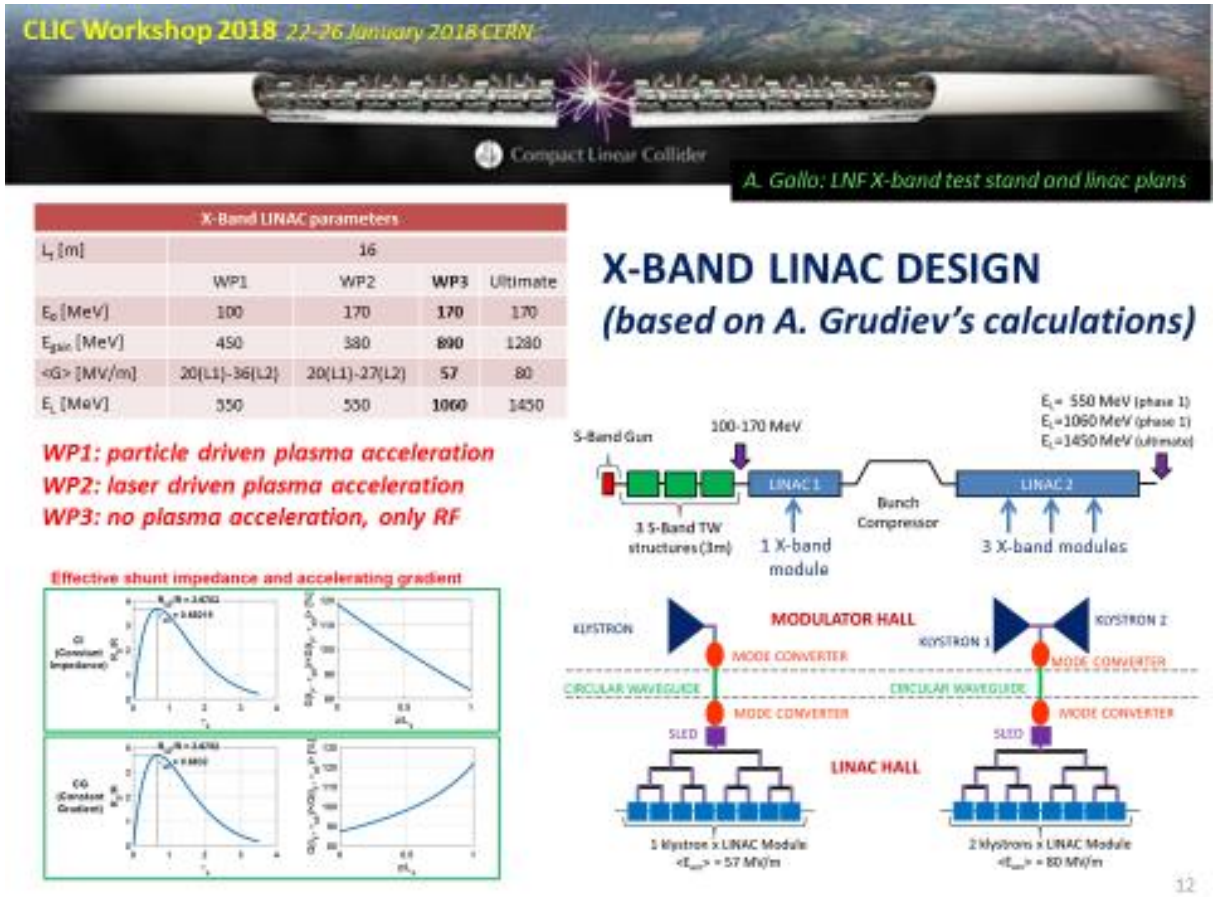
LNF X-band test stand and linac plans

Alessandro Gallo
on behalf of the INFN LNF X-band Team

EUSPARC RF / X-band Team:
D. Alesini, M. Bellaveglia, B. Buonomo, F. Cardelli, M. Diomede, G. Di Raddo, M. Ferrario, L. Foggetta, A. Gallo, A. Ghigo, S. Incremona, L. Piersanti, S. Pioli
INFN – Laboratori Nazionali di Frascati

EuSPARC 1 GeV X-band linac



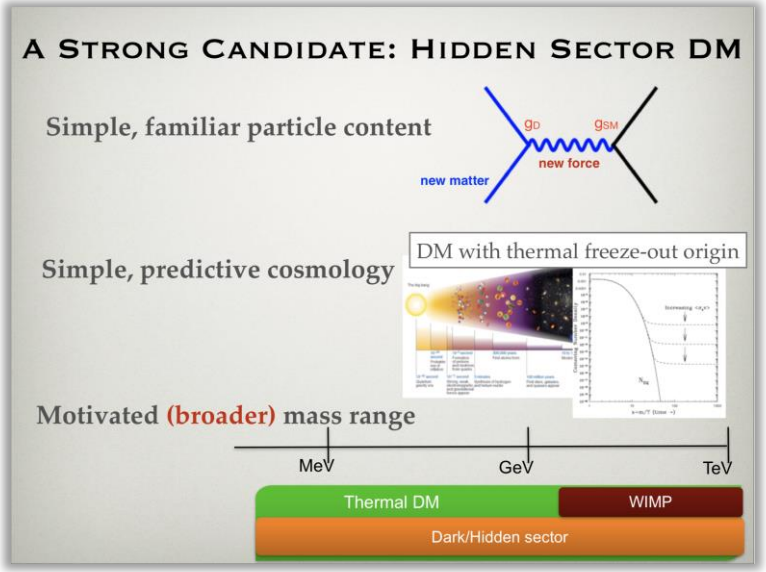


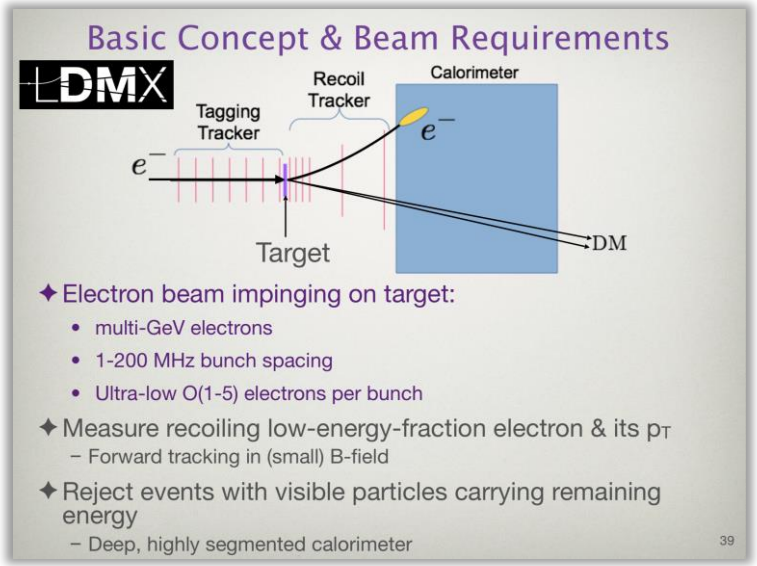
X-Band LINAC parameters				
L_t [m]	16			
	WP1	WP2	WP3	Ultimate
E_0 [MeV]	100	170	170	170
E_{gun} [MeV]	450	580	890	1280
<G> [MV/m]	20(L1)-36(L2)	20(L1)-27(L2)	57	80
E_L [MeV]	550	550	1060	1450

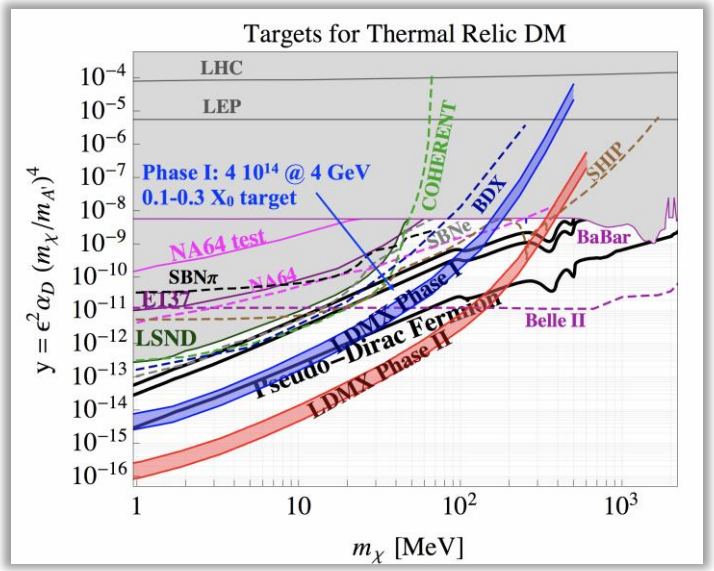
XFEL and advanced acceleration development test facility at INFN Frascati.
Based on 1 GeV, X-band, short bunch, low emittance linac.

Getting ready – X-band test stand

Physics with e-beams, example LDMX



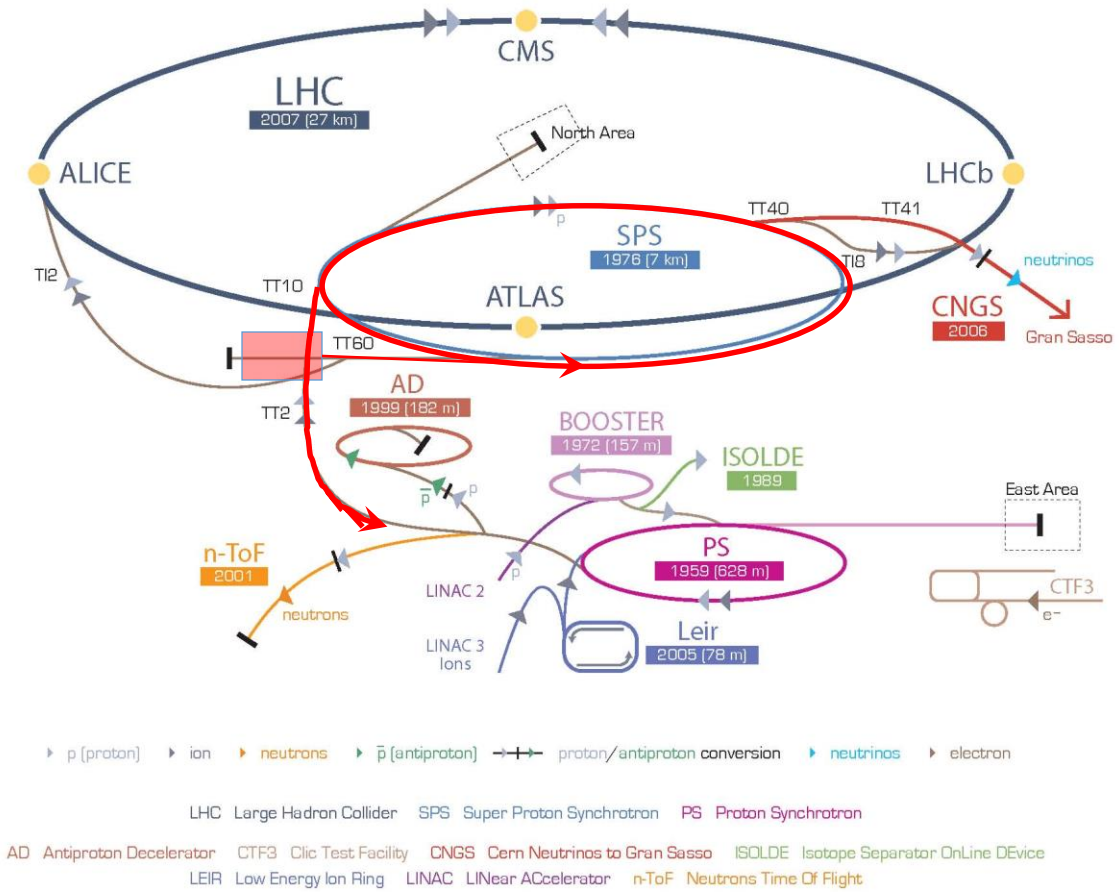




Talk by P. Schuster
"Physics Beyond Colliders" Nov 21, 2017

S. Stapnes

An e-beam facility at CERN



Accelerator implementation at CERN of LDMX type of beam

X-band based 60m LINAC to 3 GeV in TT4-5.

