High-Gradient Radio-Frequency Applications

Walter Wuensch, CERN

Introduction and outline

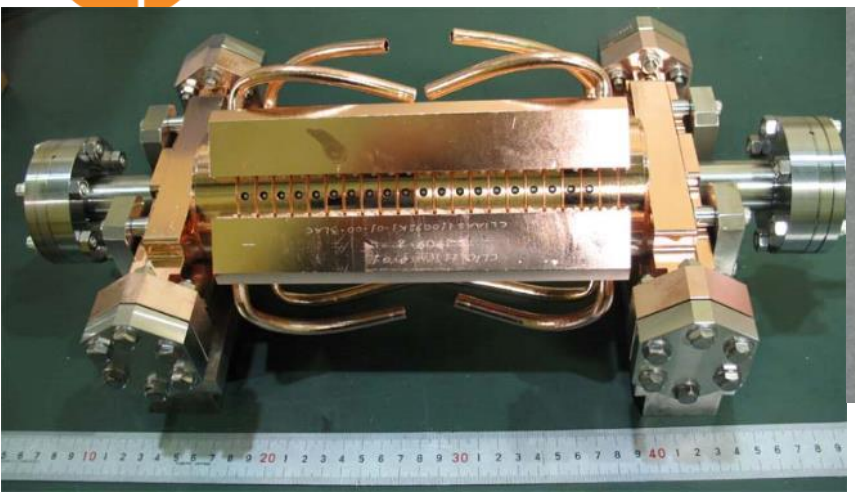
My objective is to give you an overview of applications under development which benefit from high-gradient rf structures:

- CLIC – very large scale high-energy physics facility
- XFELs – medium scale user facility for material science, biology, chemistry, etc.
- Compton-scattering sources – laboratory to room-sized X-ray sources
- Medical – compact linacs for proton and carbon ion cancer treatment
- Pulsed neutrons – very short neutron bunches for nuclear physics

More information

We recently held in Beijing a workshop dedicated to high-gradient and X-band applications https://indico.cern.ch/event/358352/.

Accelerating structure



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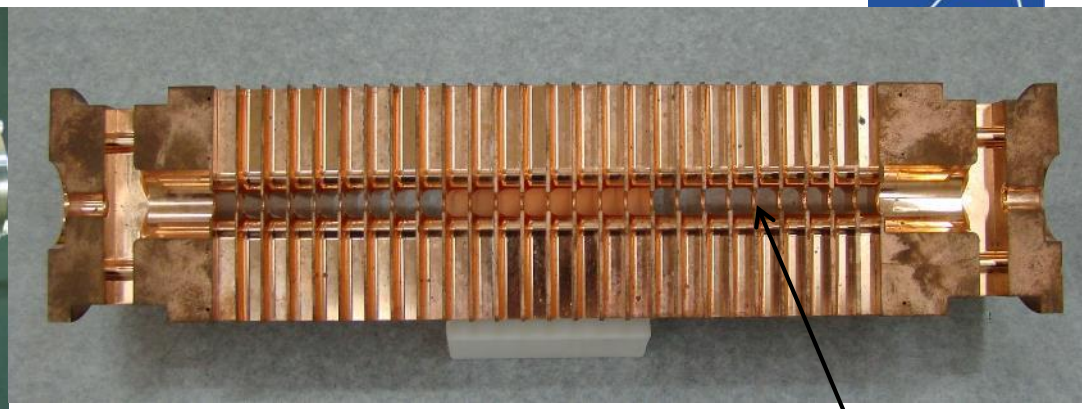
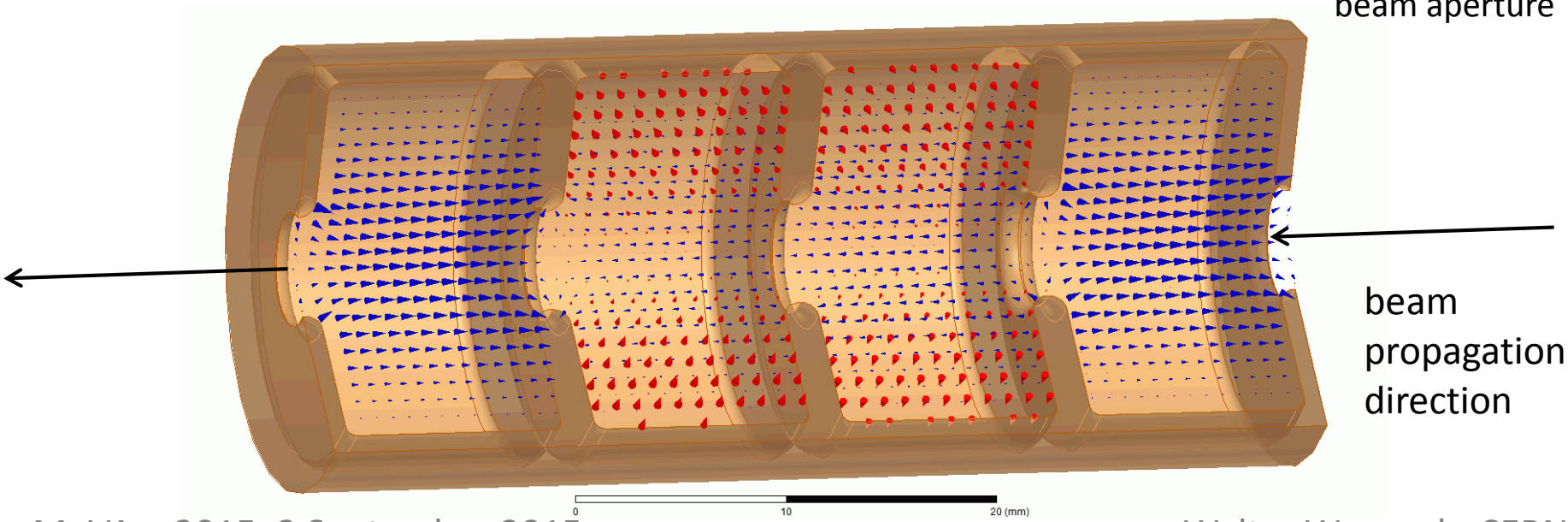


Inside

11.994 GHz X-band

6 mm diameter beam aperture



beam propagation direction

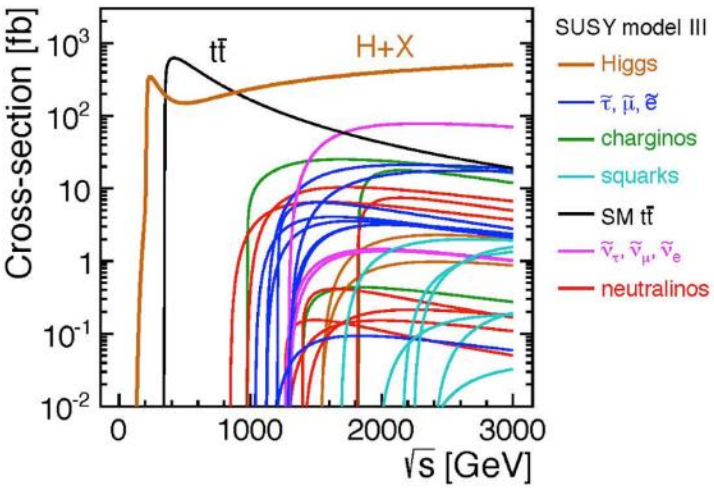
Concept

CLIC – very large scale accelerator for high-energy physics

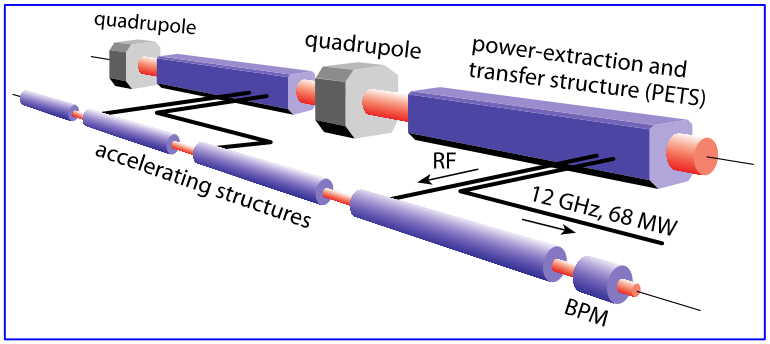
Walter Wuensch, CERN

Introduction to CLIC

CLIC is an international collaboration based at CERN dedicated to developing the technology for an **e^+e^- linear collider** for the range of **250 GeV to 3 TeV.**



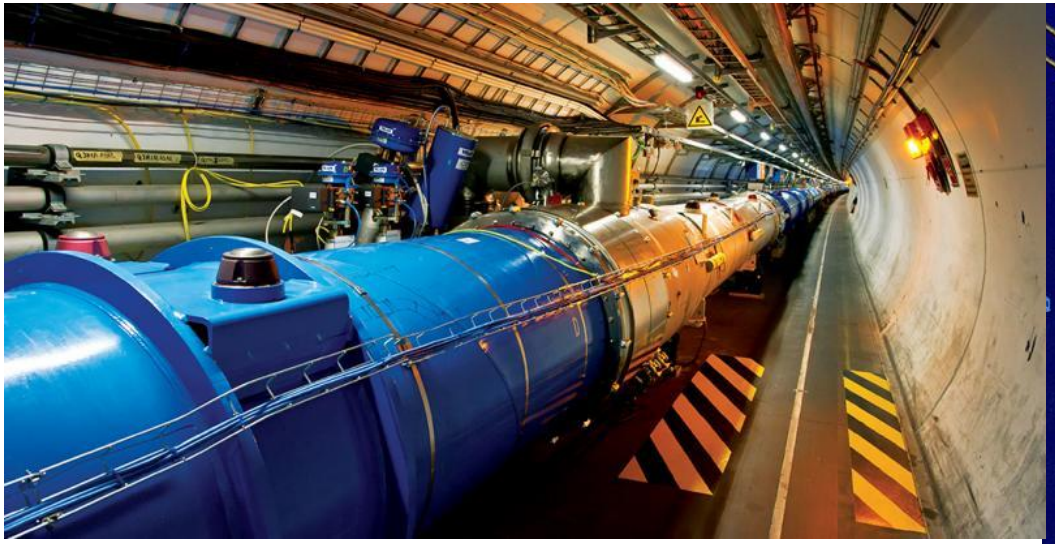
It is based on high-gradient, **100 MV/m,** normal conducting rf, low emittance beams and a two-beam power generation scheme. A klystron-based initial energy stage is also being considered.

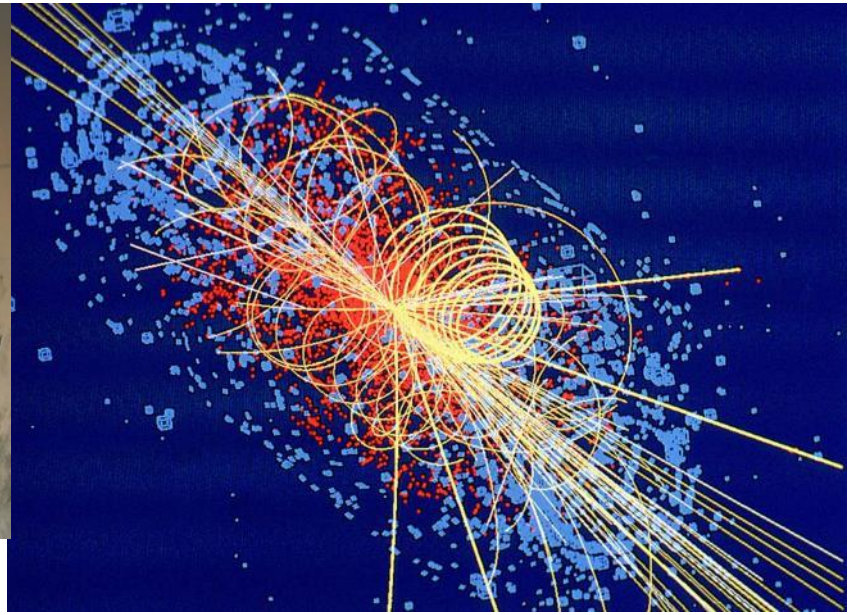


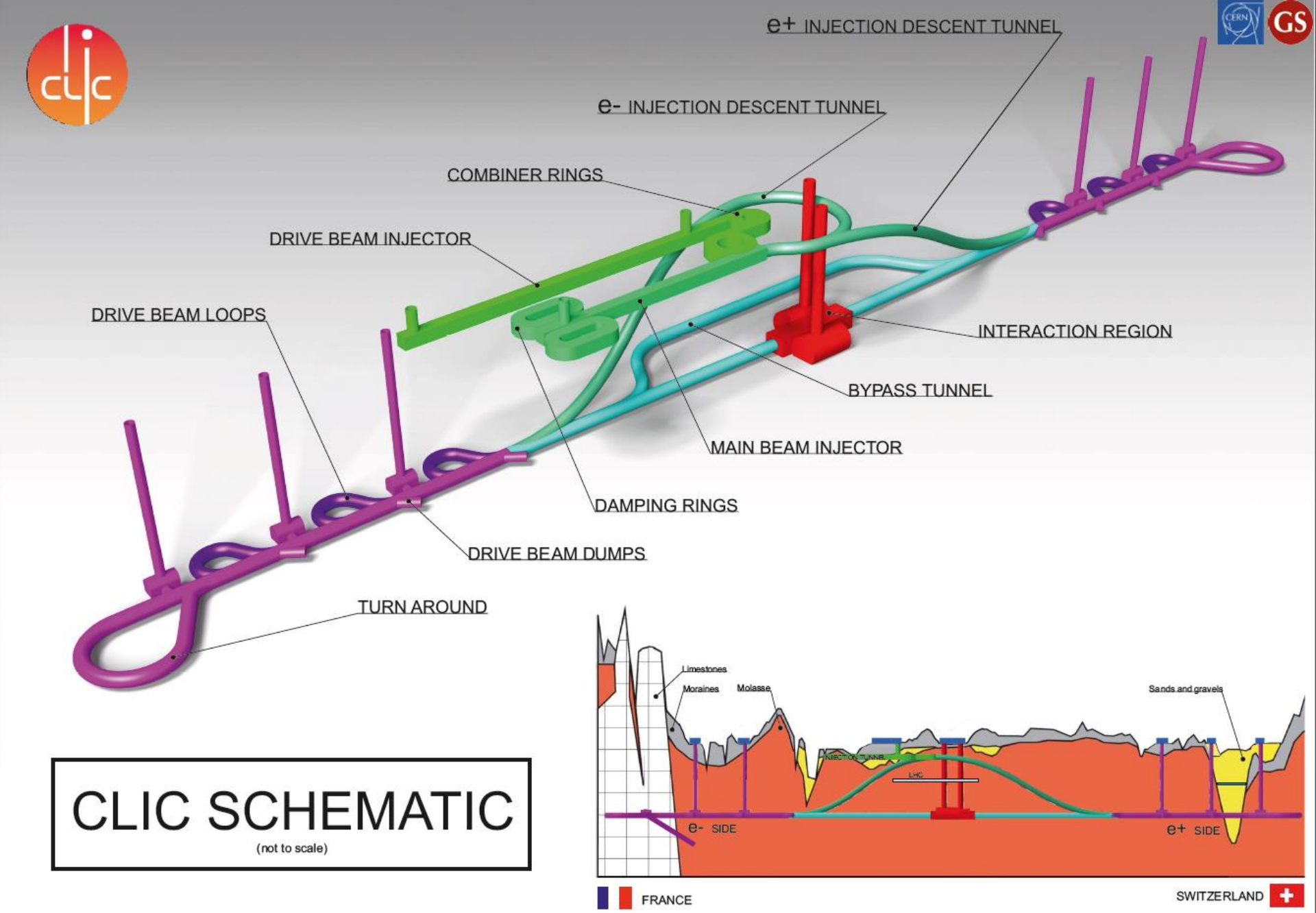
A dramatic moment

The crucial background for the CLIC study is LHC run 2 which has just started at CERN. The LHC is running at nearly full energy, 13.5 TeV compared to 7 TeV in the first run.