- Fill the SPS in 2s (bunches 5ns apart) via TT60
- Accelerate to ~10 GeV in the SPS
- Slow extraction to experiment in 10s as part of the SPS super-cycle
- Experiment(s) considered in UA2 area or – better - bring beam back on Meyrin site using TT10

Beyond LDMX type of beam:

Other physics experiments can be considered (for example heavy photon searches)

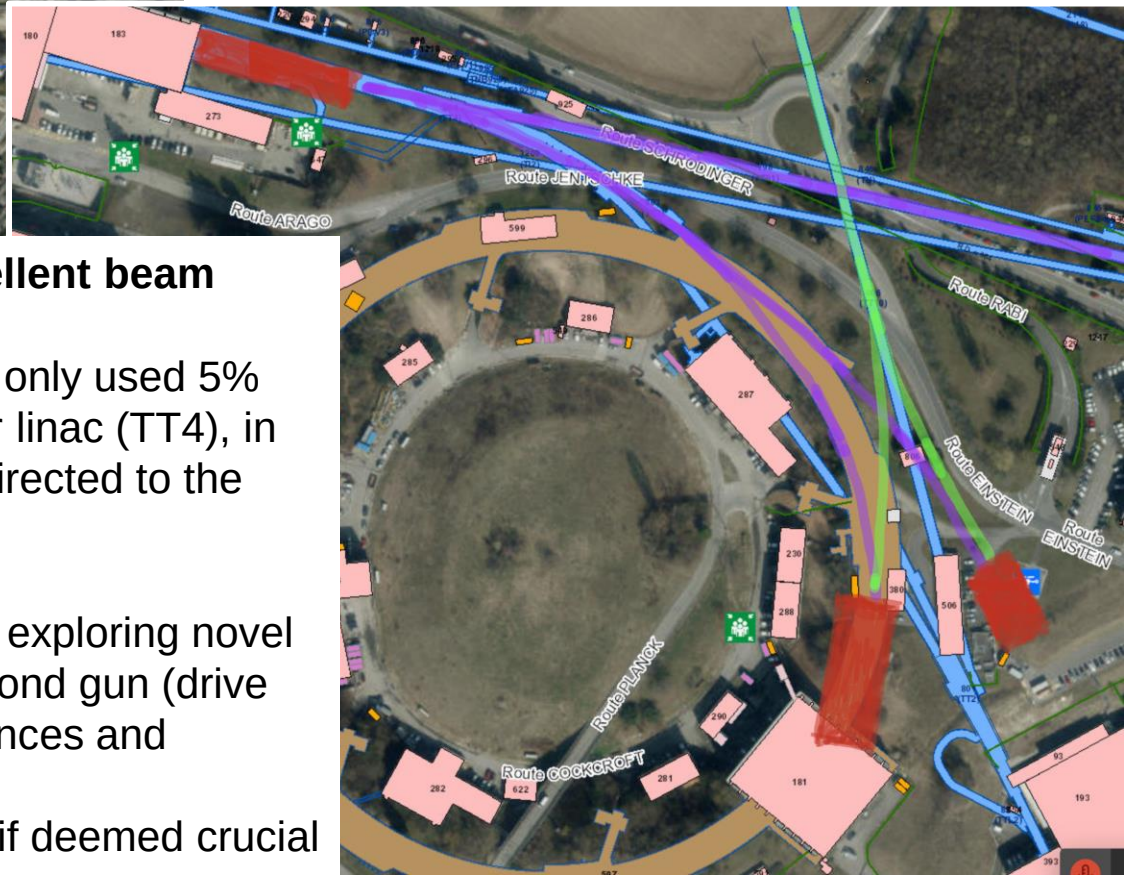
Several other possible uses of linac and SPS beams for R&D

Four/five users groups:

- Physics
- CLIC TDR overlap large
- e-AWAKE
- CLEAR(er)
- DR, positrons and ATF-like studies (possible)

GREEN: ~10+ GeV electron beam in SPS
Acc. in SPS, can also be a damped small emittance beam. Long bunches.

- Extracted to Meyrin side for LDMX like experiment.
- Can also – possibly – be guided to AWAKE.
- Other uses, either extracted or circulating to be worked out.

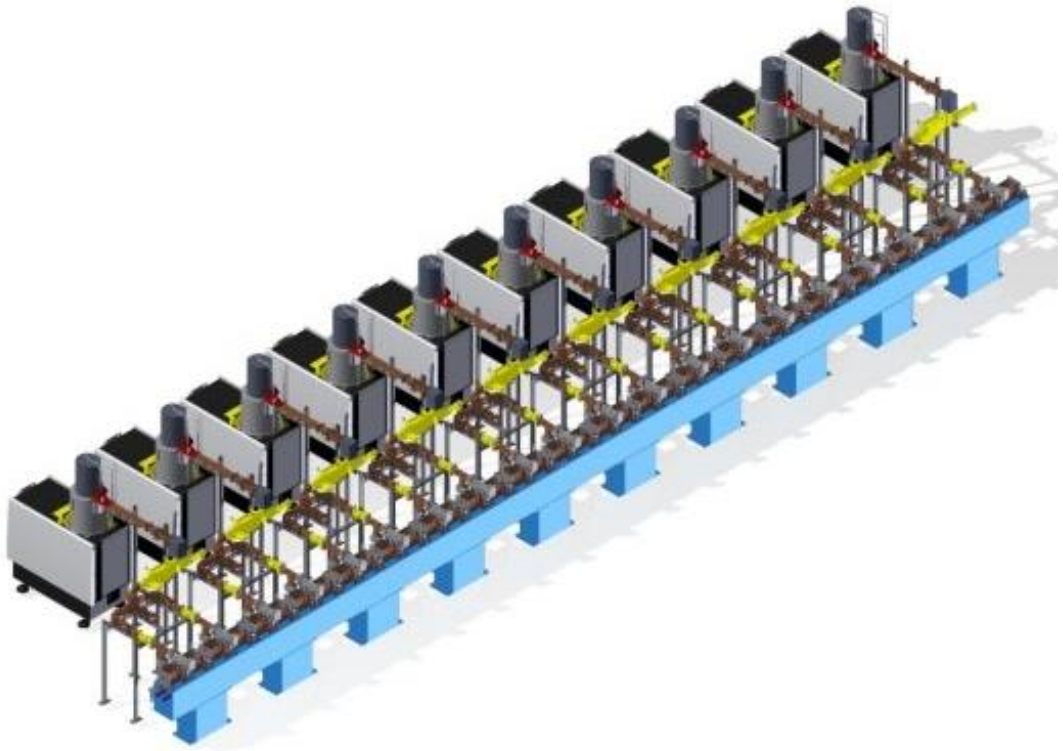


PURPLE: 3 GeV x-band linac with excellent beam quality
Short bunch electrons from X-band linac, only used 5% for filling the SPS. Can be used right after linac (TT4), in new experimental area, and/or possibly directed to the current AWAKE area.

- CLEAR type of research progamme.
- Electrons for drive and/or probe beam exploring novel accelerating techniques, including second gun (drive and probe bunches with variable distances and charges).
- Longer term possibilities for positrons if deemed crucial

S. Stapnes

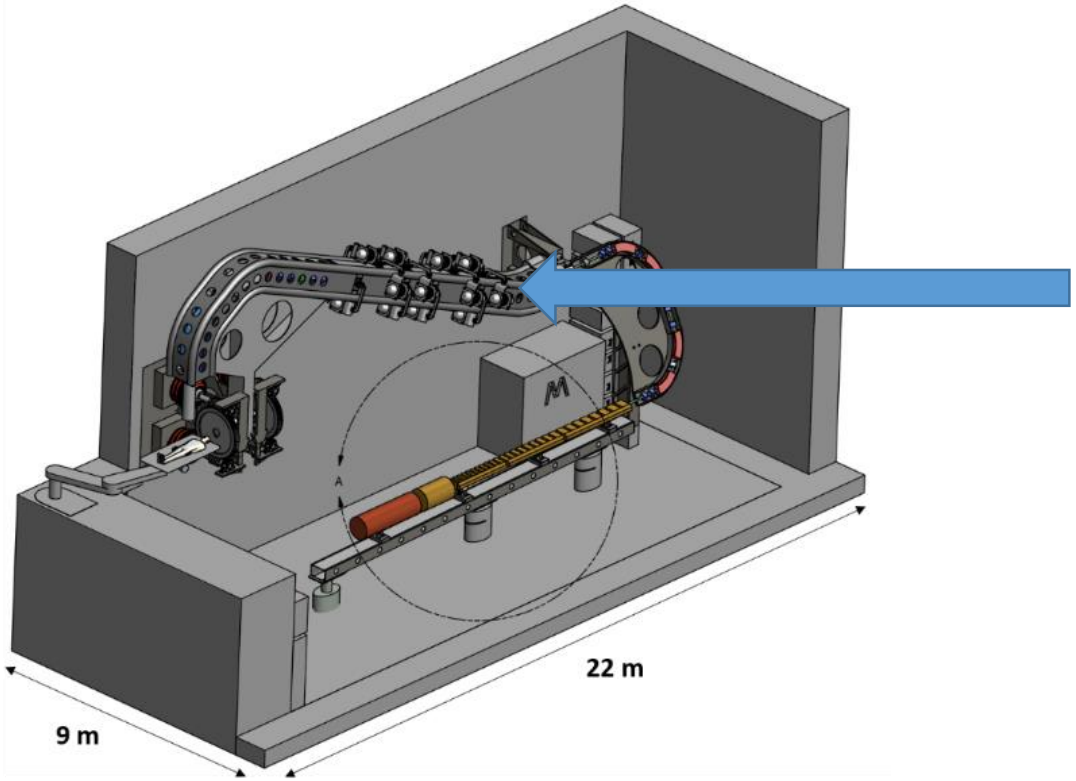
Medical accelerators – proton therapy

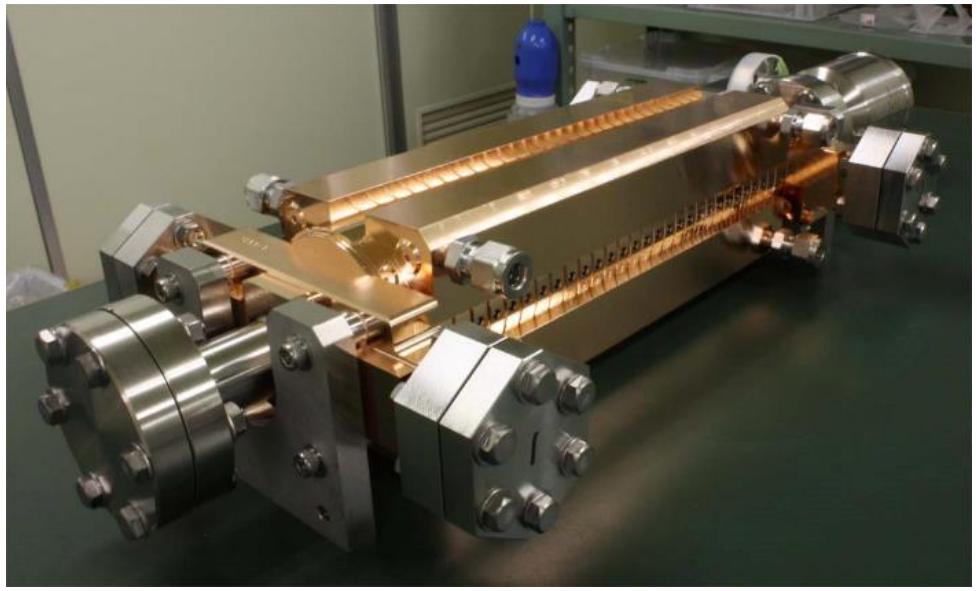


State-of-the-art and market leader: IBA superconducting synchrocyclotron (image taken from IBA website).

Can a linac based solution be competitive? ADAM is trying. Offers distinct advantages: pulsed with fast energy variation for tumor painting, follow body motion, cost (image taken from ADAM website).

The TULIP example

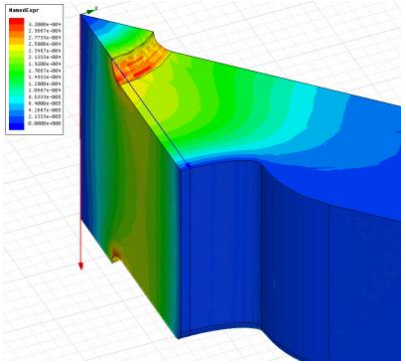


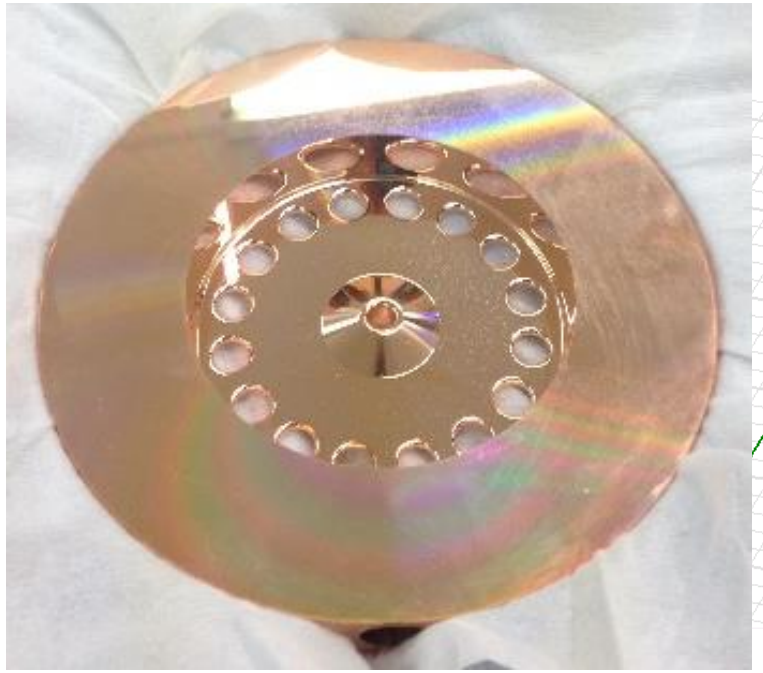


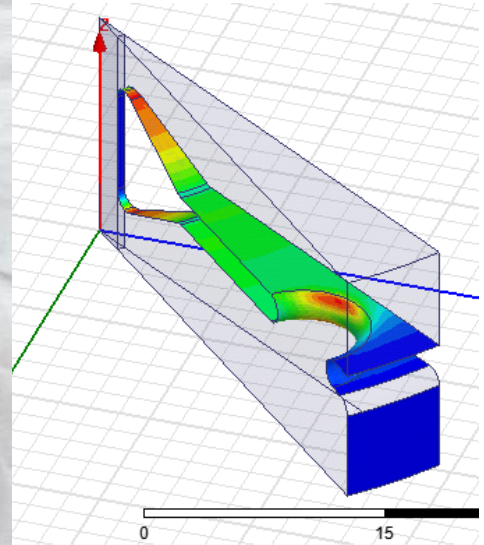
By applying CLIC high-gradient technology, we think we can raise the accelerating gradient from the <20 MV/m in LIGHT to 50 MV/m, making single room facilities like TULIP possible.

What's the ~~problem~~ challenge?

Our electron linac technology is for particles moving near the speed of light.
Protons and ions in a medical linac need to be accelerated when they are still moving slowly, in the range of half the speed of light.



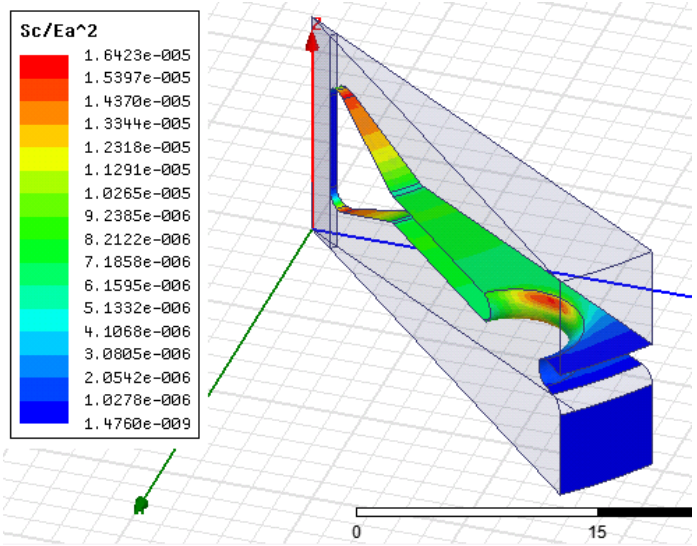


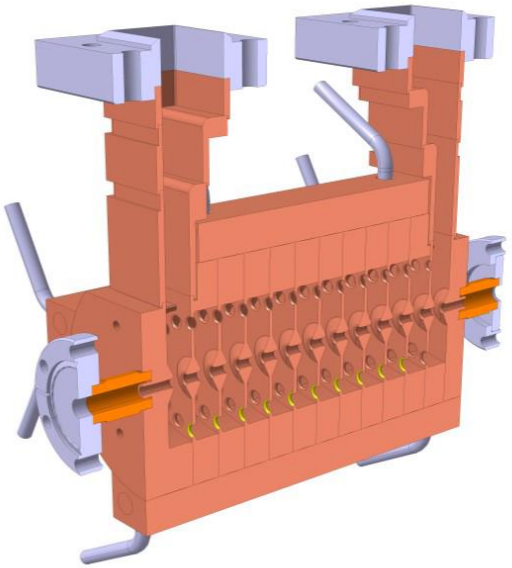


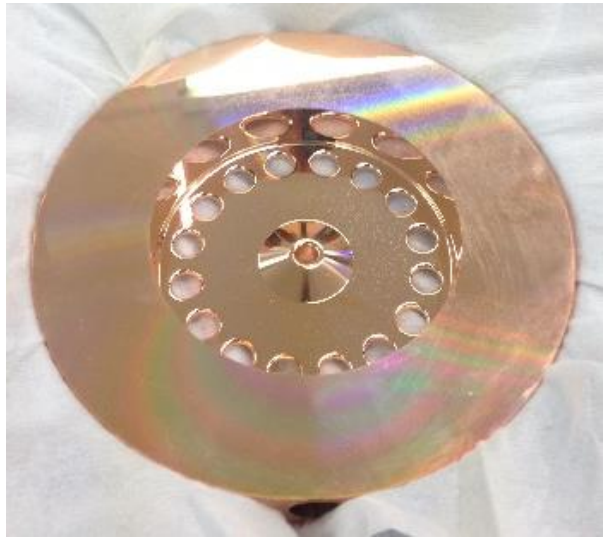
For relativistic electrons/positrons, β=1:
100 MV/m

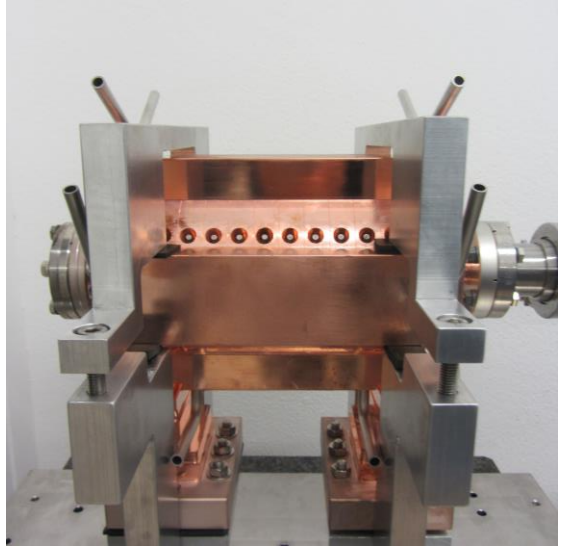
For β=0.38:
50 MV/m
Hard to extend this to lower β, higher is easy.

Let’s give it a try



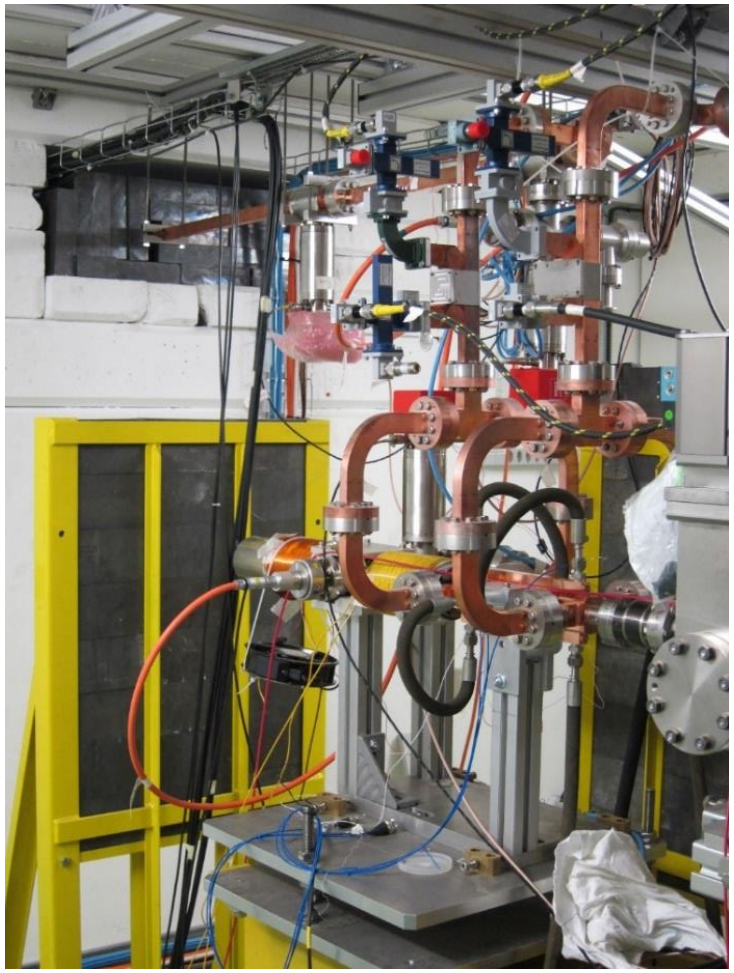


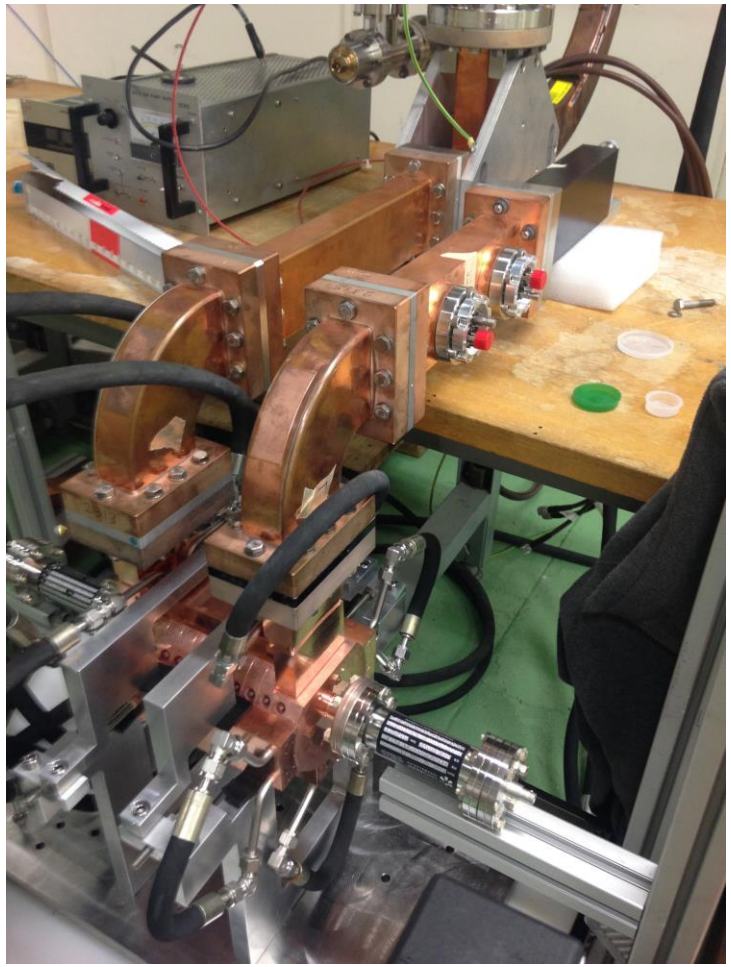




- CERN KT fund accepted our application for funding to build two such structures based on CLIC design, fabrication and operation technology.
- CLIC study members designed and are testing the structures (we get important data on high-gradients from these tests).
- Two have been built and the first is under high power test.