The physics landscape in this energy range should emerge in the next two years or so. The nature of new discoveries, or their absence, will have a tremendous impact on future high energy physics studies.



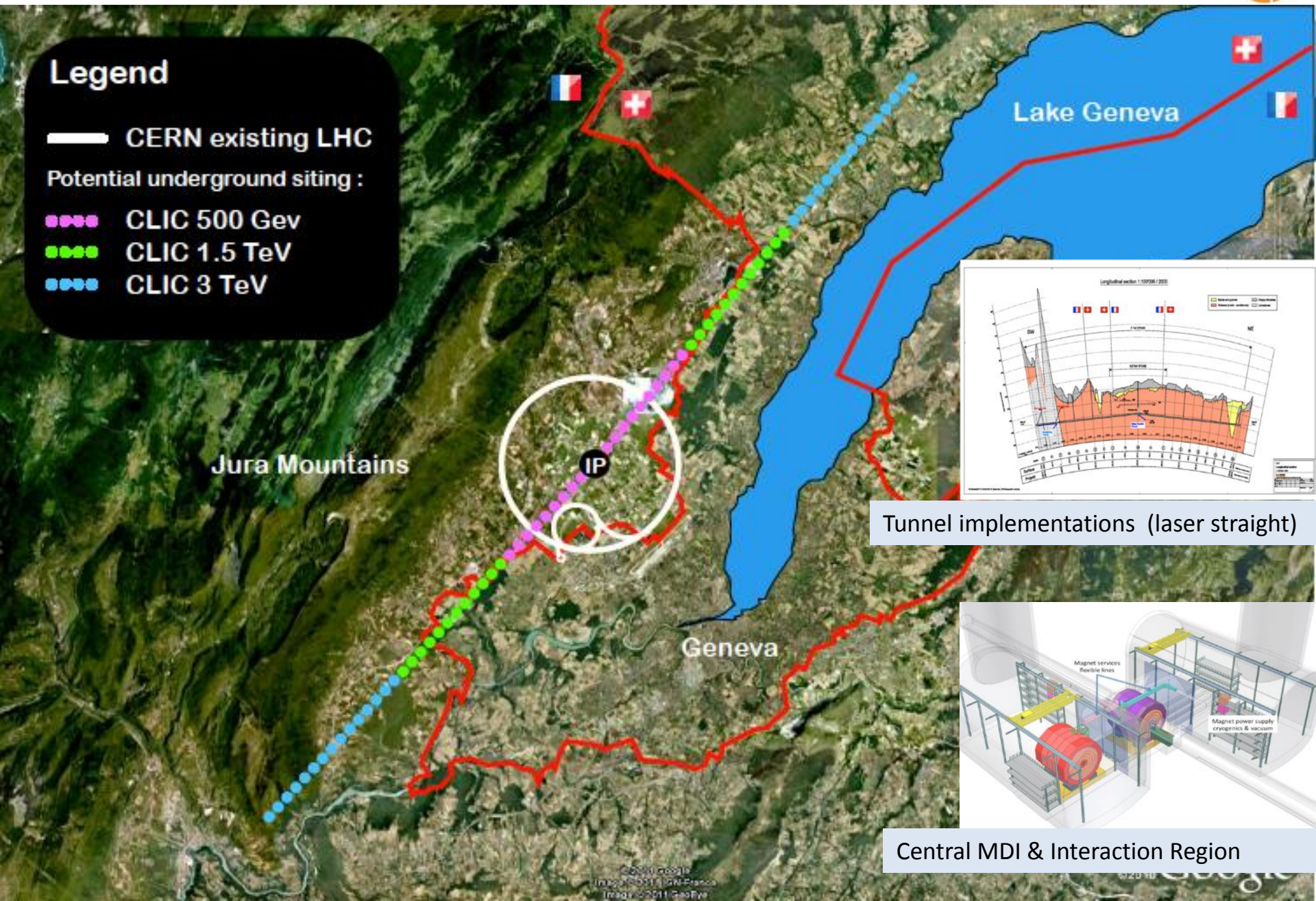




CLIC SCHEMATIC

(not to scale)

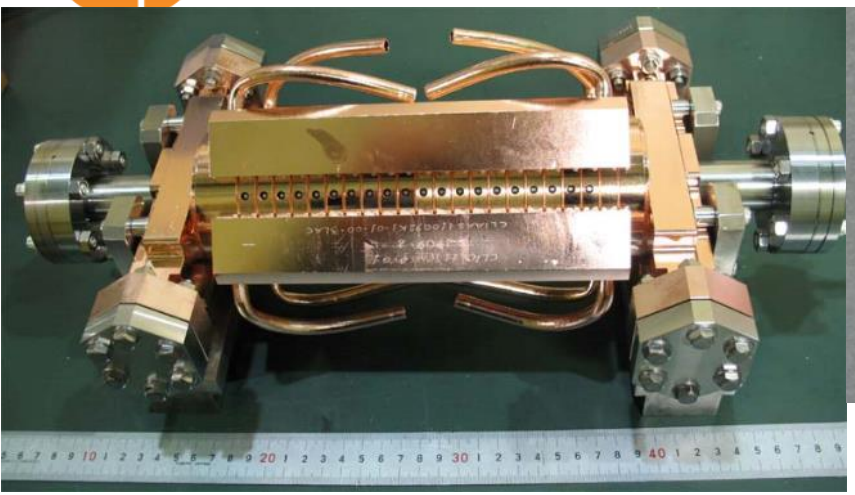
CLIC near CERN



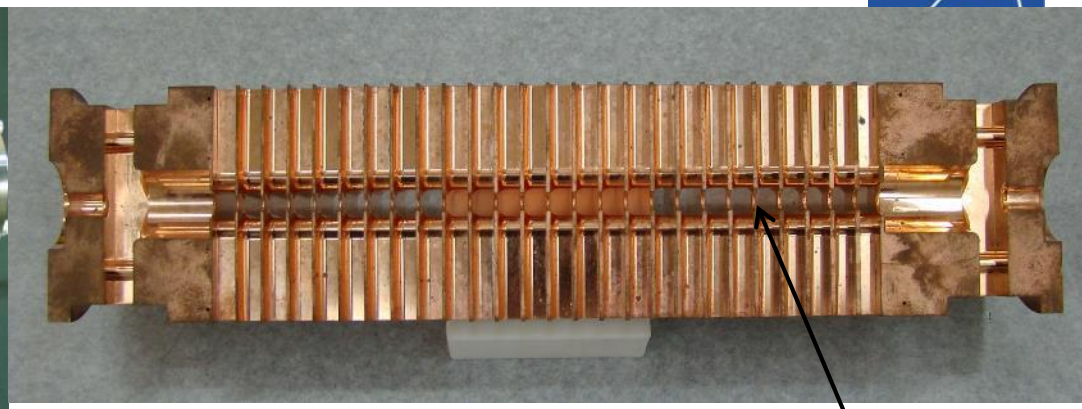
CLIC Collaboration

Accelerator collaboration has ≈ 50 institutes and the detector collaboration ≈ 25.