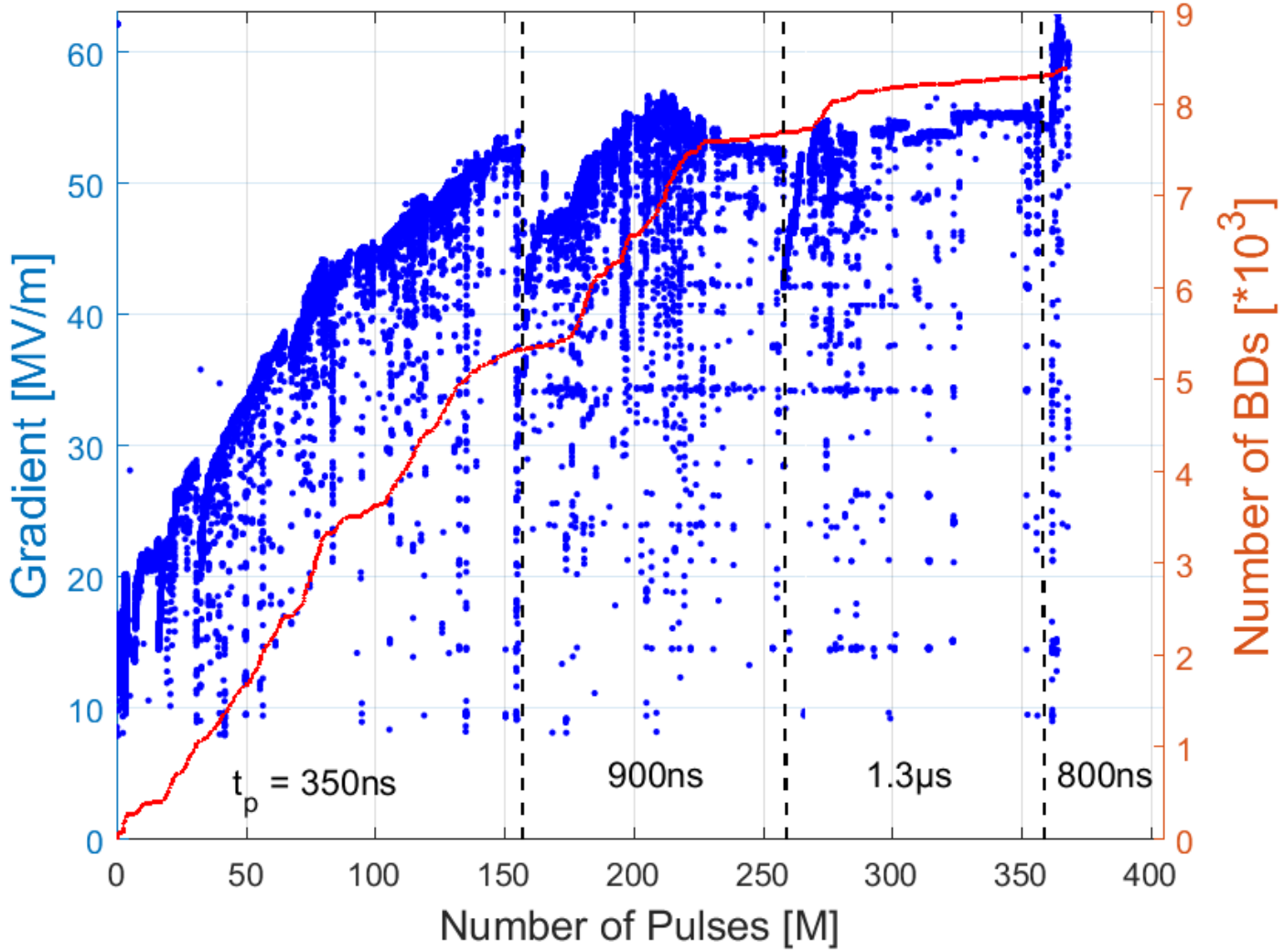
High-gradient testing



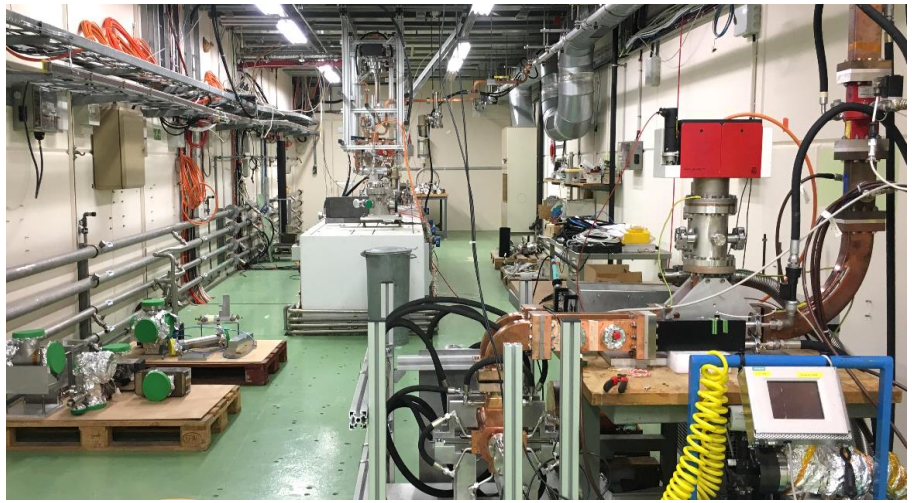


We have adapted and used experience, diagnostics, software and algorithms from the CLIC high-gradient program.

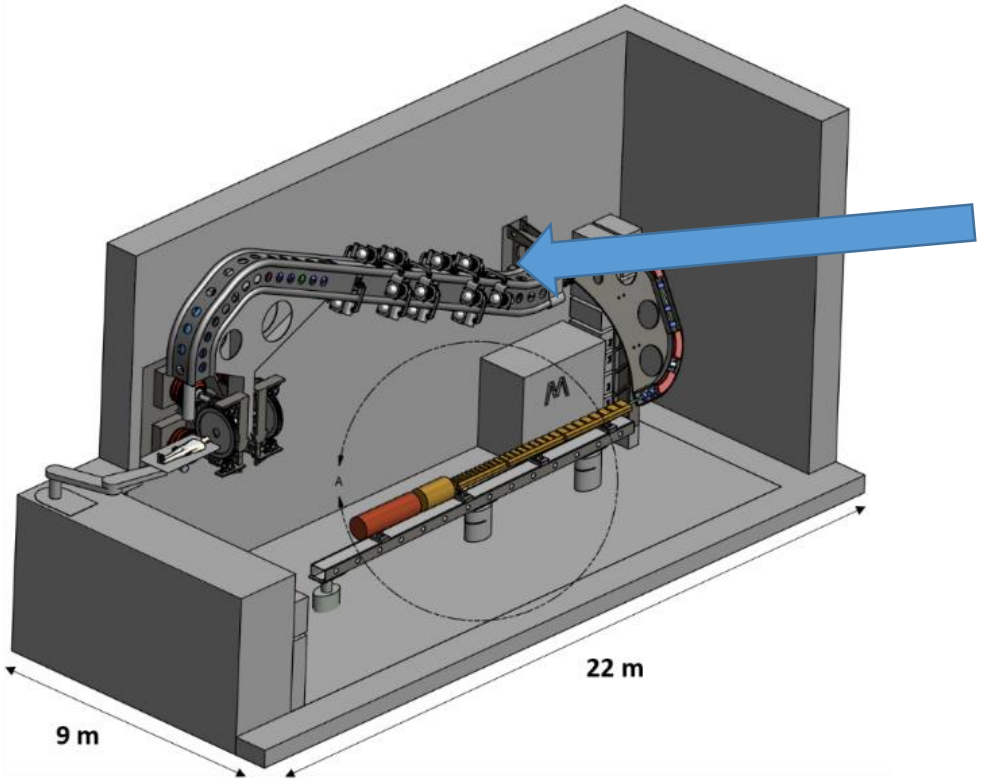
Conditioning status of the high-gradient medical linac structure

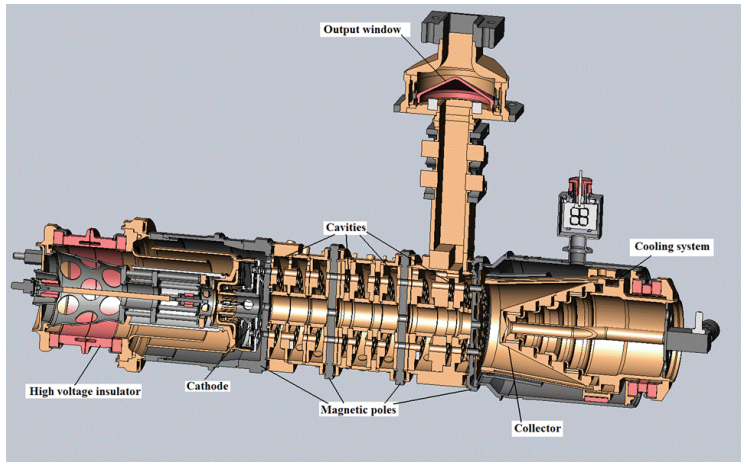


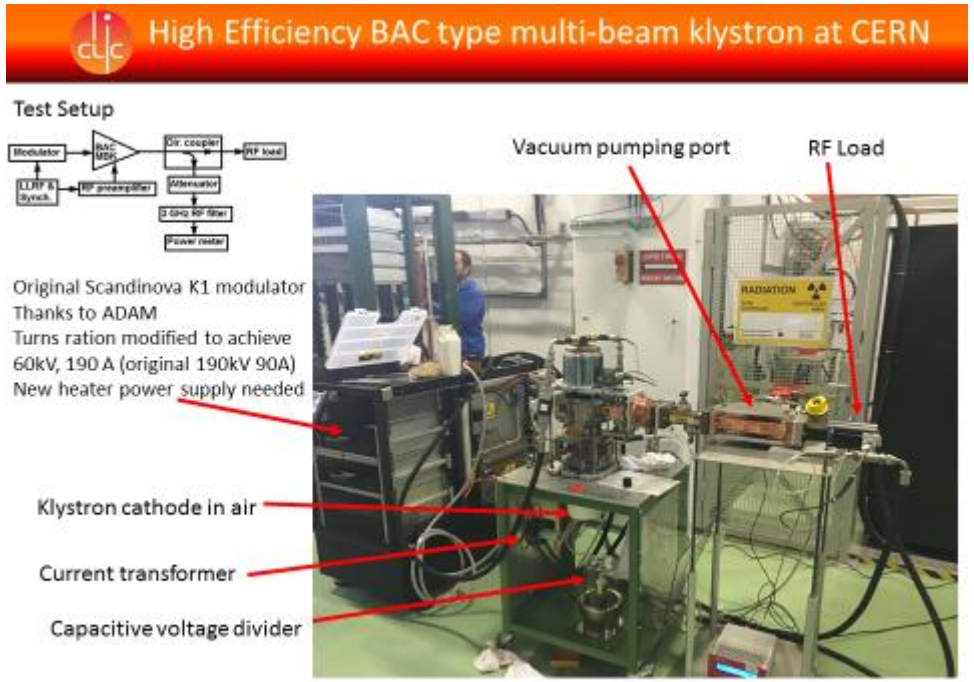
β=0.38 c, 50 MeV/m expected
Just passed 60 MV/m, testing continues.
We are very excited!
2nd structure is complete and ready to go.



Additional element: High-efficiency power source







Radio-frequency power source efficiency is also a crucial issue for CLIC.
3 GHz, > 60% efficiency, 70 kV klystron built by VDBT.
Has potential to reduce investment and operating cost.

More – proton radiography

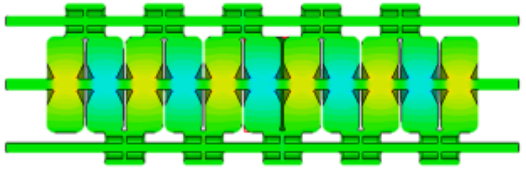
PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

Sam Pitman
Dr Graeme Burt
Dr Hywel Owen
Dr Robert Apsimon

FINAL STRUCTURE

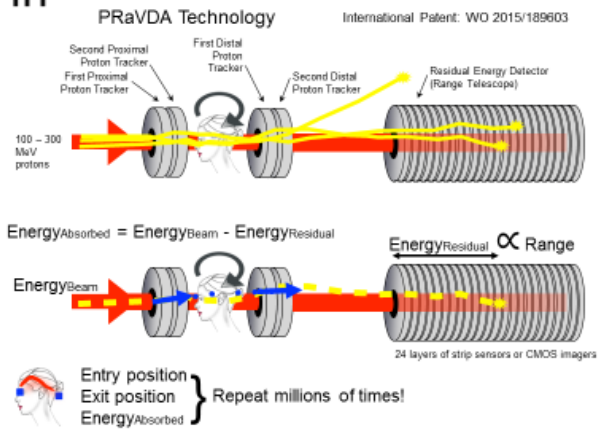
- 3 GHz- S-Band
- Side coupled 54MV/m
- Aggressive gradient limits
  - Epeak < 200MV/m
- Thin septum (2mm)
- π/2 mode
- 11 cell prototype cavity
- β=0.59

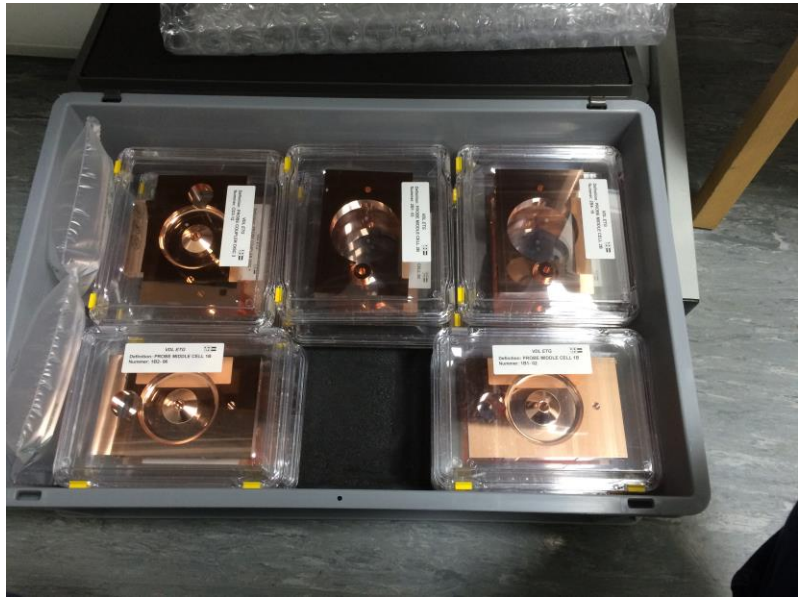
Parameter	Units	S-Band SCSWS
Phase adv.	[deg]	90
Cell Length	[mm]	29.8
Coupling Factor	[%]	2.16
Rs/L	[MΩ/m]	76
$\sqrt{Sc}$/Eacc	[$\sqrt{W}$/MV]	2.4e-2
Eacc	[MV/m]	54
Hpk	[kA/m]	254
Epk	[MV/m]	200



PROTON TOMOGRAPHY

- Several modalities can aid range verification.
- CT currently used for treatment planning – conversion from Hounsfield units produces error.
- Proton imaging measures proton stopping power.
  - Prompt Gamma also measures this.
- 250 MeV sufficient to image children and heads.
- Need 350 MeV protons to image through anybody, Bragg peak must not occur inside patient.





The sincerest form of flattery

radiabeam SYSTEMS

10th International workshop on high-gradient acceleration, Valencia, Spain

High-gradient low-β structure based on acceleration with the first negative spatial harmonic

Sergey V Kutsaev

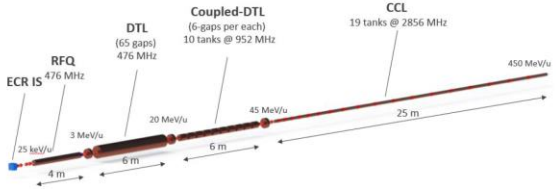
June 15, 2017

* This work was supported by the U.S. Department of Energy, Office of High Energy Physics, under Accelerator Stewardship Grant, Proposal No. 0000219678 and STTR grant DE-SC0015717

Carbon Therapy Linac

radiabeam SYSTEMS

- An Advanced Compact Carbon high gradient Ion Linac (ACCIL) is being developed by collaboration of Argonne National Laboratory and RadiaBeam Systems



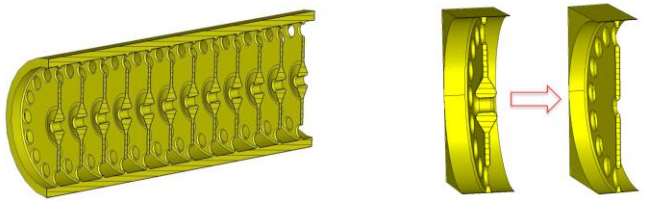
- ACCIL must provide 1 GV accelerating voltage in a 40m length
- To achieve this footprint, ~35 MV/m real-estate gradients and 50 MV/m accelerating gradients are required.
- The project goal is to develop a 50 MV/m β=0.3 structure

June 15, 2017 High-gradient low-β structure based on acceleration with the first negative spatial harmonic 8

Low beta structure for ACCIL

radiabeam SYSTEMS

- We used CERN TULIP backward travelling wave (BTW) as a reference*



- We found that at β~0.4, the required peak surface field is ~200 MV/m to sustain 50 MV/m accelerating gradient
  - Reducing these fields lead to 160 MV/m lead to a significant shunt impedance drop
- Different approach is required for β=0.3 section

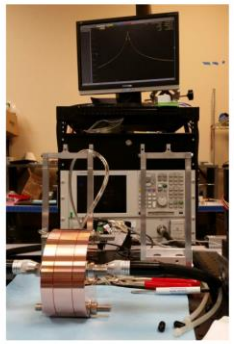
* S. Benedetti, A. Degiovanni, A. Grudiev et al., Proceedings of LINAC2014, Geneva, Switzerland.

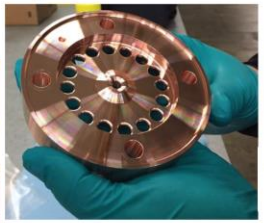
2016/06/07 High Gradient S-band Accelerating Structure for Hadron Therapy Linac 10

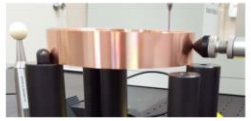
Test Cell Fabrication

radiabeam SYSTEMS

- The single test cell was fabricated to develop the machining capabilities and verify that the achieved tolerances are plausible



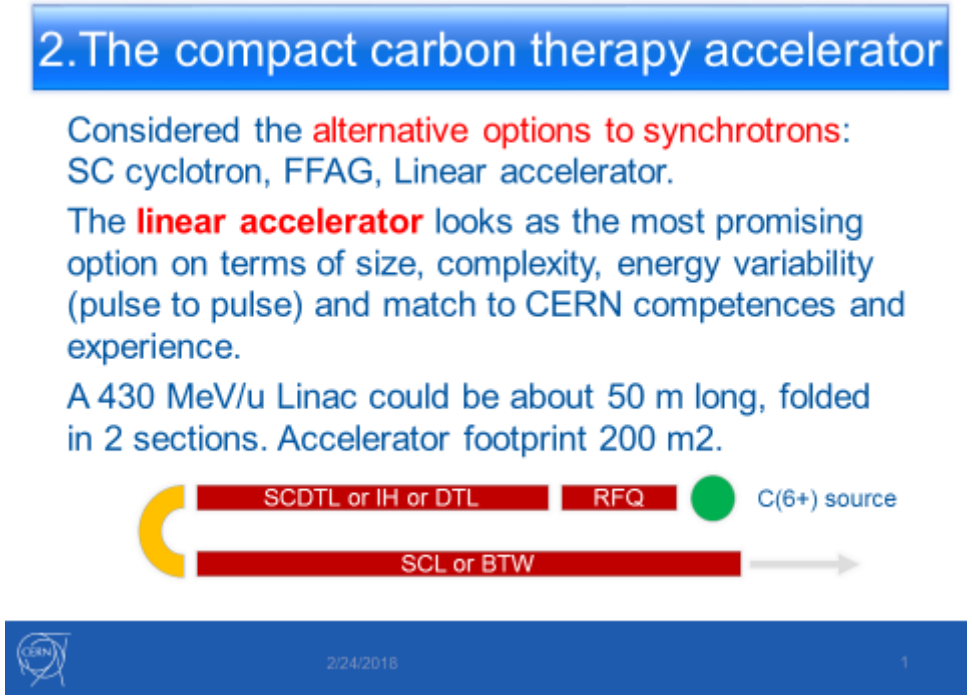


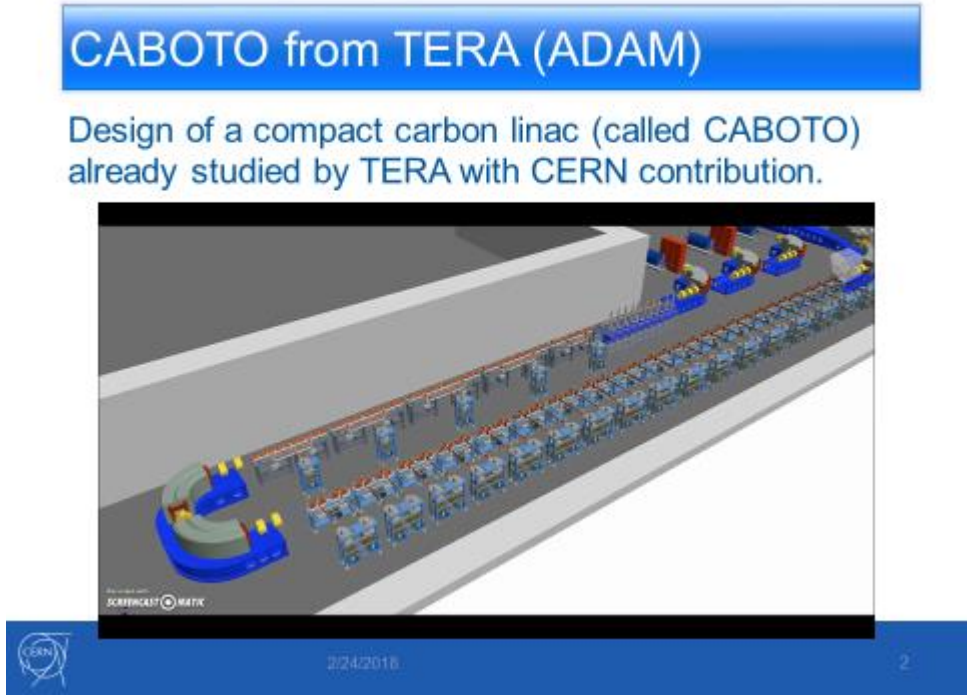


Parameter	CST (Vacuum)	Measurements w/ corr to vacuum
π-mode freq, MHz	2856.11	2855.06
Q-factor of π-mode	4700	4300 (w/ end caps)

June 15, 2017 High-gradient low-β structure based on acceleration with the first negative spatial harmonic 19

And back at CERN – PIMS2



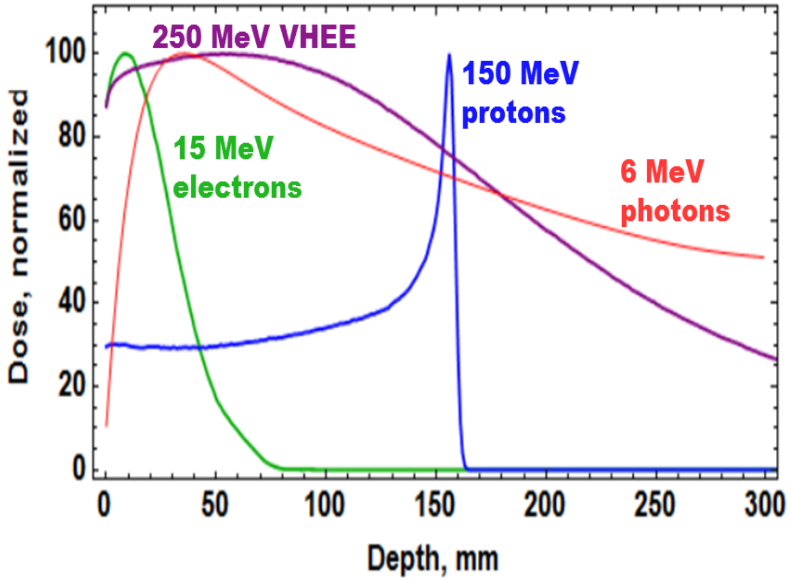


M. Vretenar

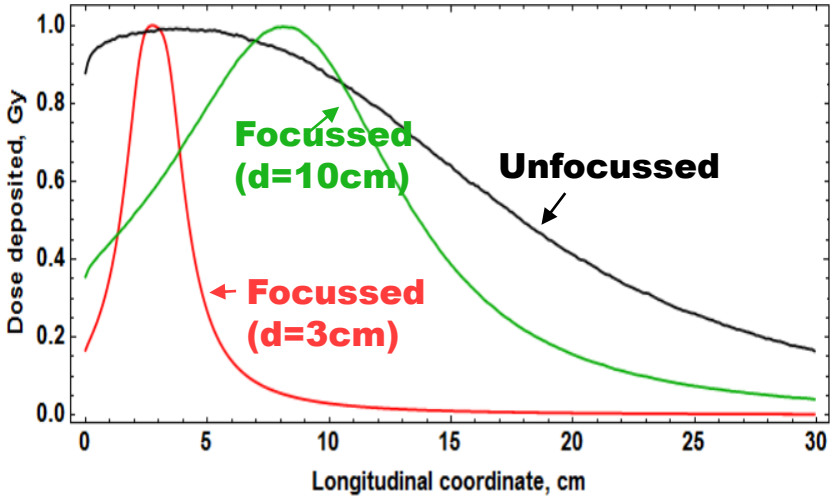
Carbon ion therapy - Another potential application of high-gradient technology? PIMS2 project recently approved.

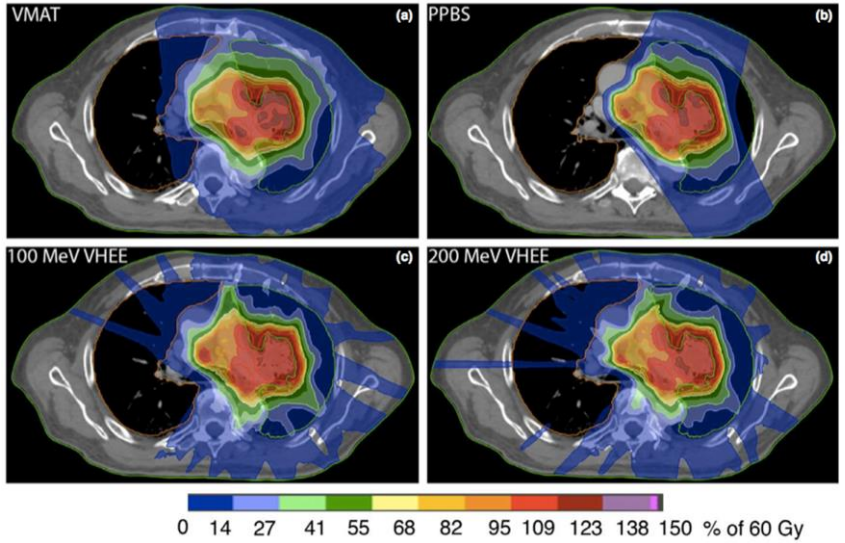
A new direction - VHEE

Very High Energy Electron (VHEE) therapy to complement existing X-ray, proton, and ion therapy.
Use 200-300 MeV electron beam to treat tumors.
Radiology is not well understood, but 100 MV/m acceleration makes attracts interest in this technique again.



Dose profiles for various particle beams in water (beam widths $r = 0.5$ cm)

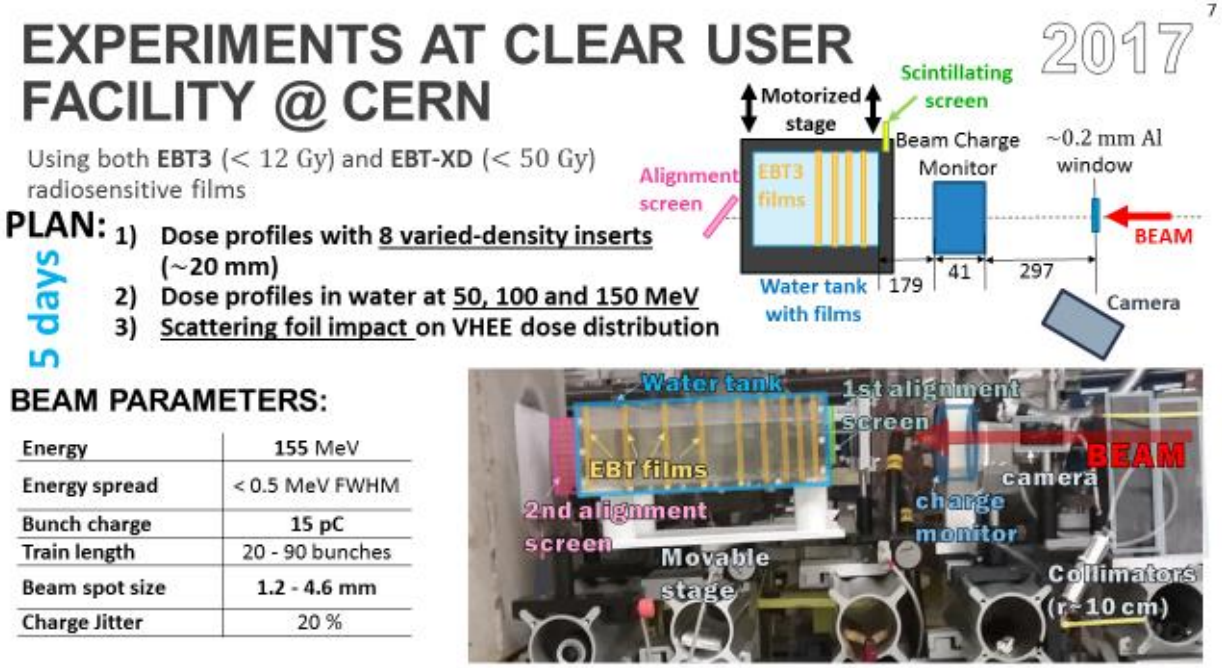




Schüler *et al.*: VHEE in radiation therapy

Med. Phys. 44 (6), June 2017

VHEE – dosimetry studies



Energy	155 MeV
Energy spread	< 0.5 MeV FWHM
Bunch charge	15 pC
Train length	20 - 90 bunches
Beam spot size	1.2 - 4.6 mm
Charge Jitter	20 %

Seeking a way forward with VHEE

FEVHER
Feasibility and Experimental Validation of Very High-Energy Electron Radiotherapy

Angeles Faus-Golfe

Manjit Dosanjh

Philip Poortmans

Roger Michael Jones

European Research Council ERC Synergy 2018

Motivation and Objectives:

The main goal of FEVHER project is to demonstrate that VHEE are suitable for innovative RT applications in particular by allowing Grid and FLASH methodologies, which are likely to represent a major breakthrough in RT.