Key performance limitation is achievable gradient



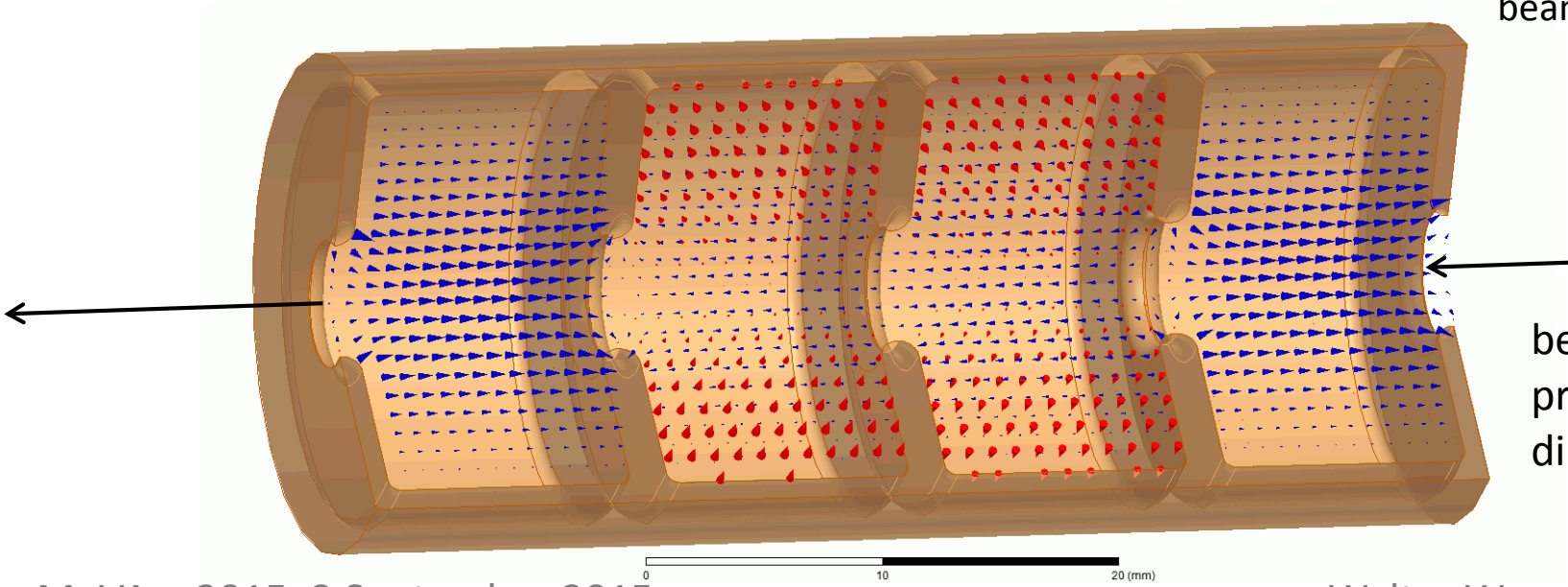
Outside



Inside

11.994 GHz X-band

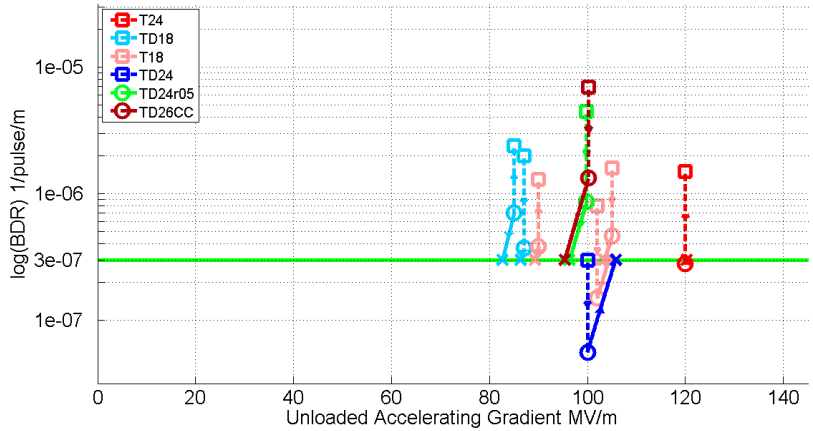
6 mm diameter beam aperture

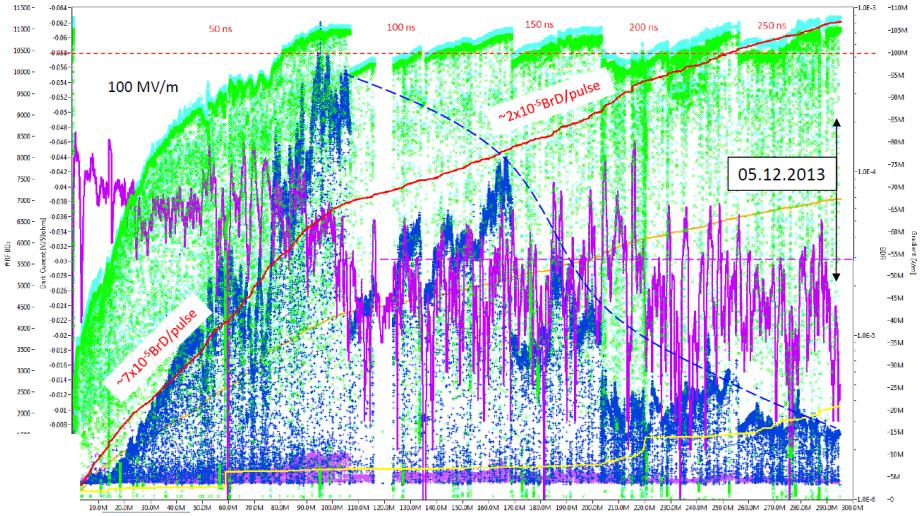


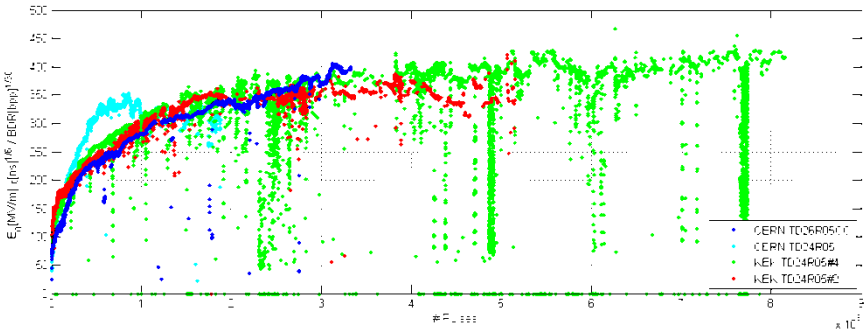
beam propagation direction

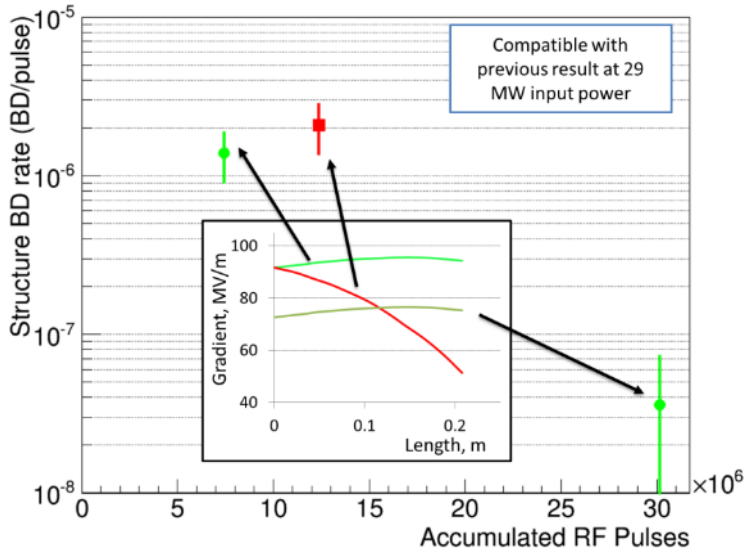
Concept

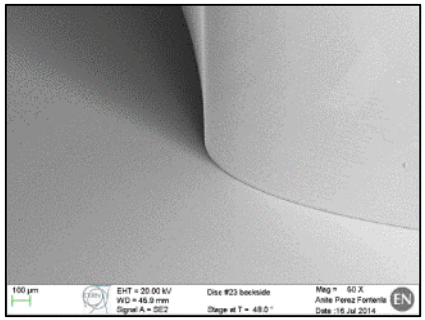
High-gradient data and analysis

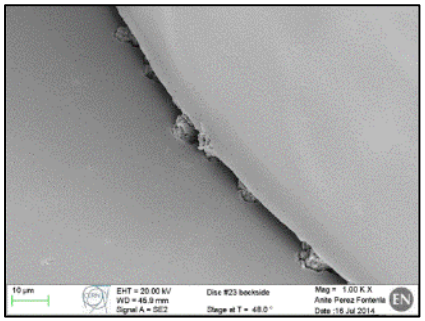




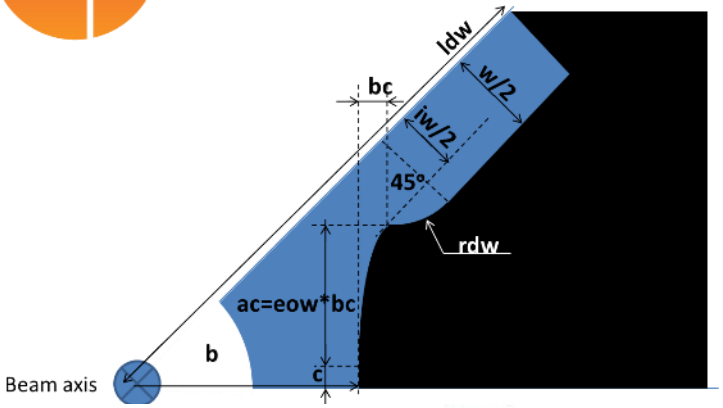


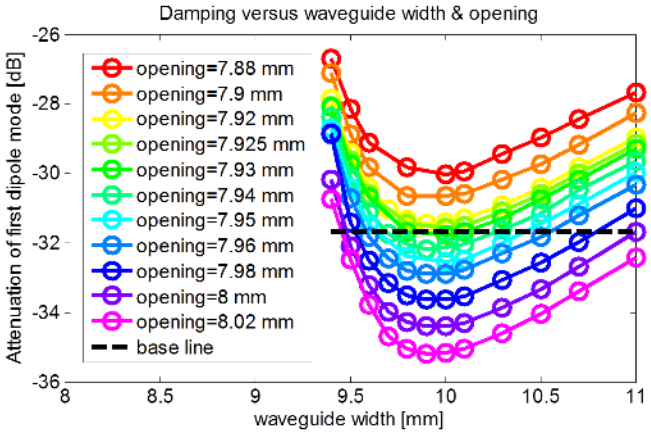


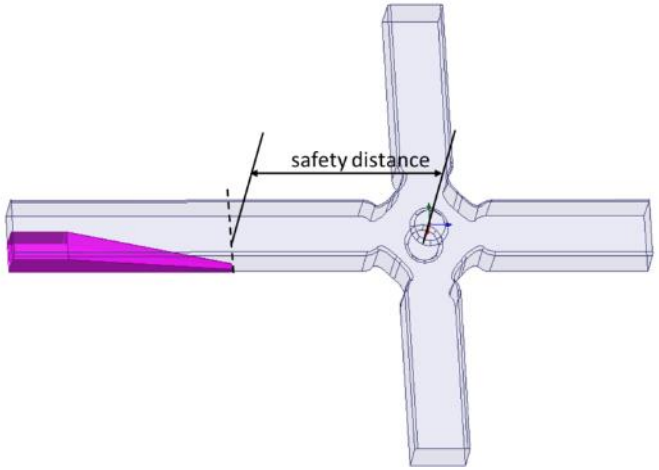


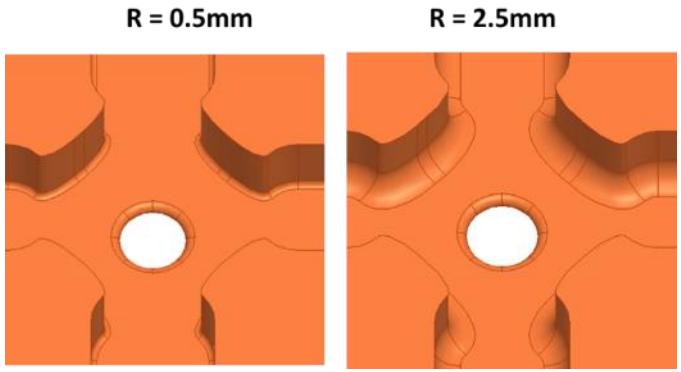


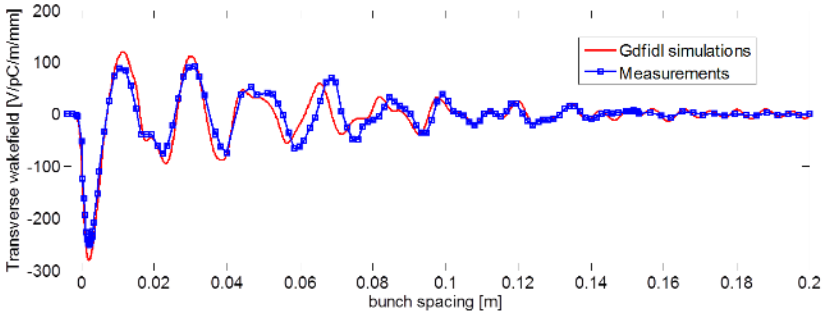
Progress in understanding and feedback on rf design

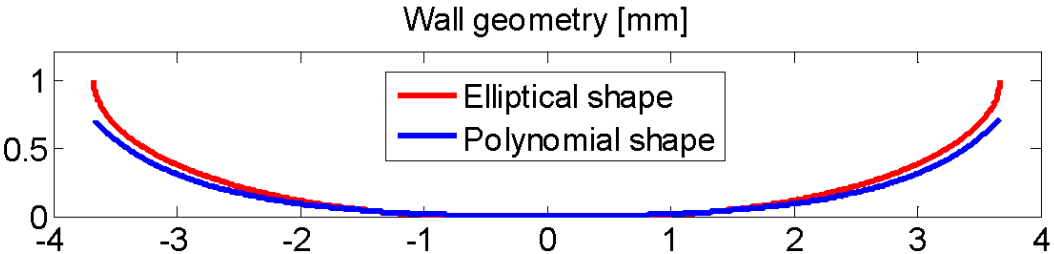












LHC results, energy staging and rebaselining

Conclusions

HZ production
- ⇨ √s ~ 250-450 GeV

Top at theshold
- ⇨ √s > 350 GeV

Recoil Mass
- ⇨ √s < 400 GeV

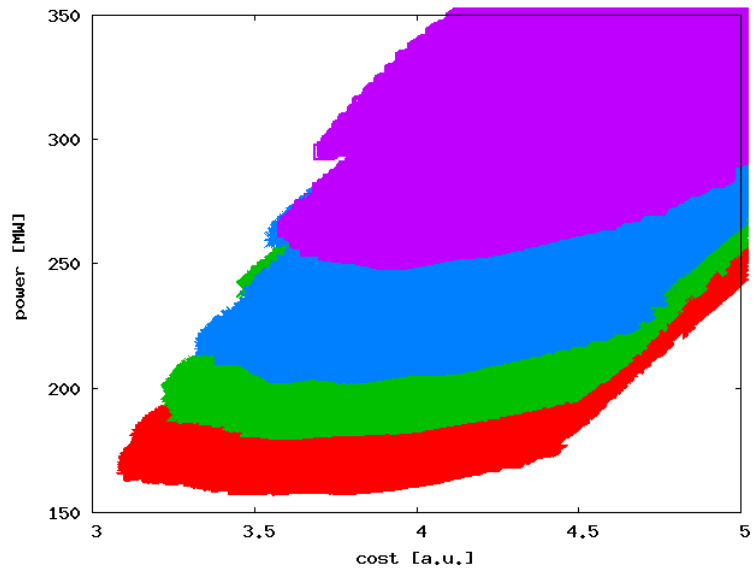
⇨ **√s ~ 380 GeV**

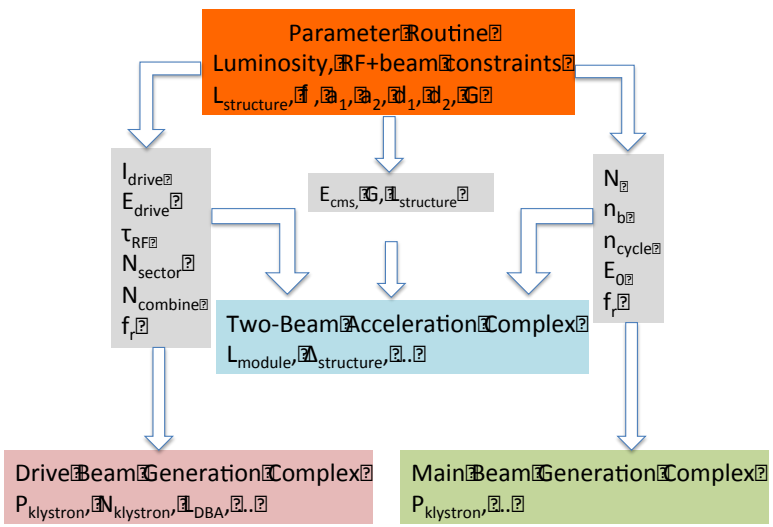
Still good for HZ
Provides valid top quark program

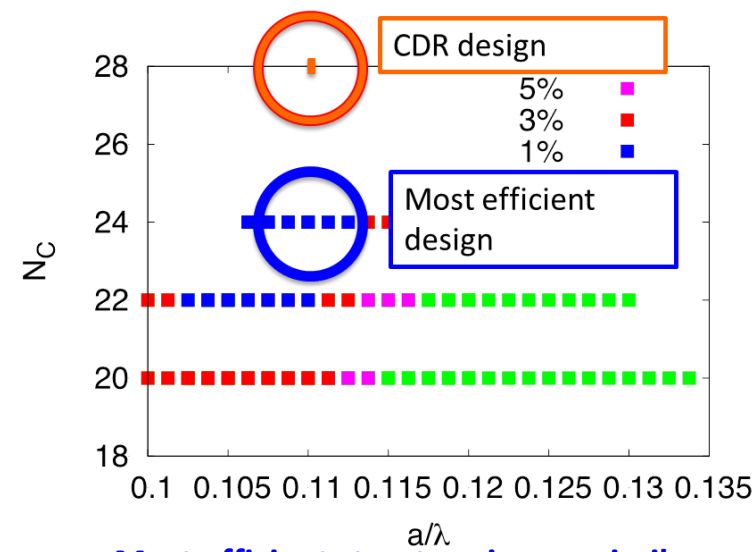
Top pair production
- ⇨ √s > 360 GeV

Top pair BSM
- ⇨ √s > 360 - ? GeV

Mark Thomson CERN, January 30, 2015 25

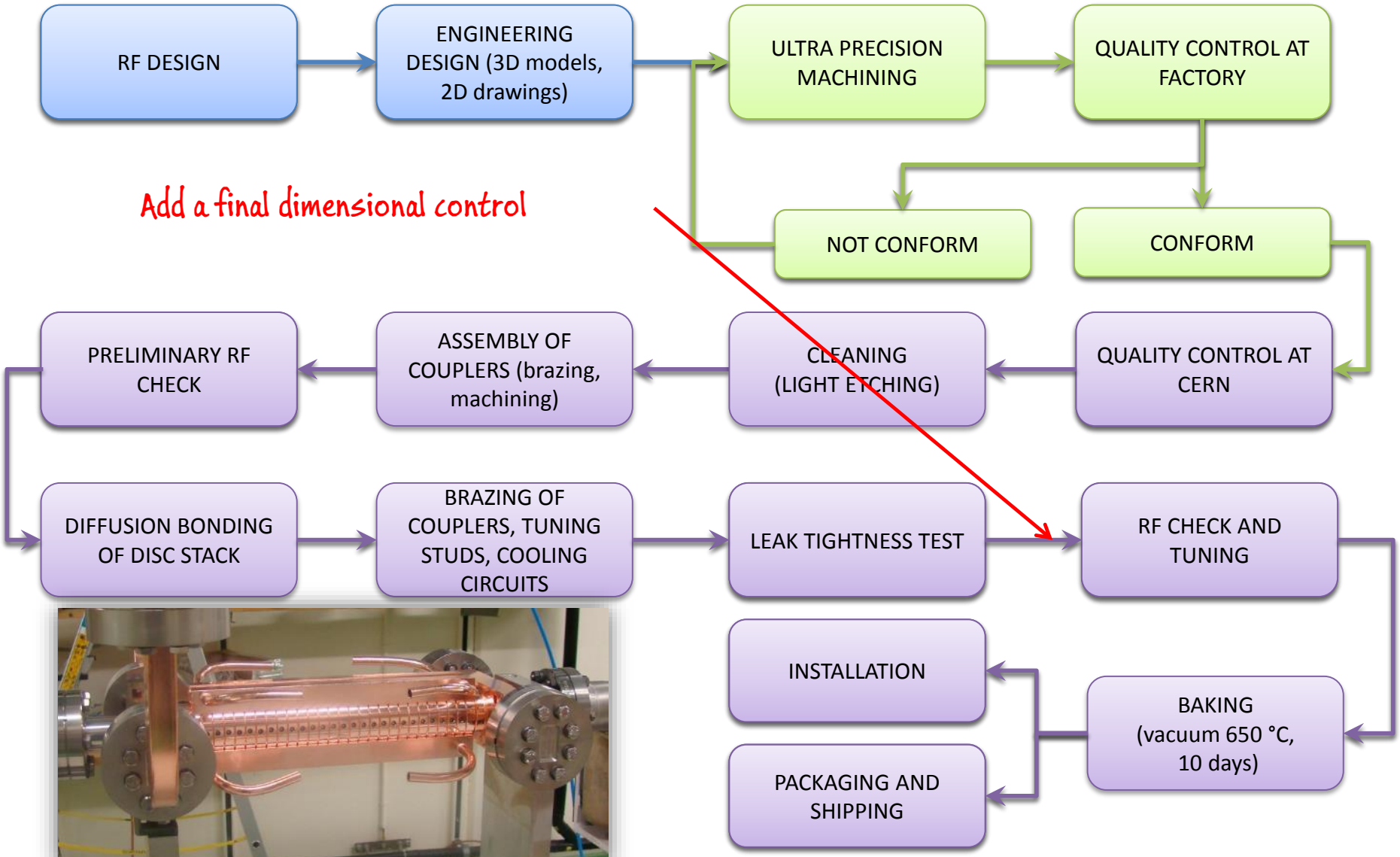






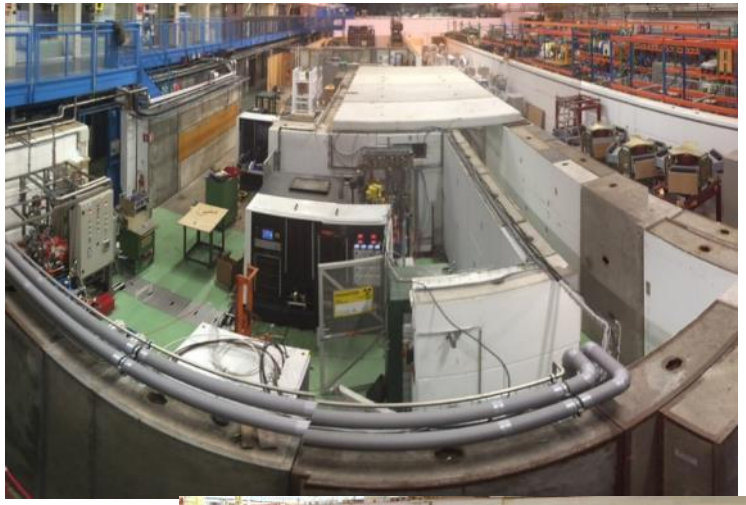
⇒ **Most efficient structure is very similar to CLIC_G**

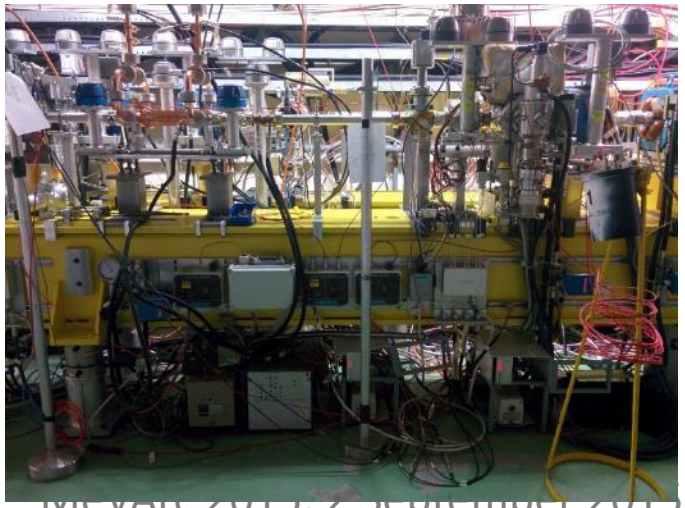
Baseline manufacturing flow



X-band test stands

One of our top priorities is to complete Xbox-3 this year and operate all our three X-band klystron-based tests stands through at least 2018.