CNRS, University of Manchester, Institute Curie, CERN

- Adaptation and Exploitation of the existing Facilities
- Medical Physics: Modelling and Dosimetry
- In Vitro Radiobiology
- In Vivo and pre-Clinical studies
- Design of an optimized future machine for VHEE

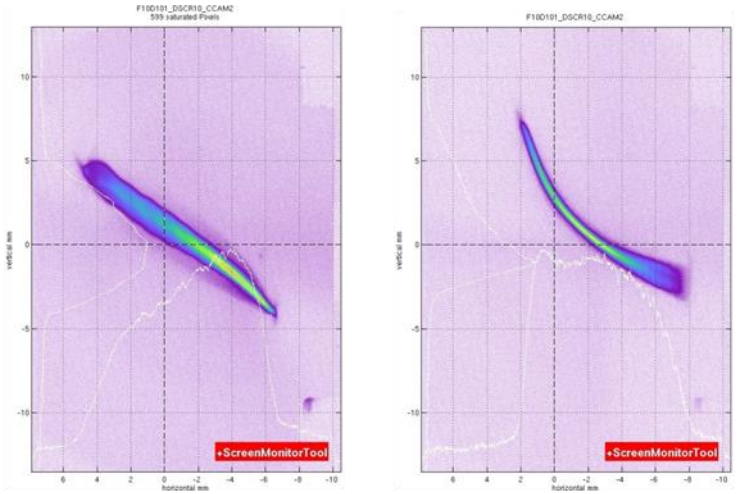
ERC SyG 2018

High-gradient acceleration will be crucial for feasibility. 300 MeV electrons in a compact facility is not easy but we are eager to have a go.

Bunch manipulation with X-band – Fast and Furious (high frequency and high gradient)

Energy spread linearization

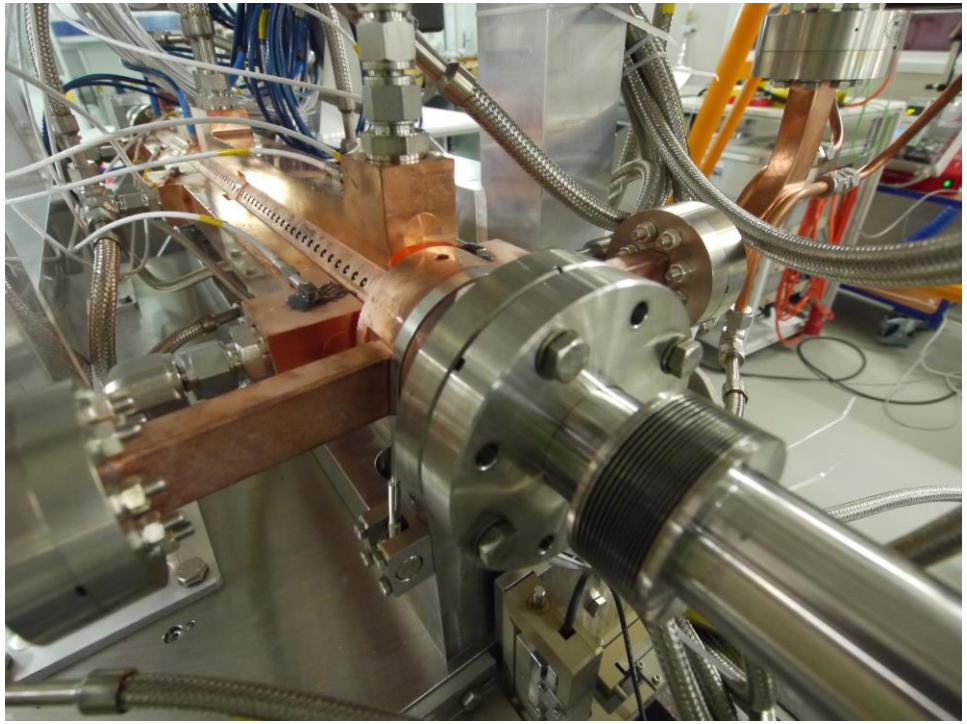
- Linear energy profile along bunch is best suited for bunch compression in magnetic chicane.
- Harmonic can take out curvature induced by acceleration.
- 12 GHz ideal for 3 GHz-based injectors
- Basically just accelerating system running on decelerating phase to take out curvature induced by acceleration.
- X-Band linearizer systems operational at FERMI and SwissFEL made in collaboration between CERN/Trieste/PSI and first klystrons purchased from SLAC.

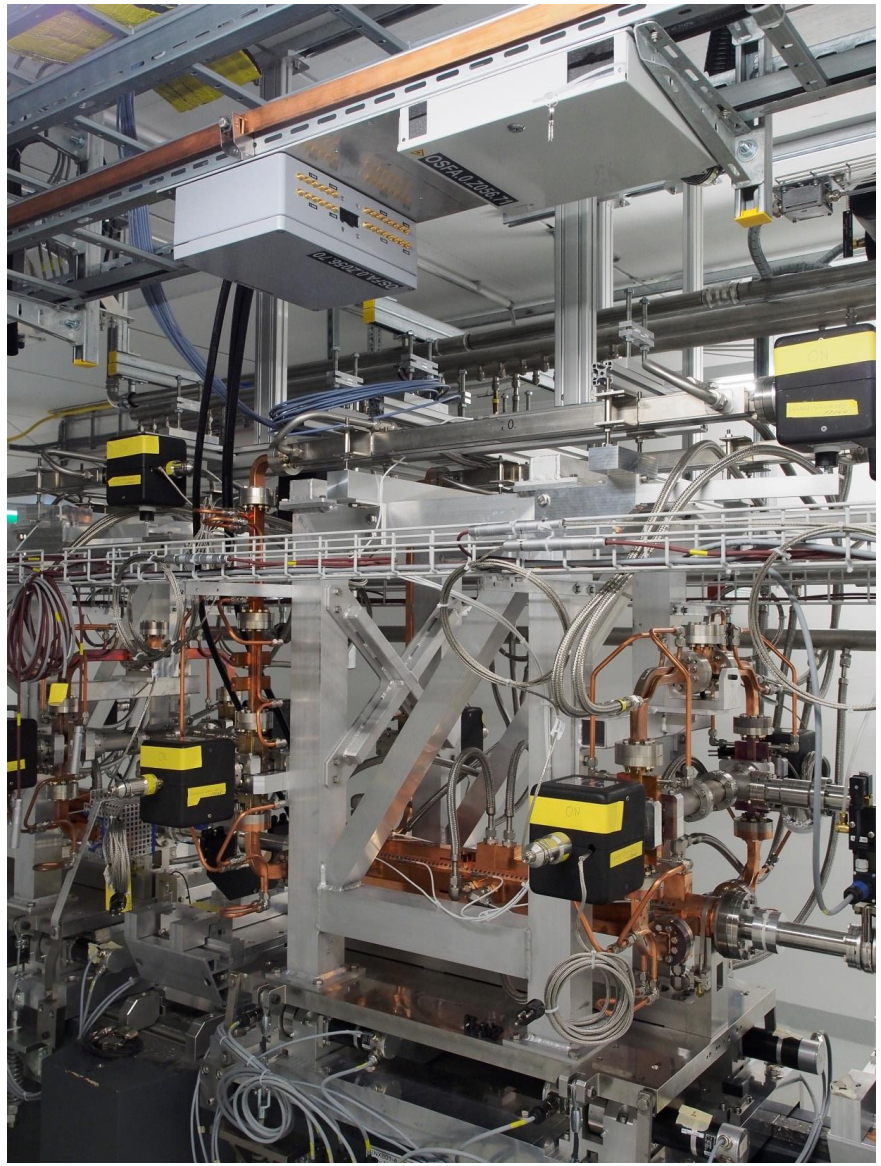


X Band on X Band off

(measurements at FERMI@ELETTRA)

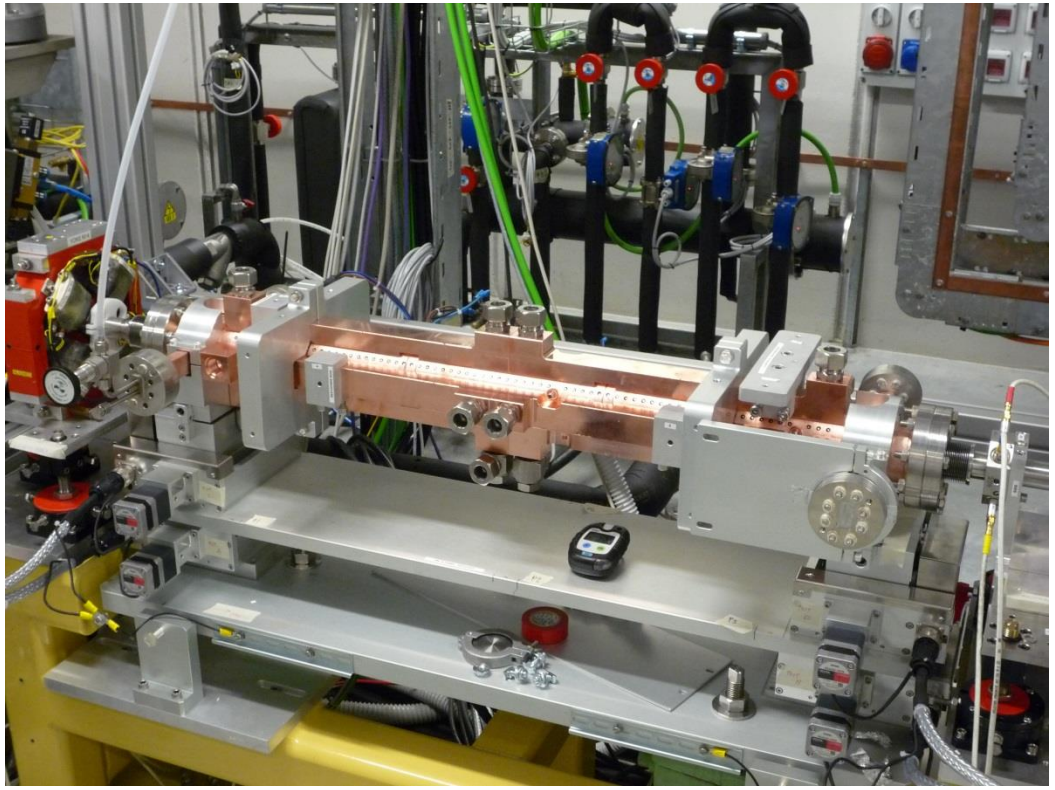
Energy spread linearization at PSI



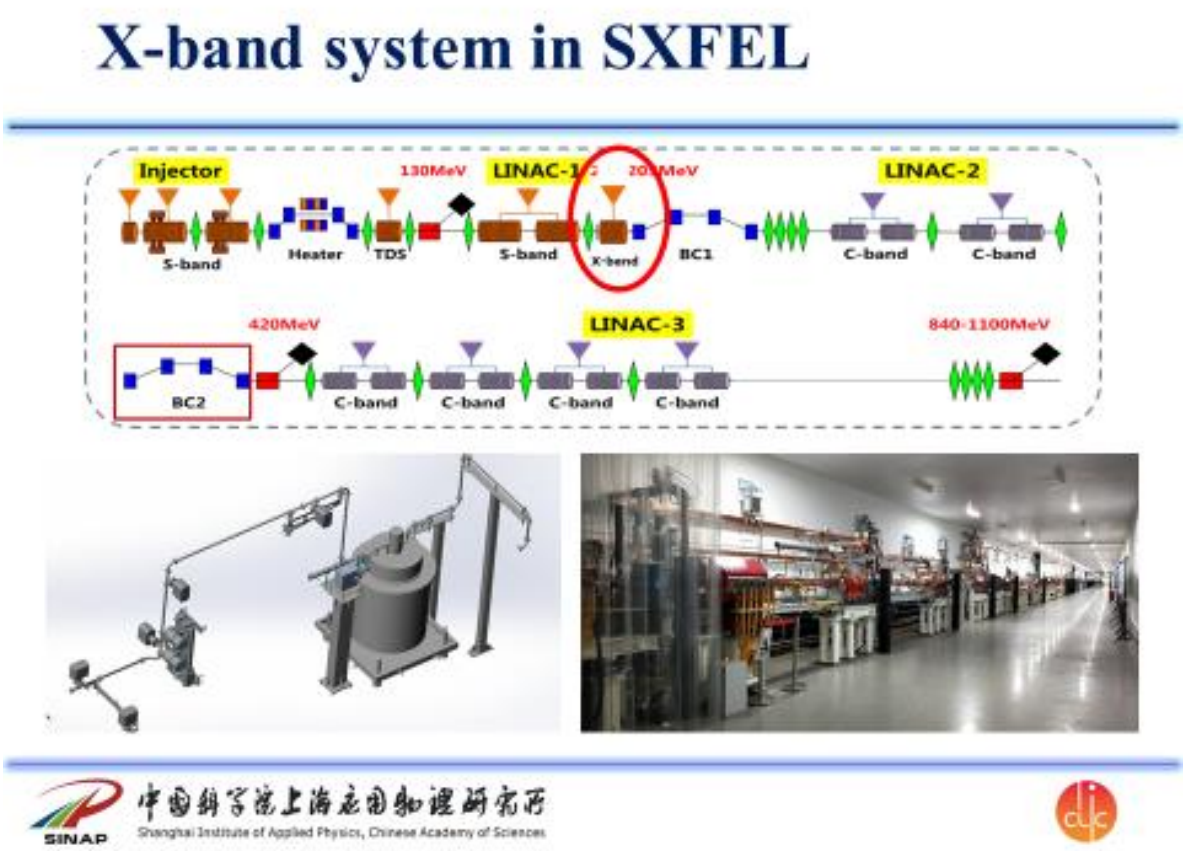


X-band linearizer installed in injector test linac and moved to SwissFEL.

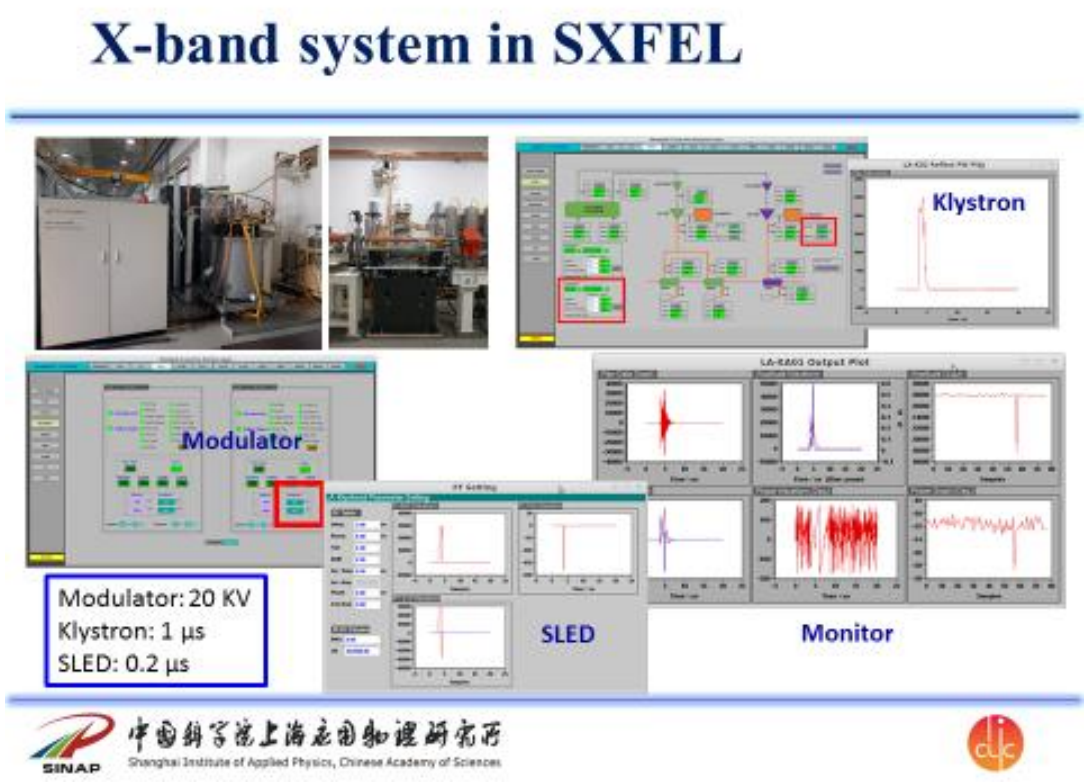
Energy spread linearization at ELETRA

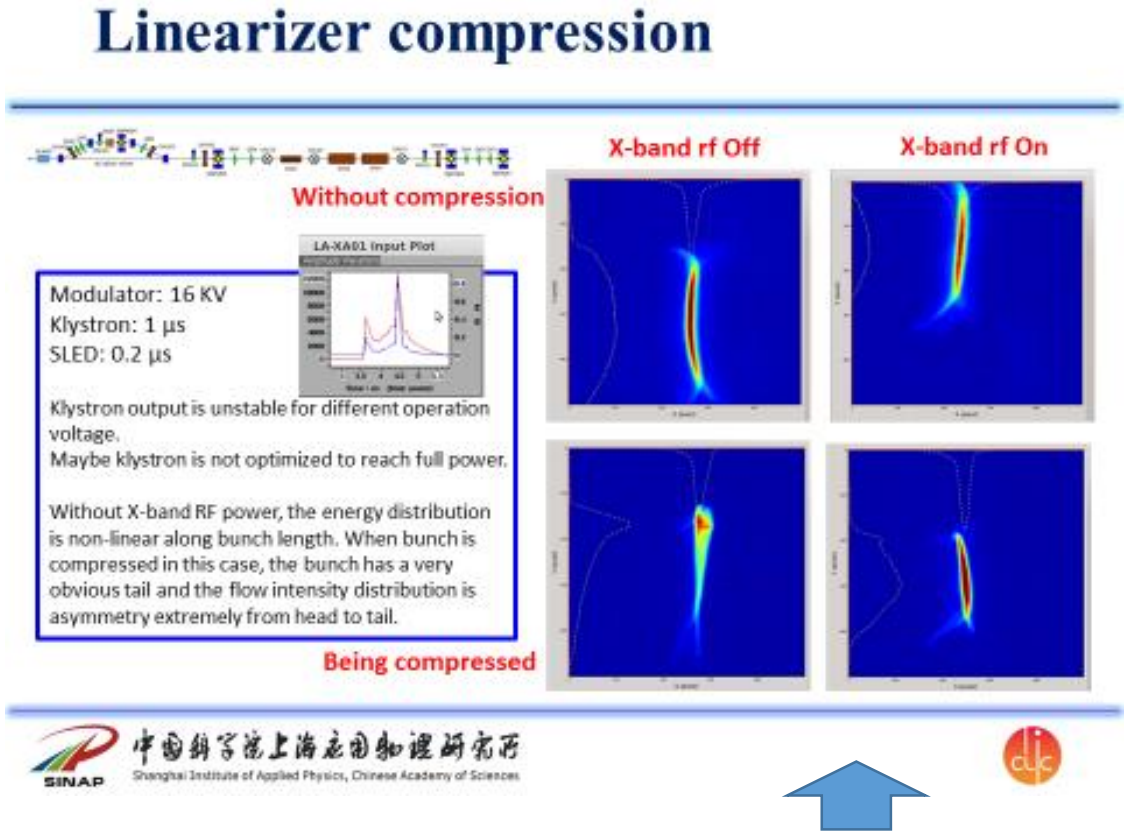


Energy spread linearization at SINAP



Energy spread linearization at SINAP



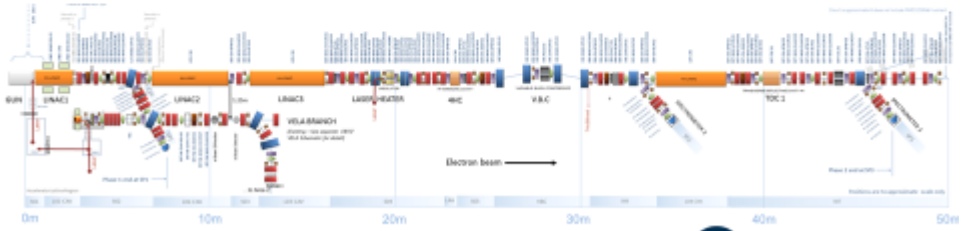


Better bunch for lasing

Energy spread linearization at Daresbury

CLARA

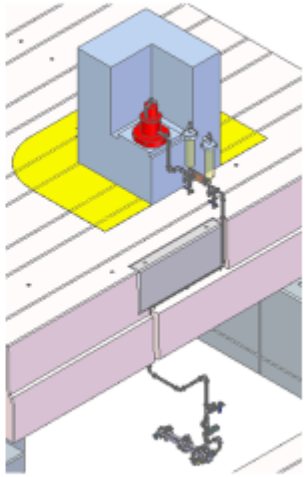
- S-band linear acceleration up to 250 MeV
- Bunch charge 20-250 pC
- High repetition rate up to 400 Hz
- Electron bunch lengths 250-850 fs
- FEL wavelengths in the UV



ASTeC

Proposed system

- CERN/PSI type X-band RF structure with integrated alignment monitors[1]
- 16.3 MW required at the cavity for 30 MV/m operation
- 6 MW Toshiba klystron with Scandinova K200 modulator
- SLED I type pulse compression
- LLRF from industry
- Vaccum WR90 waveguide



1. Dehler et al., Phys. Rev. ST Accel. Beams 12, 062001 (2009)

ASTeC

ASTeC
Accelerators in a new light

An X-band system for phase space linearisation on CLARA

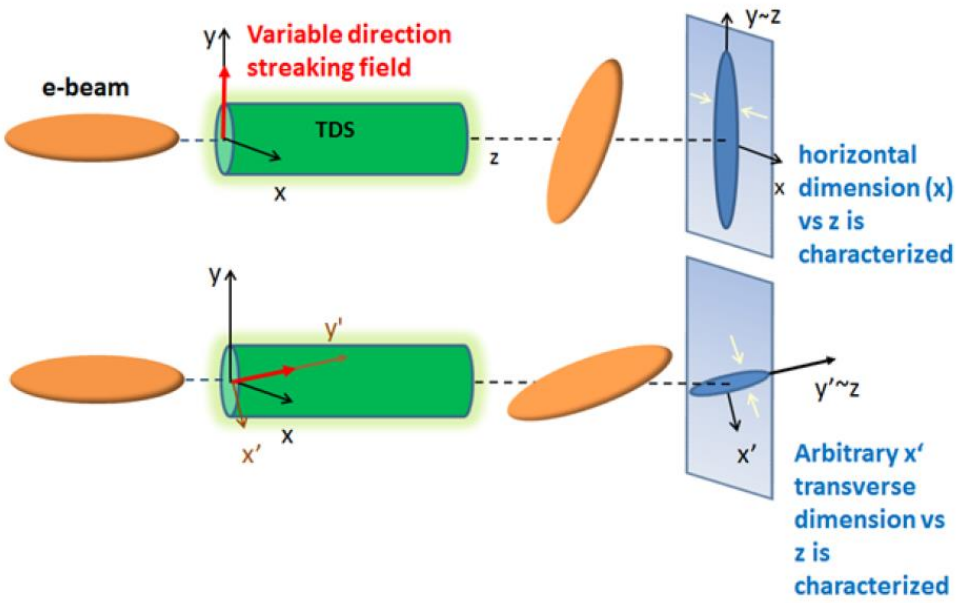
Louise Cowie
On behalf of the 4HC system design team at Daresbury Laboratory

NVEC 2017 University of Huddersfield

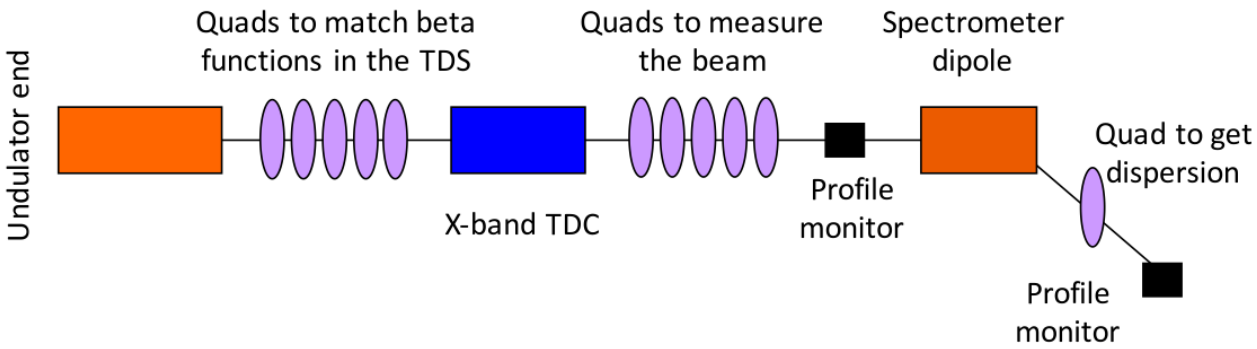
CLARA XFEL test facility is under construction.
They are implementing an Xbox-3, Toshiba 6 MW klystron, type rf system for energy spread linearization.
Procurement underway.