TNA

In order to facilitate the use of the XBoxes by collaborators we have proposed to include them in EUCARD3 as a Trans National Access. If approved this would be a source of funding for collaborators to come to CERN to make tests.

Preparation for the next Integrating Activity call

M. Vretenar,
on behalf of ESGARD
21 April 2015

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Integrating Activities in H2020

Independently from the call at which we will apply, we must take note that Integrating Activities for Advanced Communities in H2020 are different from FP7 (as seen in the first call) and in particular need:

1. More focus on **Transnational Access**
2. Innovation and **partnership with industry**.
3. Demonstration of the **added value and the progress** beyond current achievements of a continuation project

"EU funding will be provided to support the trans-national access to European research infrastructures, as well as the cooperation, networking and joint developments between research infrastructures, their scientific communities, industries and other stakeholders. Integrating Activities in particular should contribute to fostering the potential for innovation of research infrastructures by reinforcing the partnership with industry, through e.g. transfer of knowledge and other dissemination activities, activities to promote the use of research infrastructures by industrial researchers, involvement of industrial associations in consortia or in advisory bodies. A specific work package on innovation is therefore recommended in all Integrating Activity proposals".

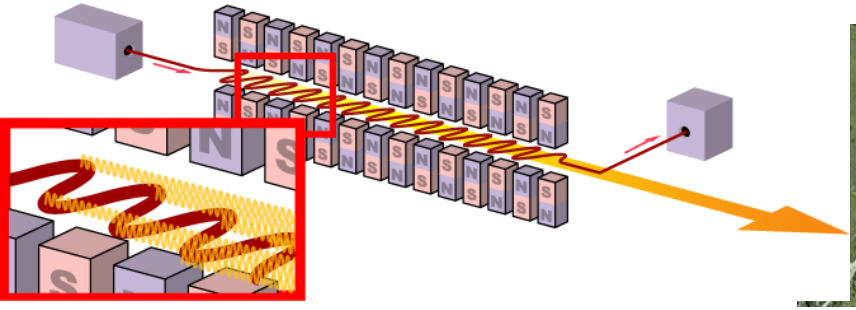
Results of the consultation

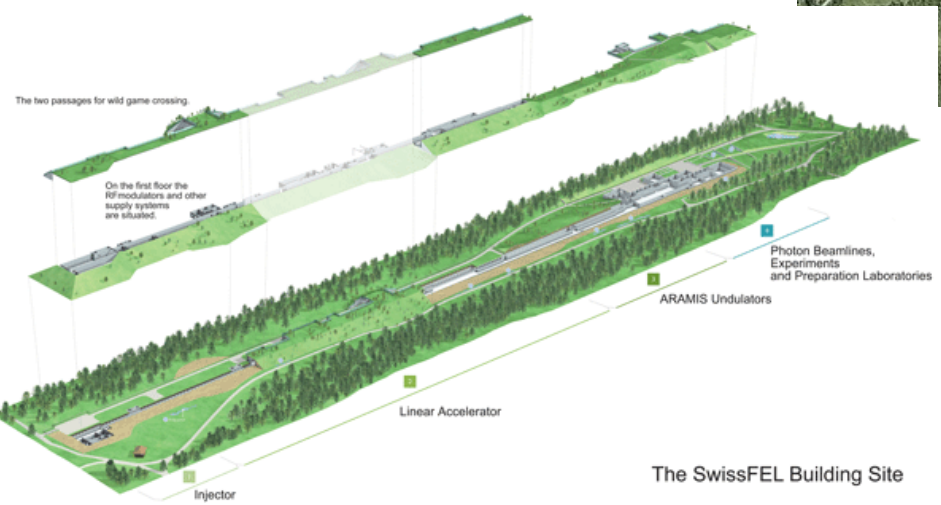
- **50 LoI's** received until February 2015, for a total requested budget of 32.6 M€ (3.2 x maximum budget).
- **10 Networks, 40 R&D, no TNA**.
- Origin of LoI's: 25 Germany, 7 UK, 7 CERN, 5 Spain, 2 Switzerland, 2 shared, 1 Sweden, 1 France.
- Notable absences: no high-field magnets (community busy with HL-LHC, high cost for continuing HTS). Little on RF (only thin films and some SC).
- A few new potential partners.

XFEL –large scale accelerator for biology, chemistry, material science, etc.

Walter Wuensch, CERN

XFELs – operating and under construction



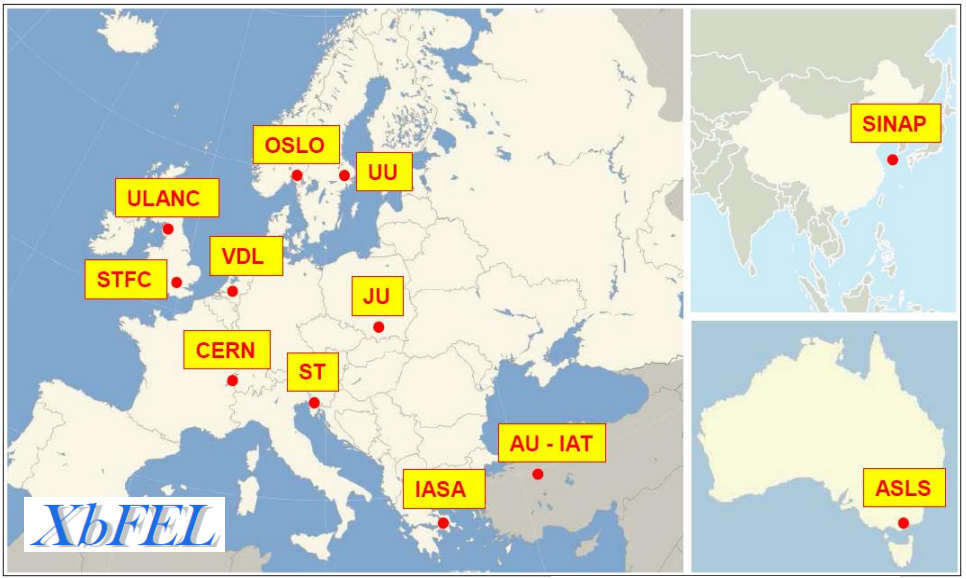


Typically needs 6 to 20 GeV electron beams

The XbFEL Collaboration

The aim of the XbFEL Collaboration is to promote the use of X-band technology for FEL based photon sources.

http://xbandfel.web.cern.ch/



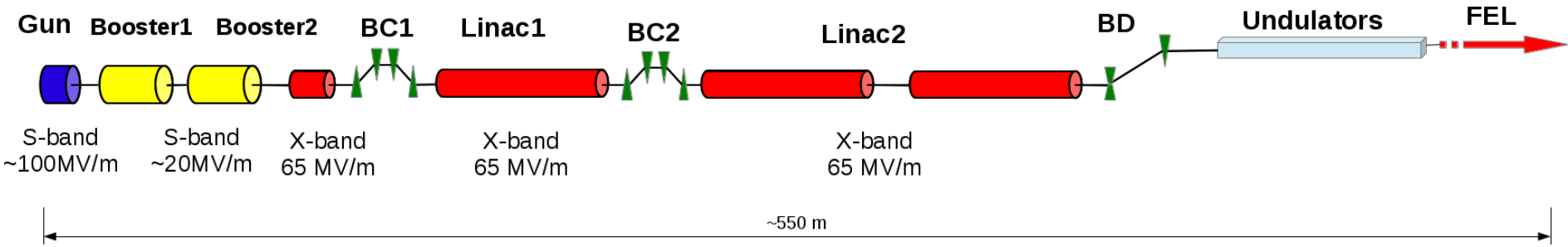
ST	*Elettra - Sincrotrone Trieste, Italy.*
CERN	*CERN Geneva, Switzerland.*
JU	*Jagiellonian University, Krakow, Poland.*
STFC	*Daresbury Laboratory Cockcroft Institute, Daresbury, UK*
SINAP	*Shangai Institute of Applied Physics, Shanghai, China.*
VDL	*VDL ETG T&D B.V., Eindhoven, Netherlands.*
OSLO	*University of Oslo, Norway.*
IASA	*National Technical University of Athens, Greece.*
UU	*Uppsala University, Uppsala, Sweden.*
ASLS	*Australian Synchrotron, Clayton, Australia.*
UA-IAT	*Institute of Accelerator Technologies, Ankara, Turkey.*
ULANC	*Lancaster University, Lancaster, UK.*

Motivations

- **The demand for new FEL facilities is worldwide continuously increasing, spurring plans for new dedicated machines. This led to a general reconsideration of costs and space issues, particularly for the hard X-ray sources, driven by long and expensive multi-GeV NC linacs.**

- **For these machines the use of X-band technology can greatly reduce cost and capital investment, reducing the linac length and the size of buildings, opening the way to the construction of a multitude of affordable *"Regional Facilities".***

Proposed Layout



It consist of:

- RF photocathode gun → S band structure delivering beam @7 MeV with 250 pC charge, 2.5 ps (800µm) lengt and 0.25 mm rad emittance
- Injector → S-band structures and one X-band structure as linearizer, accelerating beam up to 300 MeV
- Two main linacs → Two X-band modules: stage one 0.3 GeV → 2.0 GeV
  stage two 2.0 GeV → 6.0 GeV
- Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line(s)

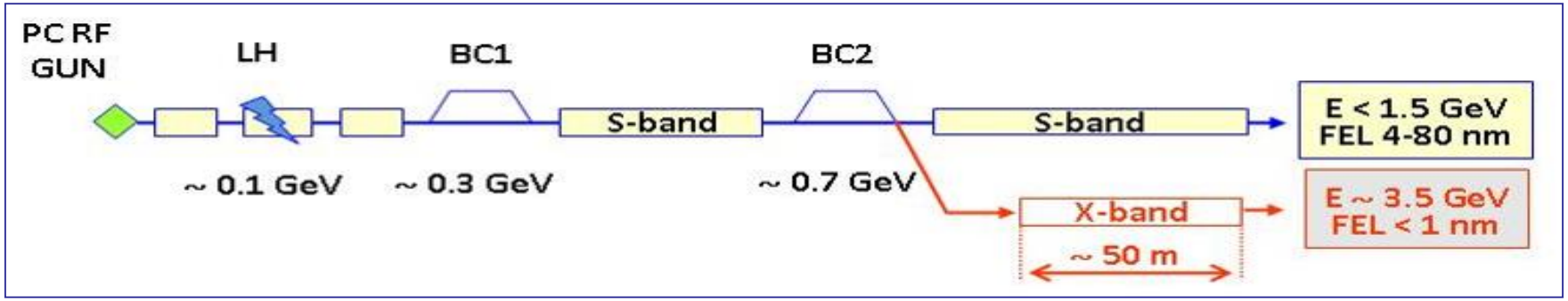
The advantage of using X-band:

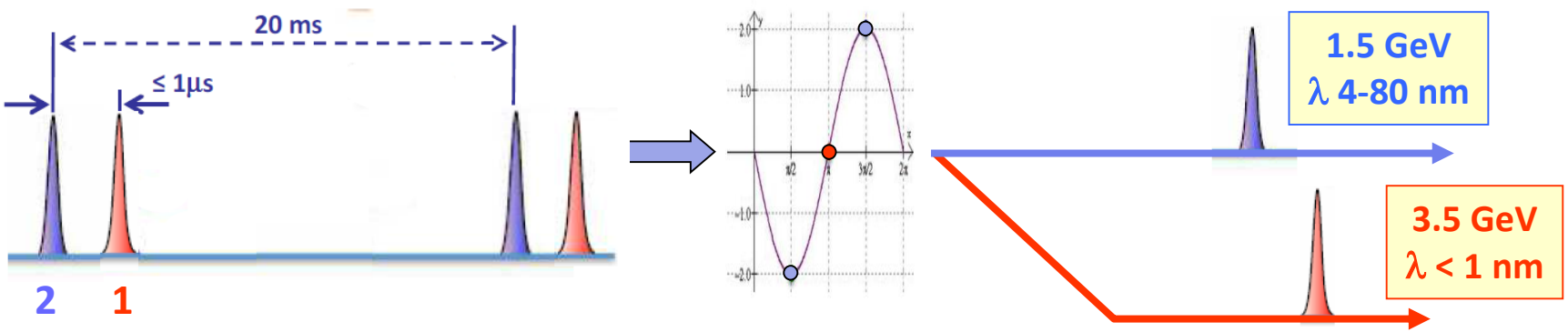
- Compact reduction of length with high gradient
- Costs reduction
- Possibility to go to a high repetition rate (up to kHz regime)