Deflector for longitudinal bunch profile measurement

- Collaboration between DESY, CERN and PSI;
- Design and realisation of a X-band Transverse Deflecting Structure (TDS) with a novel Variable Polarization Feature;
- A common mechanical design matches the space and voltage requirements of three experiments at DESY (FLASHForward, FLASH2, SINBAD) and one experiment at PSI (ATHOS and at SwissFEL);
- The TDS will allow for fs and sub-fs bunch characterization in the time domain;
- The variable polarization feature offers new opportunities for novel diagnostics techniques.

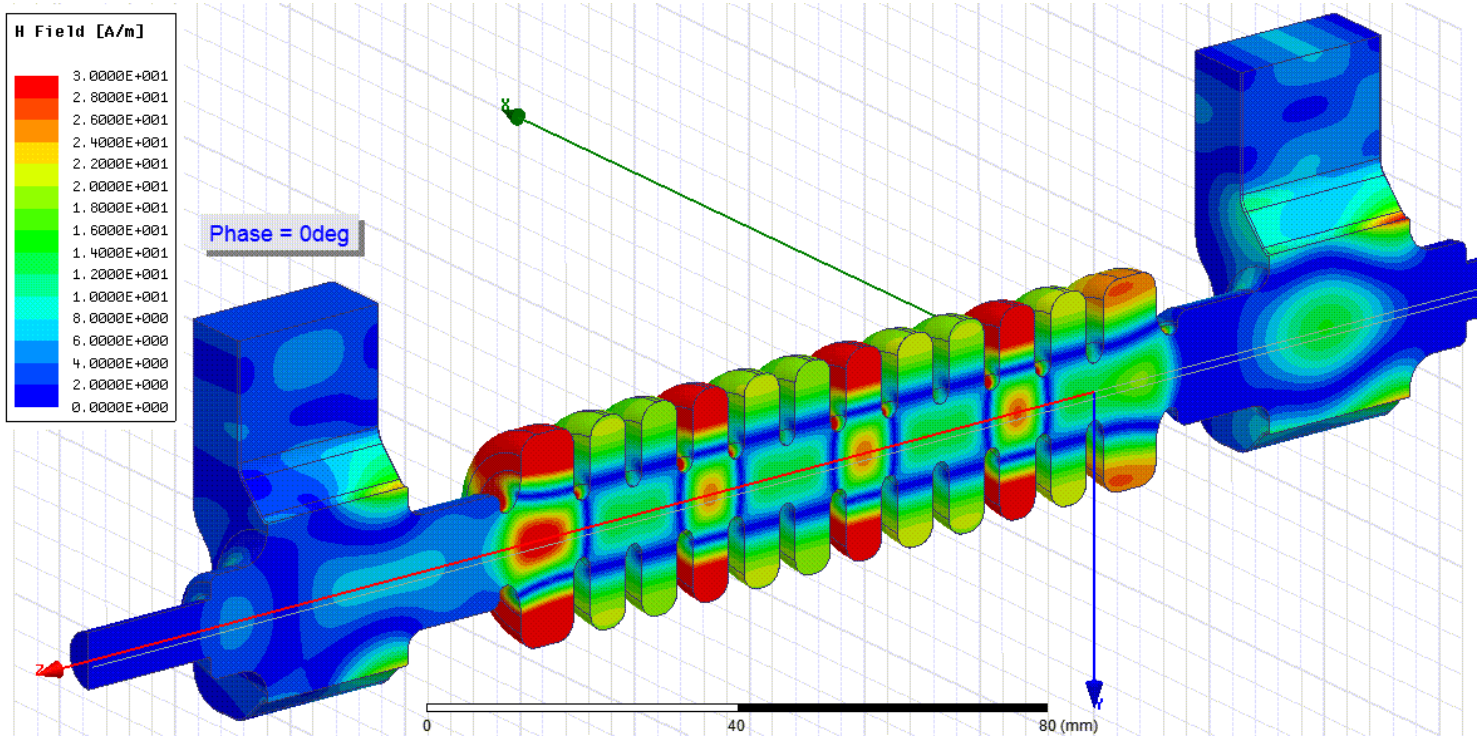


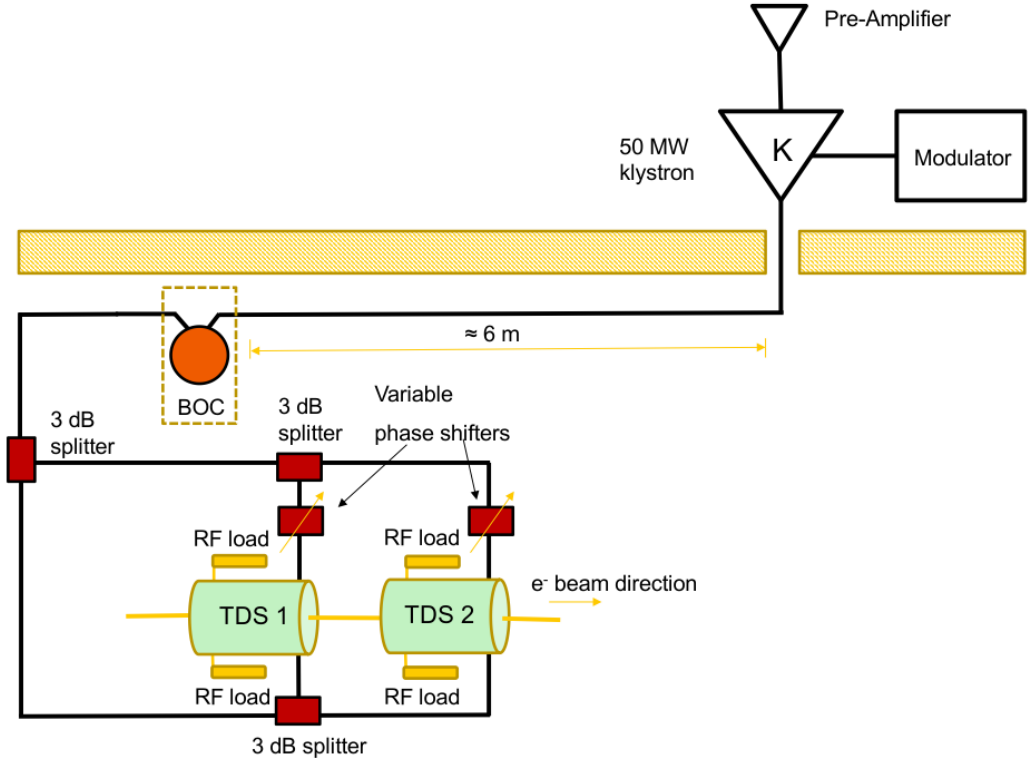
Concept of the post-undulator diagnostic section:



Will result in three new X-band installations!

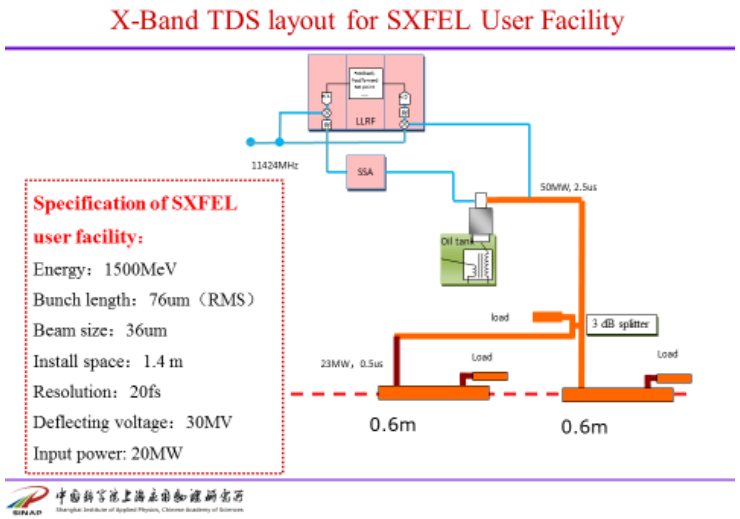
Deflector for longitudinal bunch profile measurement

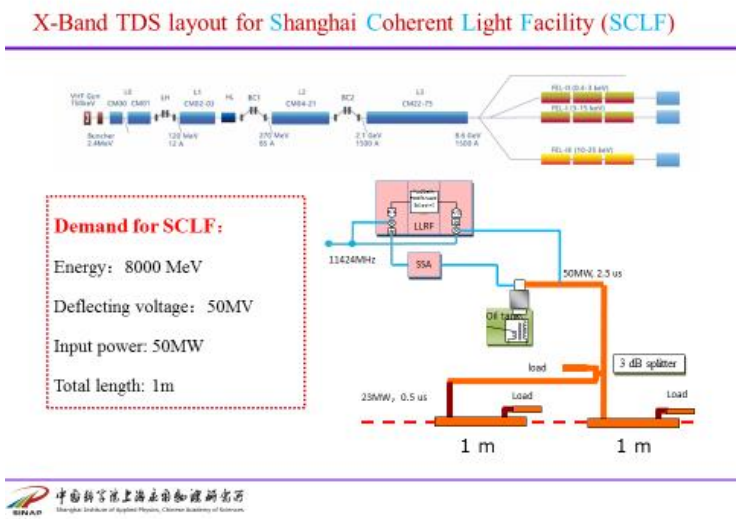


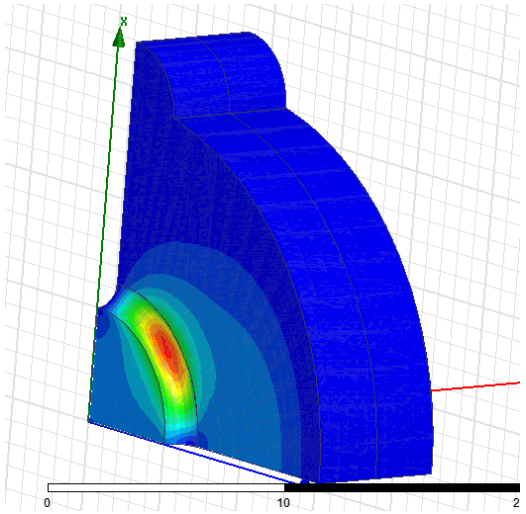


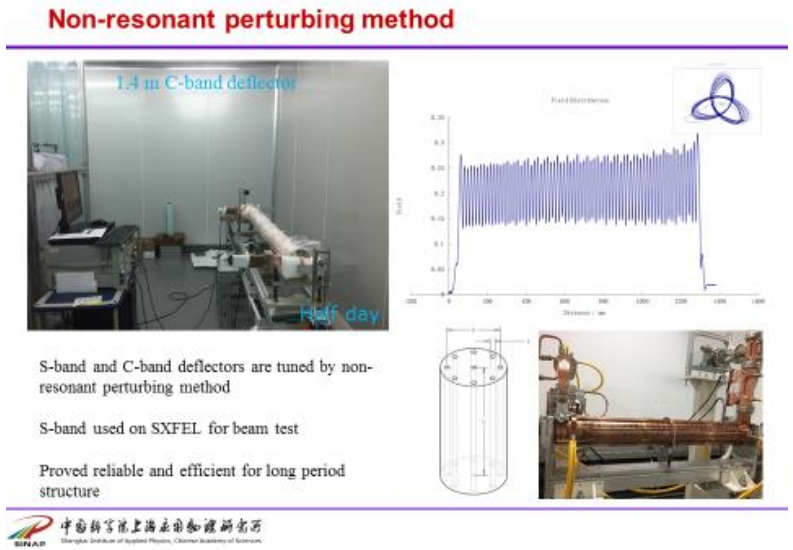
Innovative variable polarization deflector, rf design by CERN. DESY and PSI are procuring rf power systems based on Xbox test stands. PSI will build structures using experience of SwissFEL and X-band accelerators.

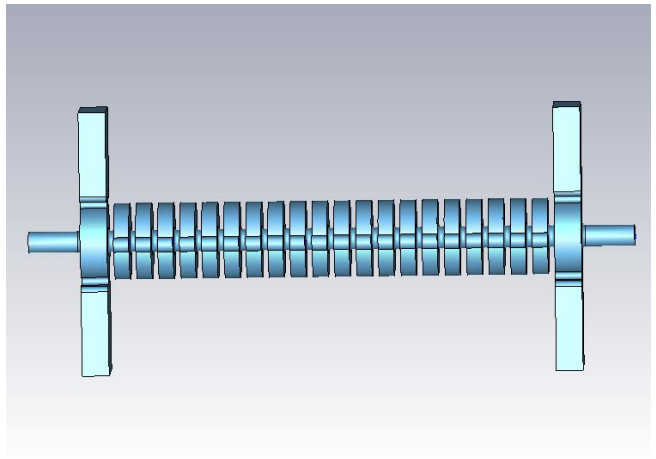
Deflector at SINAP











Conclusions

- Dynamic and growing community of high-gradient and X-band users.
- Initial period of growth driven by linear colliders.
- Proliferation of smaller-scale applications, total level of activity now overtaking linear colliders.
- We look forward to exciting and interesting times as the cross fertilization takes off.
- The benefit for CLIC has far exceeded the investment in helping other applications get started.

I would like to express my sincere thanks:

- To my CLIC high-gradient colleagues,
- To the many colleagues from the different applications I described today,
- To those from whom I have taken slides,
- To you the audience for your attention!