Turkish project

Courtesy of A. Aksoy

FERMI perspectives





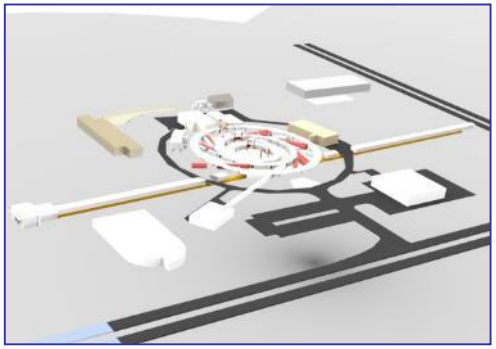
S-band linac
two e-bunches/RF pulse

HF bunch separator

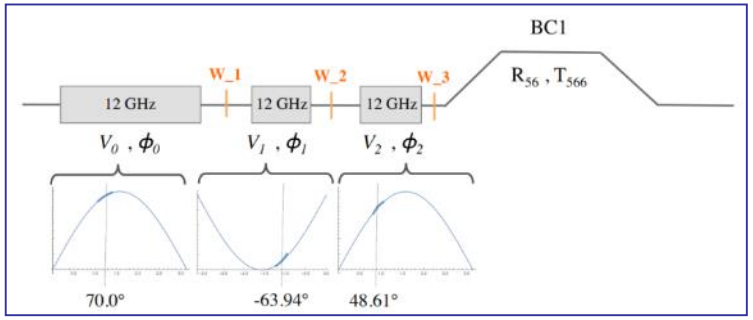
Two separate linacs at 50 Hz
S-band → 1.5 GeV
X-band → 3.5 GeV

X-Band Activities in Australia

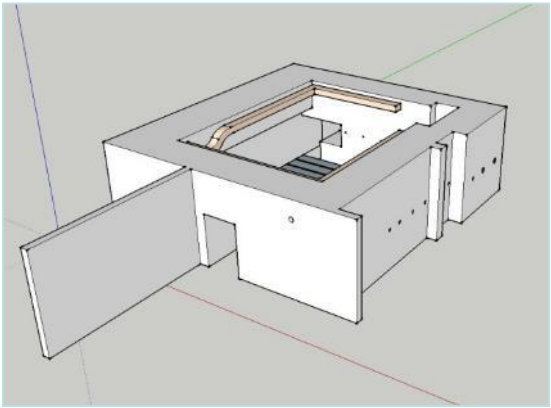
- **Part of the XbFEL Collaboration spun out from CLIC, planning XbFEL as an upgrade path for the Australian Synchrotron light source.**
- **Modelling all XbFEL linac with novel linearlisation scheme.**
- **Propose an "XBOX3" type test stand at the University of Melbourne.**



Concept drawing of AXXS Australian X-Band X-Ray Source. (M. Boland)



Phase Modulation Linerisation in an all X-band Linac (T. Charles *et. al.* , Proceedings of IPAC 2015)



Bunker for former 35 MeV betatron at the University of Melbourne. (M. Boland)

Courtesy of M. Boland

Shanghai Photon Science Center at SINAP

SXFEL: Shanghai Soft X-ray FEL
S-band, C-band, X-band
Energy: 0.84GeV (Phase I),
1.3GeV (Phase II)

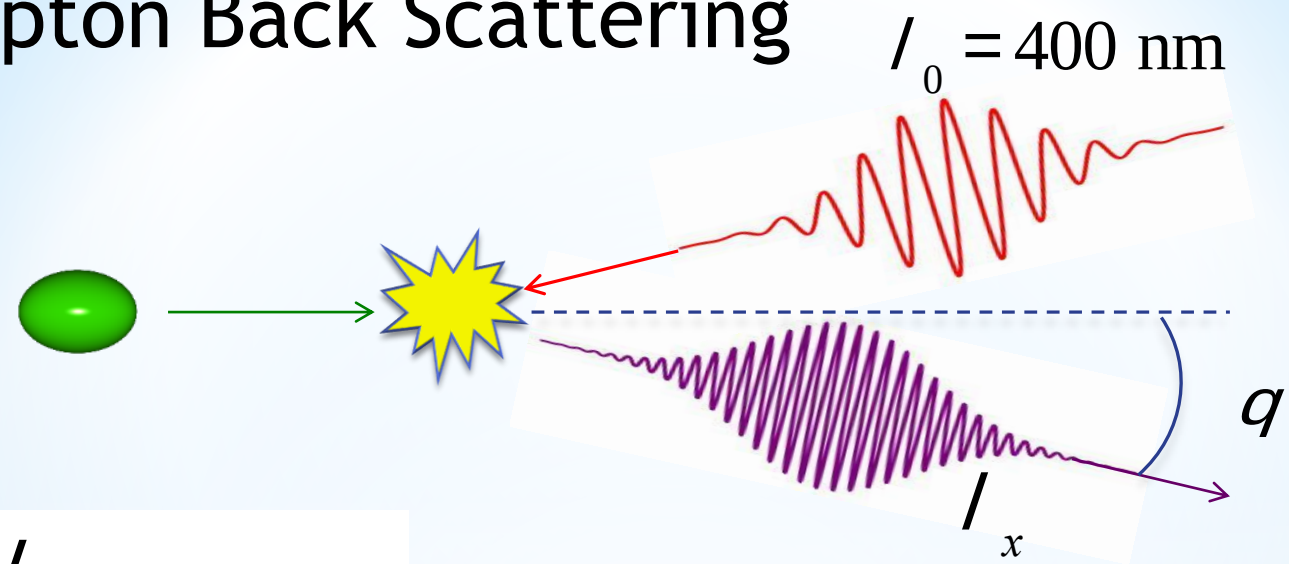
Compact hard X-ray FEL (X-band, S-band)
Energy: 6.5GeV, 8GeV (200m linac)
Total length: About 550 meters

SSRF: Shanghai Synchrotron Radiation Facility
Energy: 3.5GeV, user operation

Courtesy of W

Compton-scattering X-ray source –very high energy X-rays and/or compact sources for biology, chemistry, material science, etc.

Compton Back Scattering



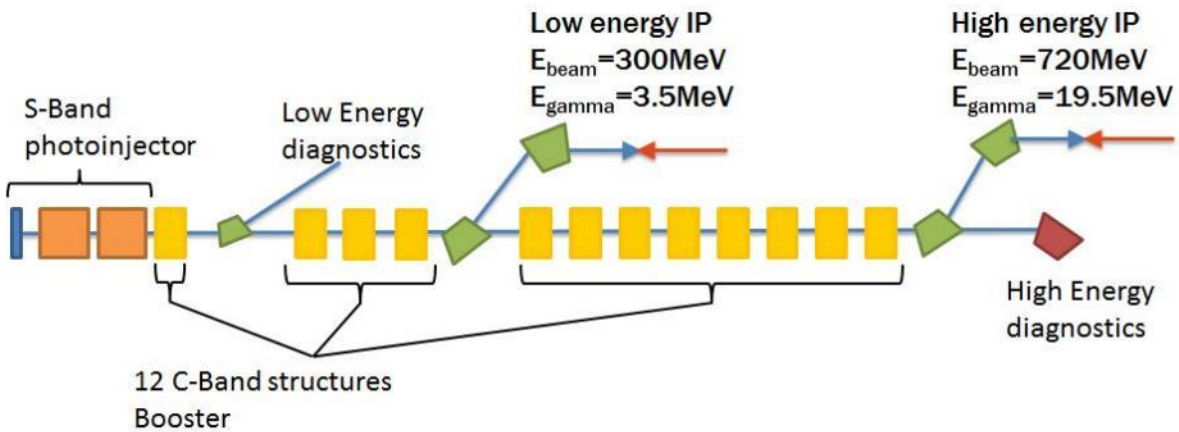
$$l_x = \frac{l_0}{4g^2}(1+g^2q^2)$$

- 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	Emission angle 0.1 γ^{-1}
5 MeV	11	8.6 Å	1.4 keV	9 mrad
15 MeV	30	1.1 Å	11 keV	3 mrad
30 MeV	60	0.28 Å	44 keV	1.7 mrad
45 MeV	89	0.13 Å	98 keV	1.1 mrad

ELI-NP GAMMA BEAM SYSTEM

An advanced **Source of Gamma-ray photons** will be built in Magurele (Bucharest, **Romania**) in the context of the **ELI-NP** Research Infrastructure by the "EuroGammaS" Association. 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 an energy of the gamma photons tunable between 1 and 20 MeV with a narrow bandwidth (0.3%) and a high spectral density (10^4 photons/sec/eV). The machine is based on a RF Linac operated at C-band (5.712 GHz) with an S-band photoinjector delivering a high phase space density electron beam in the **300-720 MeV energy range**. The repetition rate of the machine is **100 Hz** and, within the RF pulse, up to **32 electron bunches** will be accelerated, each one carrying **250 pC** of charge, separated by **16 ns**. The linac booster is composed of **12 TW C-Band** disk loaded accelerating structures, each structure, 1.8 m long, is a quasi-constant gradient structure with $2\pi/3$ field phase advance per cell.



Bunch charge	250 pC
Number of bunches	32
Bunch distance	16 ns
C-band average accelerating gradient	33 MV/m
Norm. emittance	0.4 mm·mrad
Bunch length	<300 μm
RF rep Rate	100 Hz

The **"EuroGammaS" Association** is 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.

MOTIVATION OF THE ACCELERATING STRUCTURES CHALLENGES IN THE ELI-NP GBS PROJECT

To increase the gamma flux we need to **increase the number of collision per second** → **100 Hz** repetition rate

Multi bunch

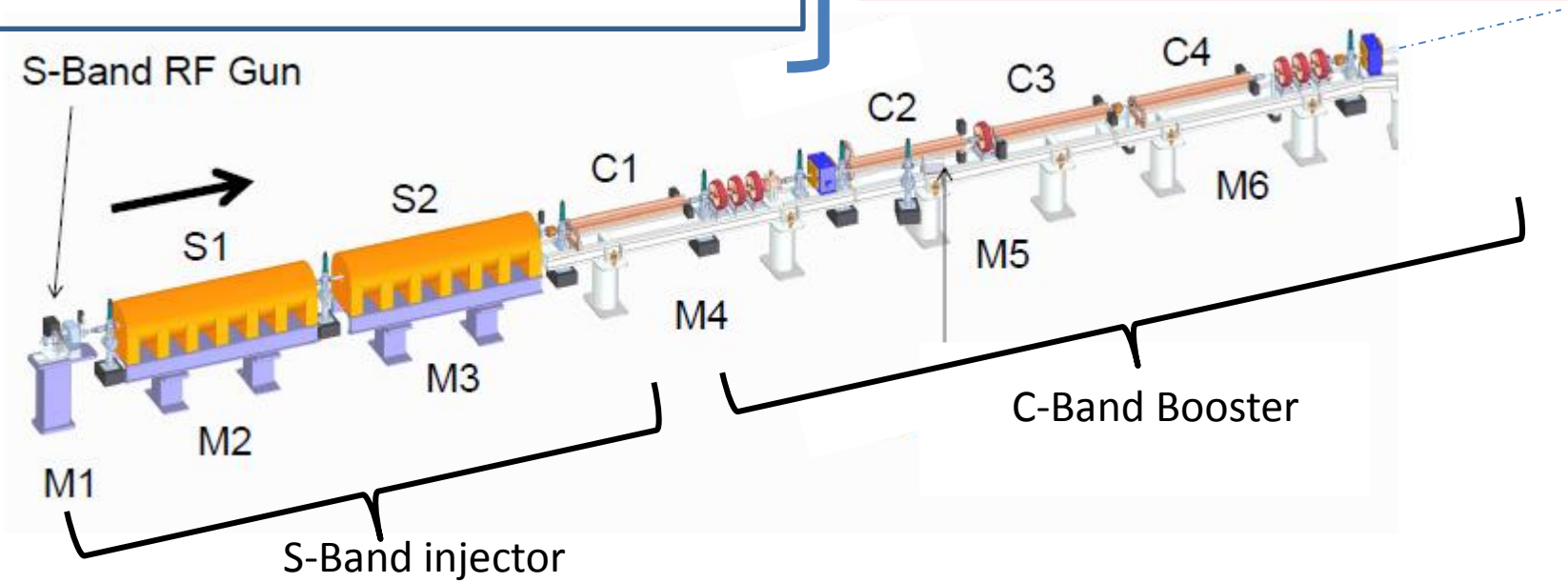
-**Damping of HOM** in RF structures to avoid BBU instabilities

-Compensation of **beam loading effects**

-**accurate thermal design (high average dissipate power)**

To reduce the accelerator overall dimensions: **compact system** → **High gradient**

-C-band LINAC combined with an S-band Injector is the best compromise between BD and compactness of the system



C-BAND STRUCTURES: HIGH POWER TEST RESULTS (1/2)

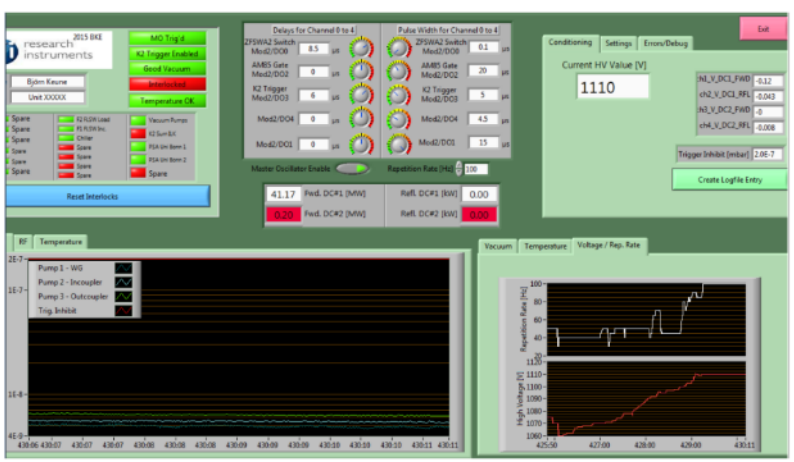
The aim of the RF conditioning is to reach **40 MW** at the input coupler at **100 Hz** repetition rate and **820 ns** pulse width. The **conditioning started at 10 Hz, 100 ns** input pulse and minimum power. The **forward/reflected power signals** at the input coupler and output coupler were measured using diodes from INFN and an oscilloscope. These readings were recorded to the Labview GUI which calculates the corresponding power levels.

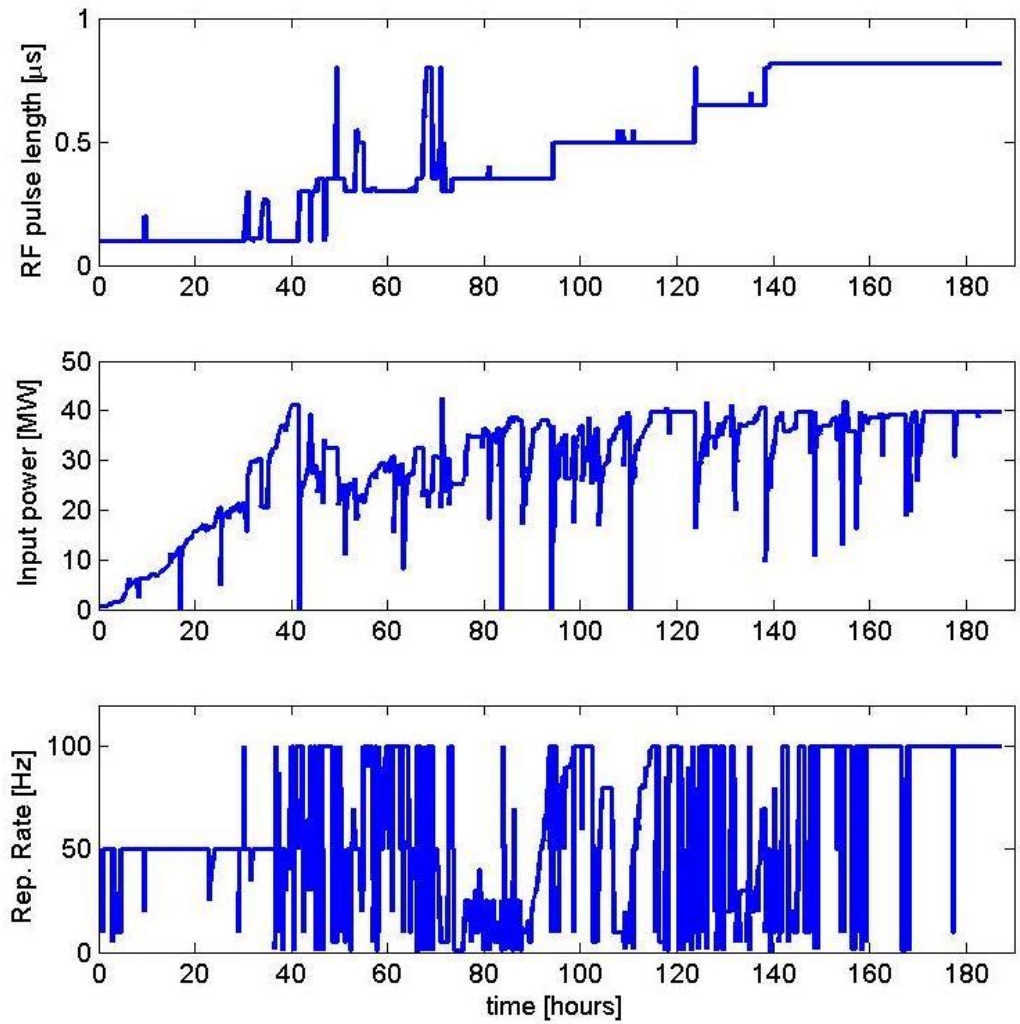
The conditioning of the structure **started on 18.03.2015 and ended on 23.04.15**. The klystron power was progressively increased (by increasing the HV of the modulator) and the current of three ion pumps connected around the structure and the RF signals from pickups were monitored.

The **conditioning procedure was semi-automatic** and the switch-off on the HV were caused by:

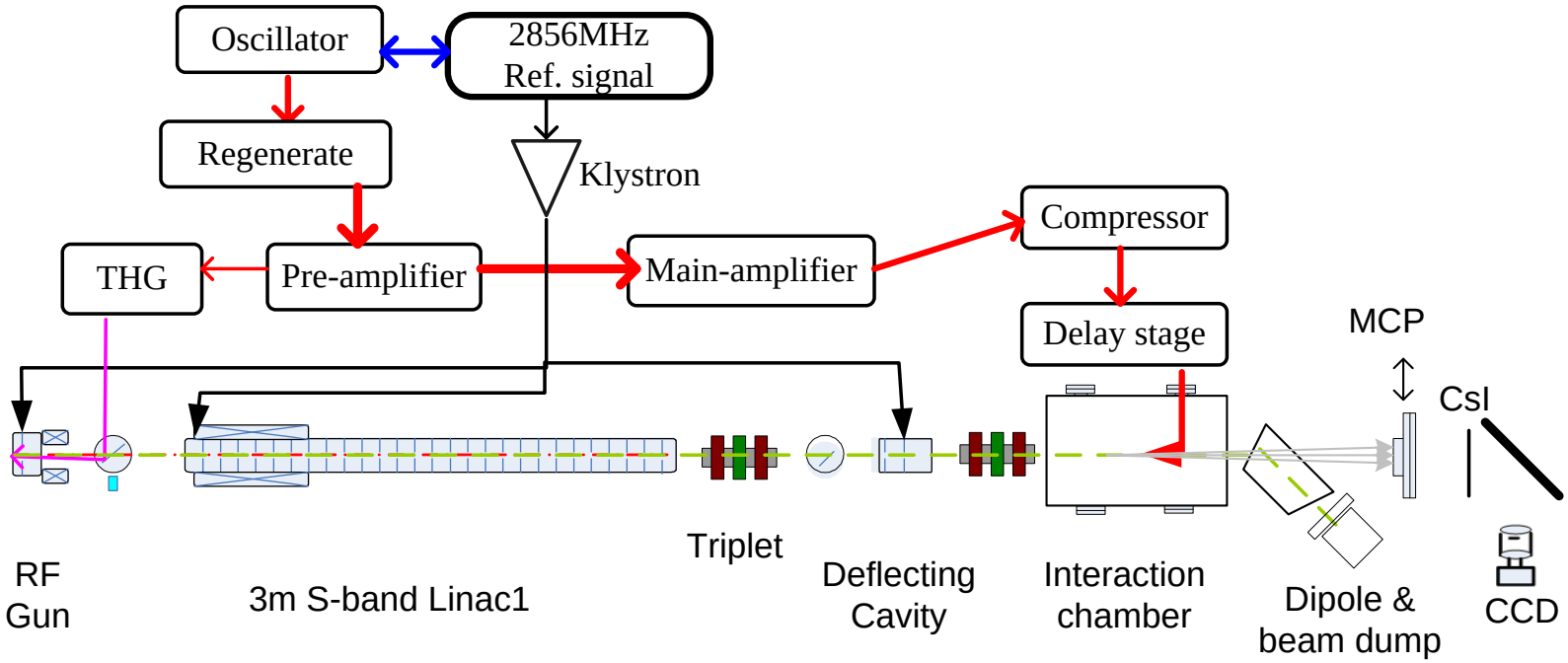
(a) operators;
(b) threshold on the ion pumps current absorption (>1x10^{-7} mBar)
(c) reflected power to the klystron exceeding a certain threshold.

The RF conditioning for the first RF structure lasted about **190 hours**





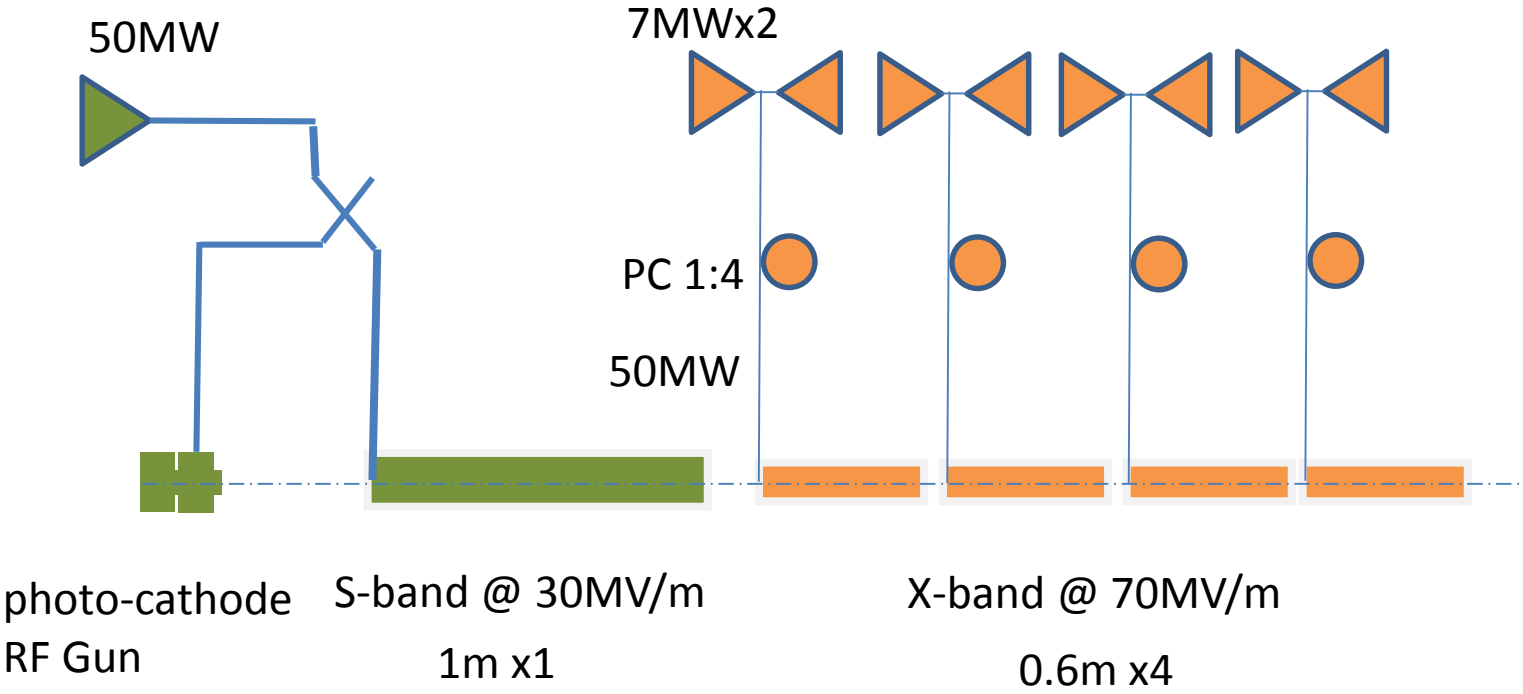
Tsinghua Thomson scattering X-ray source (TTX)



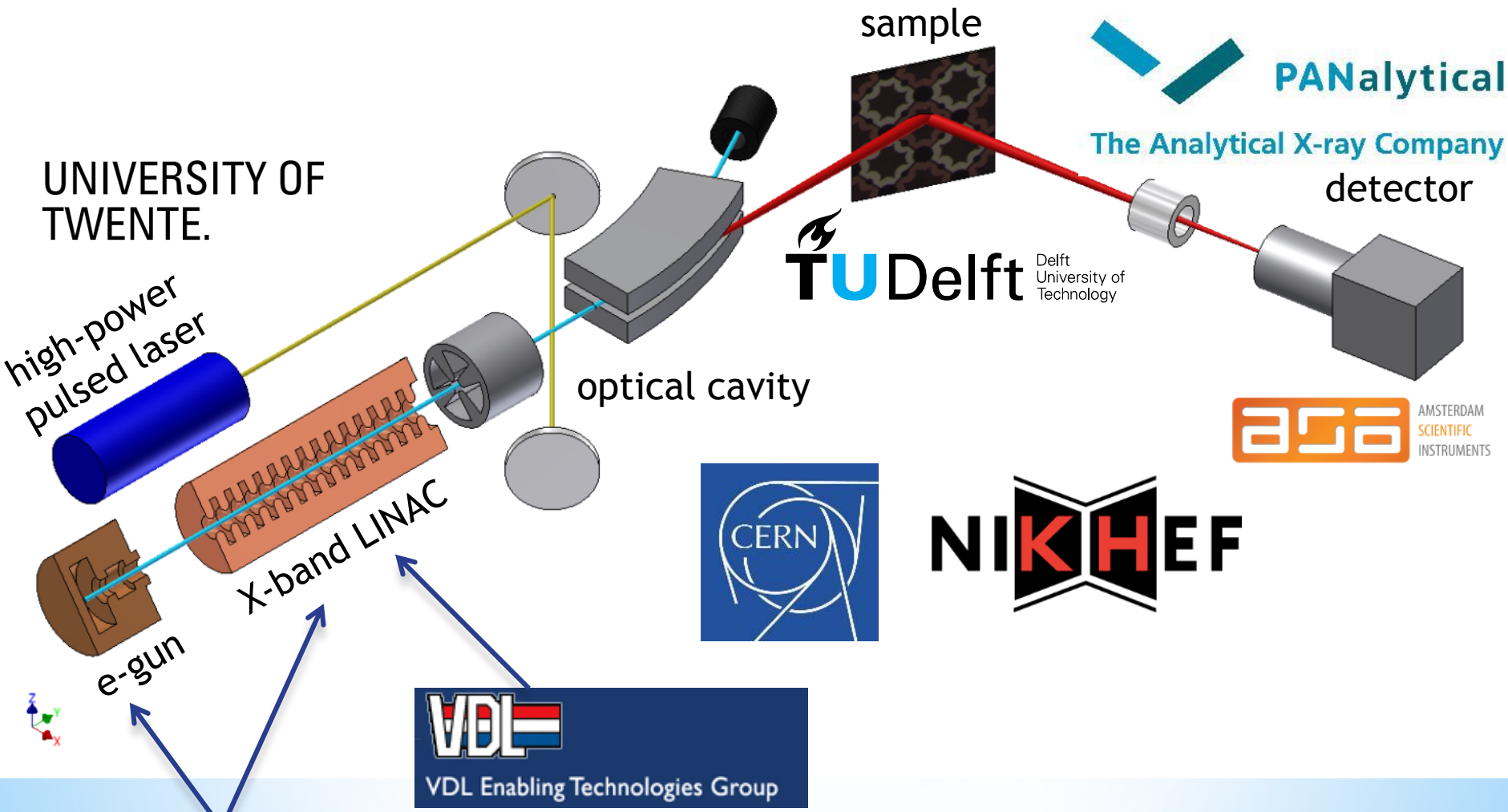
Electron beam		Laser beam	
Energy	45MeV	Wavelength	800nm
Bunch length	1~4ps	Pulse duration	~30fs
Charge	~0.7nC	Pulse energy	~500mJ
Beam size	30x25um	Beam size	~30um

Parameters of Scattering X-ray	
Photon energy	24(90deg)~48(180deg)kev
Pulse duration	0.16(90deg)~3(180deg)ps
Number photons	$8.4X10^6$(90deg)~$5.5X10^7$(180deg)

200MeV linac layout (Preliminary design)

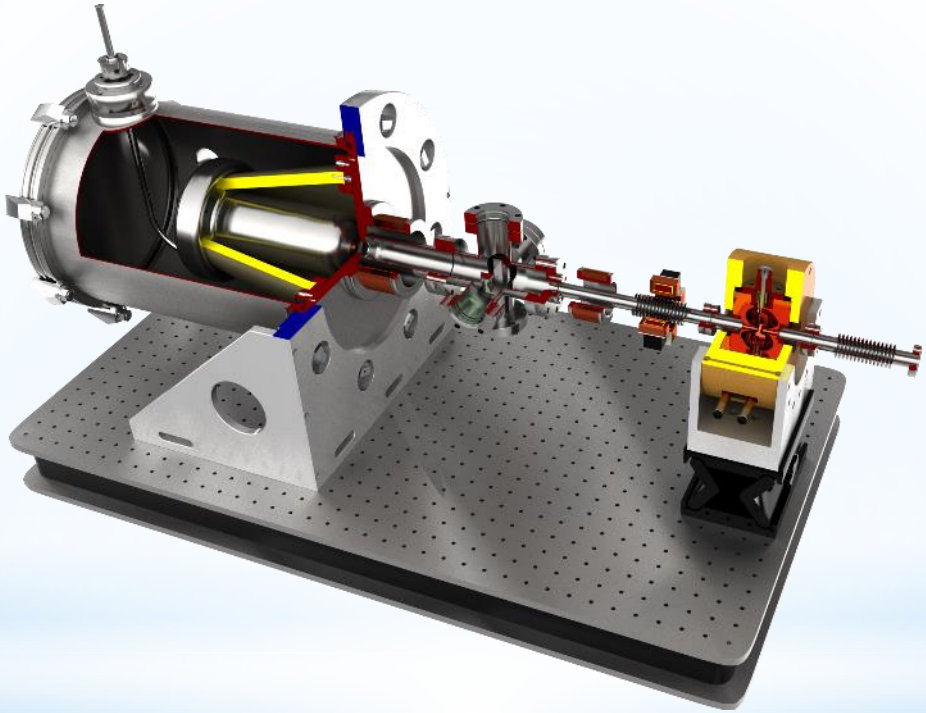


Compton Back Scattering source



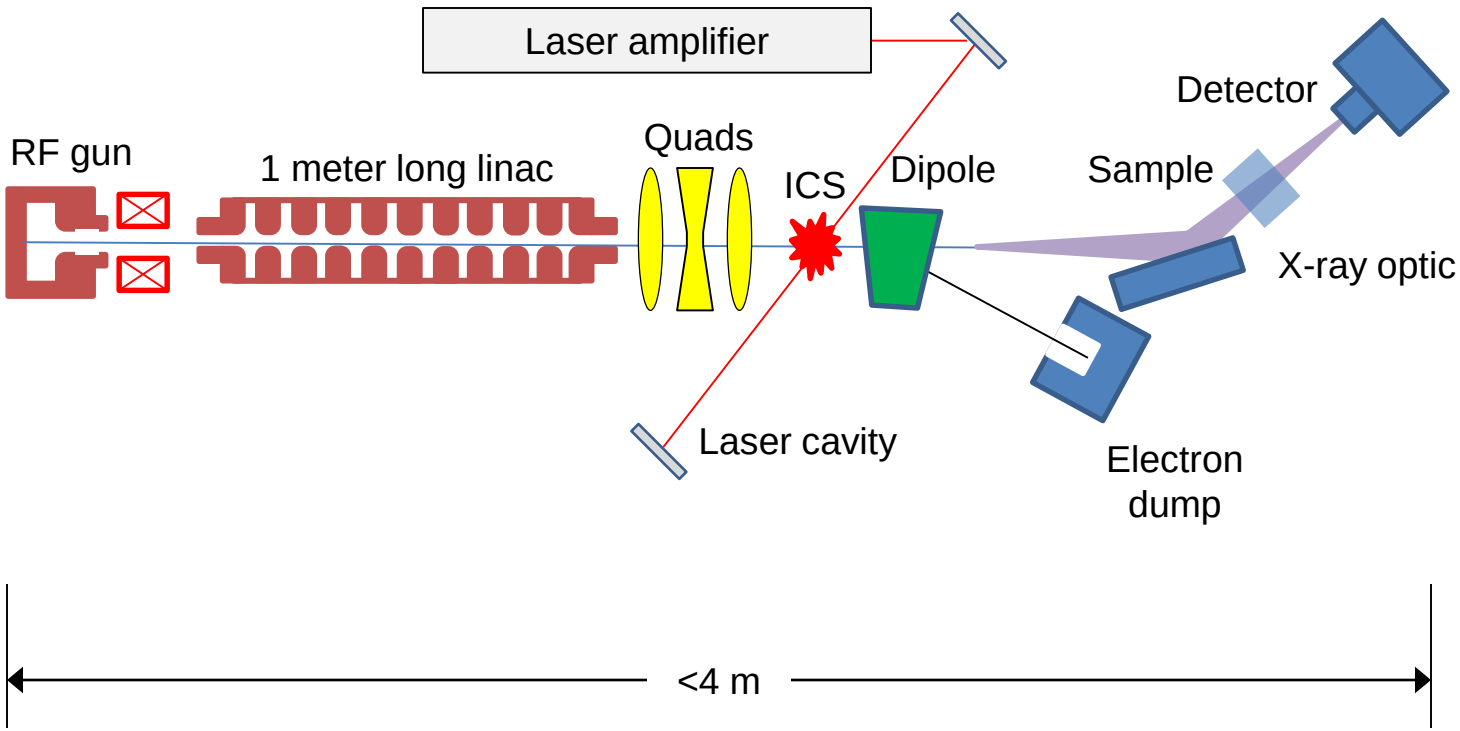
TU/e Technische Universiteit Eindhoven University of Technology

Low-emittance pulsed electron gun

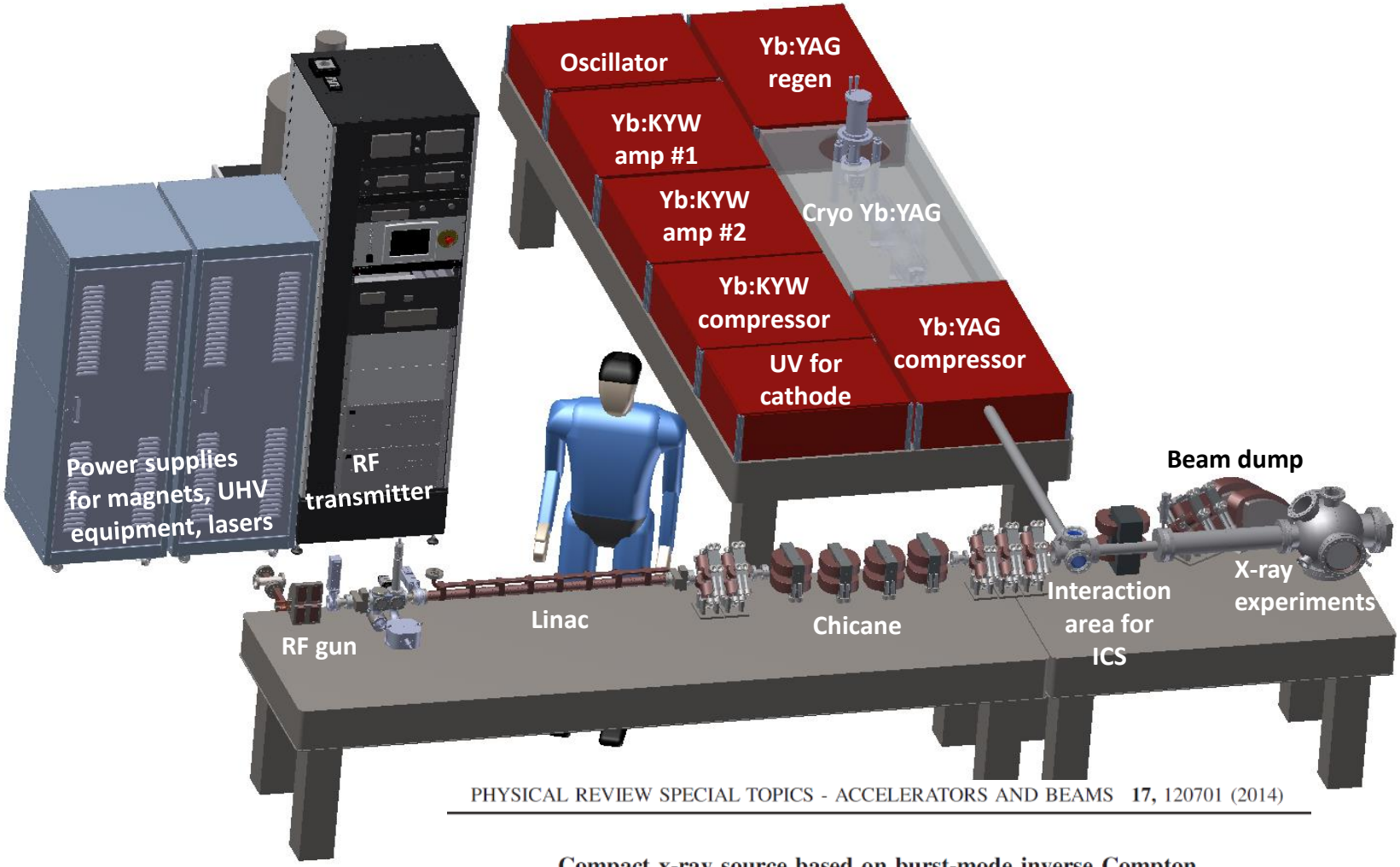


- 100 keV DC electron gun;
- pulsed operation by femtosecond laser photoemission;
- 1 pC bunches @ 40 nm rad normalized emittance;
- 10 pC bunches @ 120 nm rad normalized emittance;
- developed @ TU/e, sold through AccTec BV;
- currently under development: pulsed CeB_6 thermionic operation.

Basic Layout for ICS



Compact X-ray Light Source (CXLS)



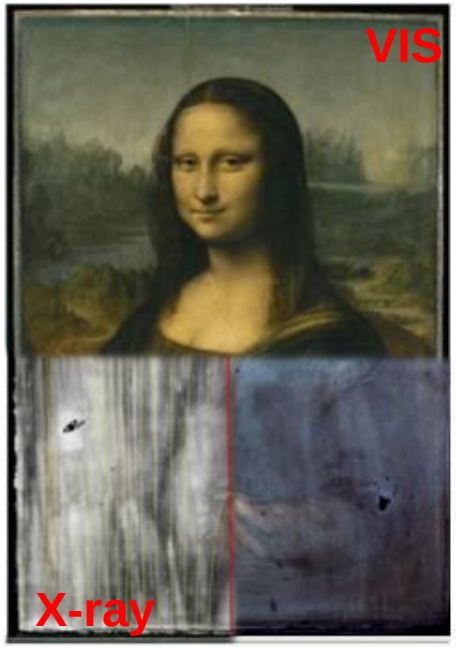
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 120701 (2014)

Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz

W. S. Graves,[1,*] J. Bessuille,[2] P. Brown,[2] S. Carbajo,[3] V. Dolgashev,[4] K.-H. Hong,[1] E. Ihloff,[2] B. Khaykovich,[1] H. Lin,[1] K. Murari,[3] E. A. Nanni,[1] G. Resta,[1] S. Tantawi,[4] L. E. Zapata,[1,3] F. X. Kärtner,[1,3] and D. E. Moncton[1]

Cultural Studies - Louvre

-Philippe Walter



Objectives: Research, expertise and support for curators and conservators thanks to physico-chemical analyses.

Ø Necessity of non destructive testing with high sensitivity because the studied materials are very complex

1989: Installation of the accelerator AGLAE in the Louvre = ion beam analysis with an external microbeam (elemental analysis, direct on the artifacts)

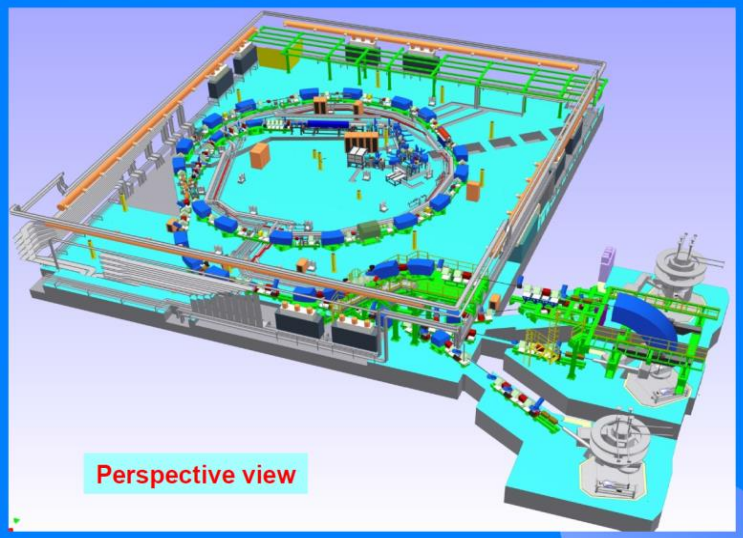
1997: Development of synchrotron radiation analysis = structural and molecular analysis but necessity of samples

2009: Project of combination of AGLAE with an ICS in the Louvre for non destructive structural and elemental analysis (XRF, XANES, XRD) as well as for 3D imaging of works of art.

Medical linacs – proton and carbon ion beams for cancer therapy

Walter Wuensch, CERN

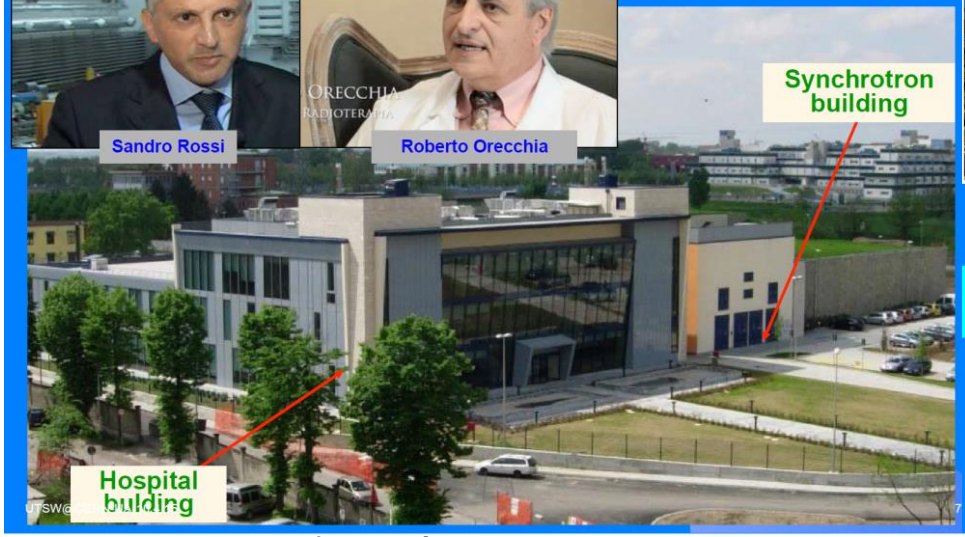
CNAO at Pavia



MedAustron is being completed in Wiener Neustadt

MedAustron bought from CNAO Foundation the construction drawings for 4 million Euro (agreement with CERN-CNAO-INFN)

CNAO = Centro Nazionale di Adroterapia Oncologica

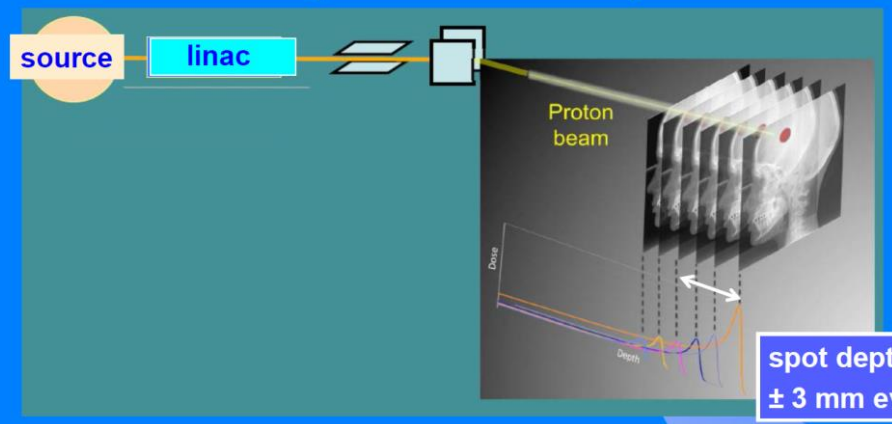


MedAustron participated in PIMMS

Protons have been sent to treatment room

With linacs the dose deposition depth can be adjusted every 3 ms

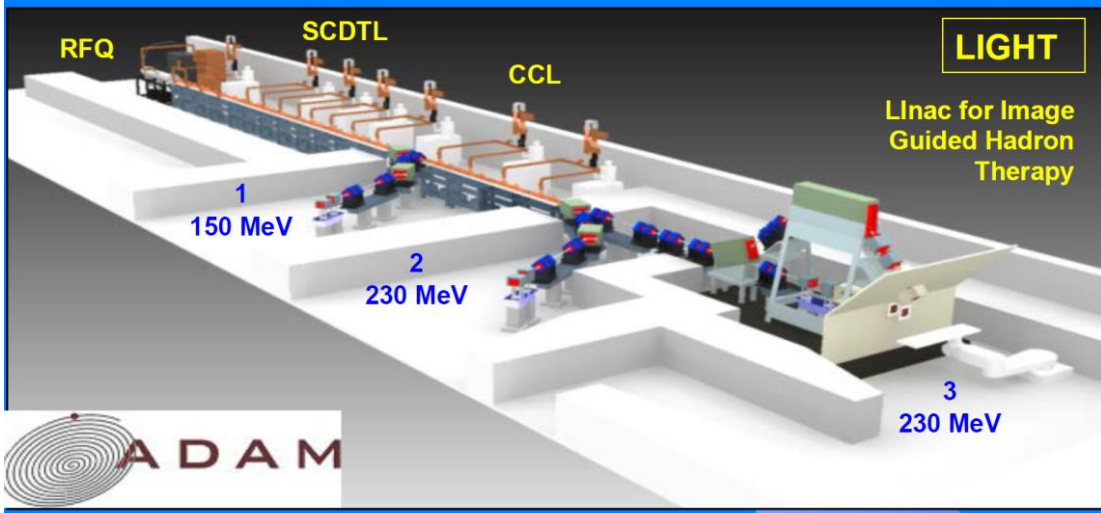
linac pulses: 200 - 400 times per second



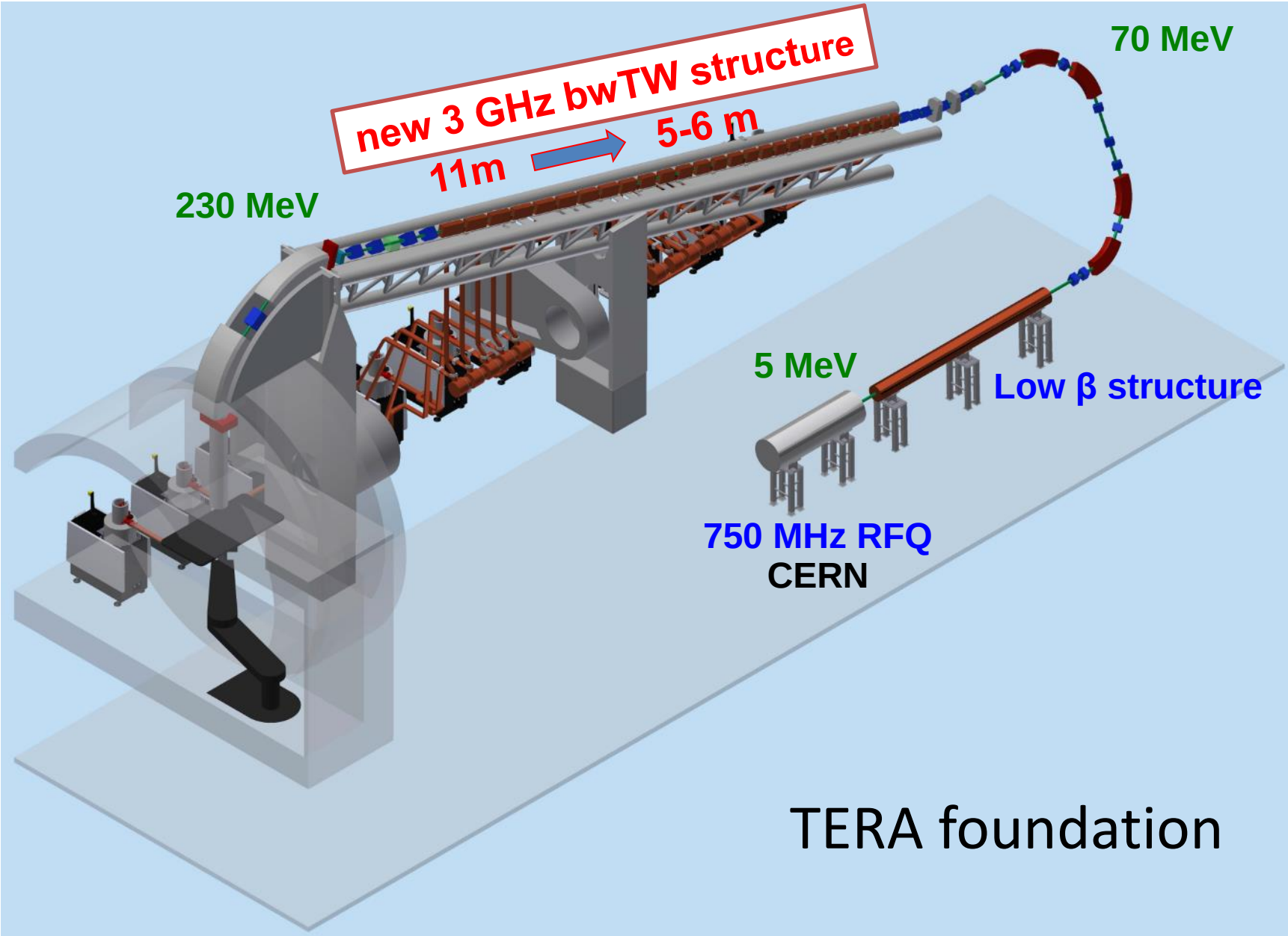
spot depth:
± 3 mm every pulse

To follow moving organs in 4D - with spot scanning, motion feedback and more than 10 paintings - the beam time structure of linacs is better than the ones of cyclotrons and synchrotrons

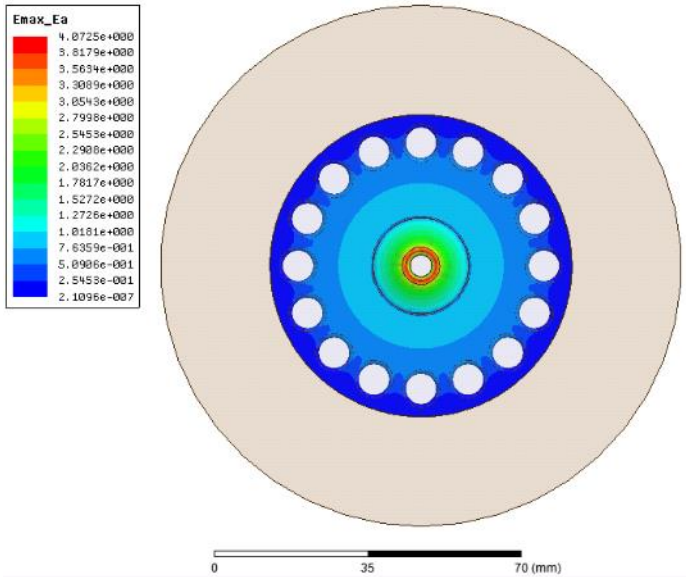
Centre offered by A.D.A.M. – a CERN spin-off Company



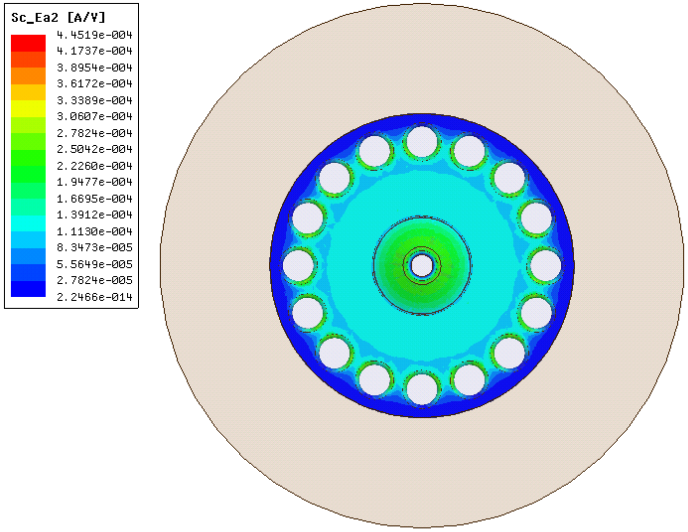
The TULIP Project



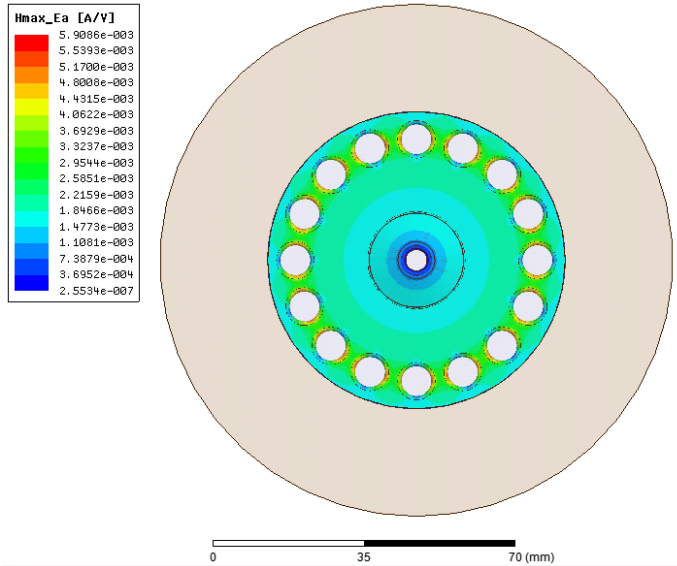
RF design and diamond machined disk



E

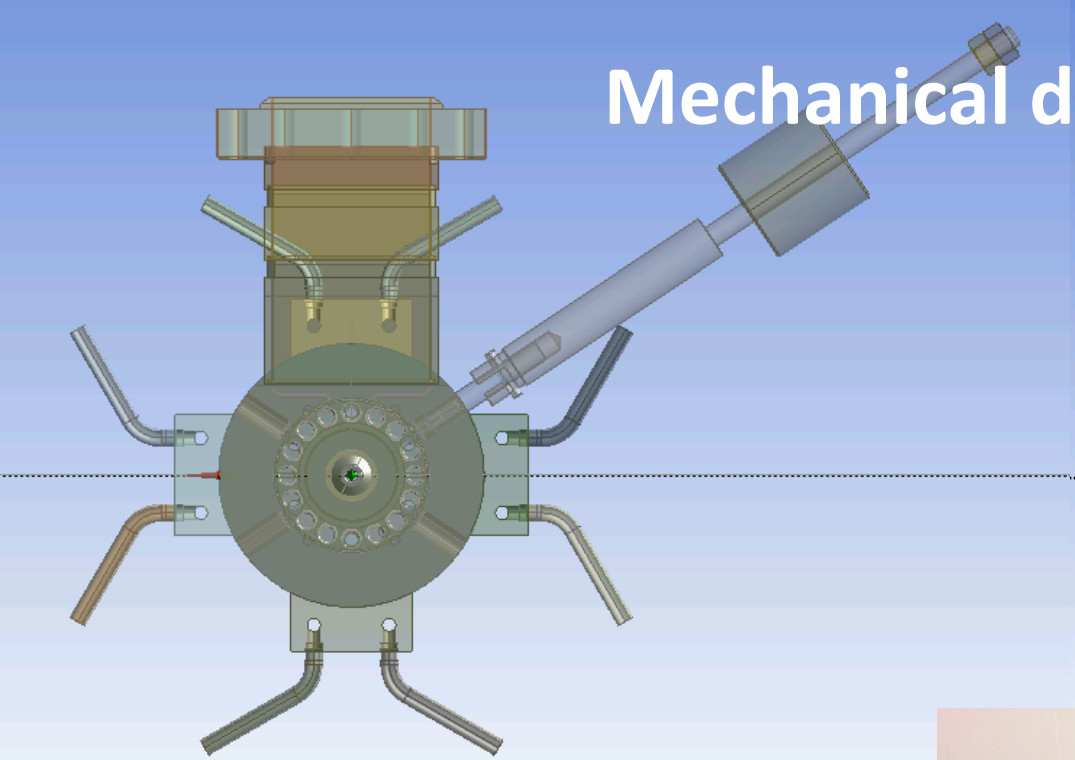


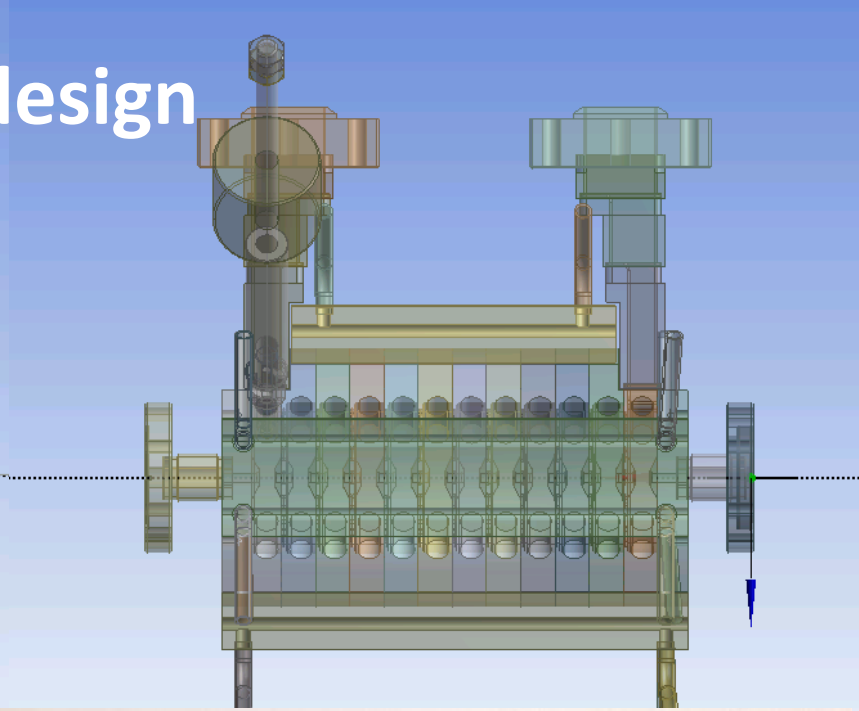
S_c

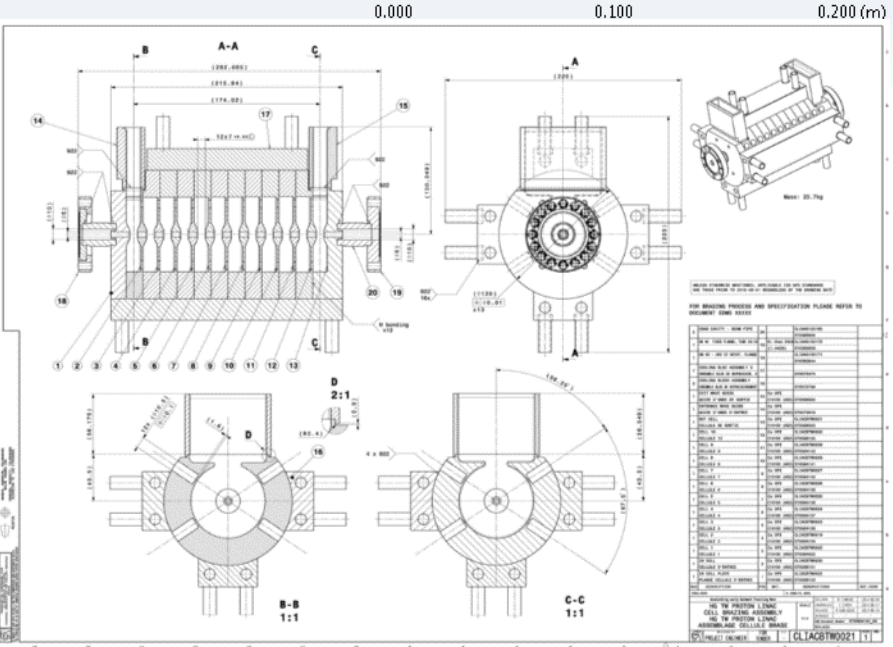


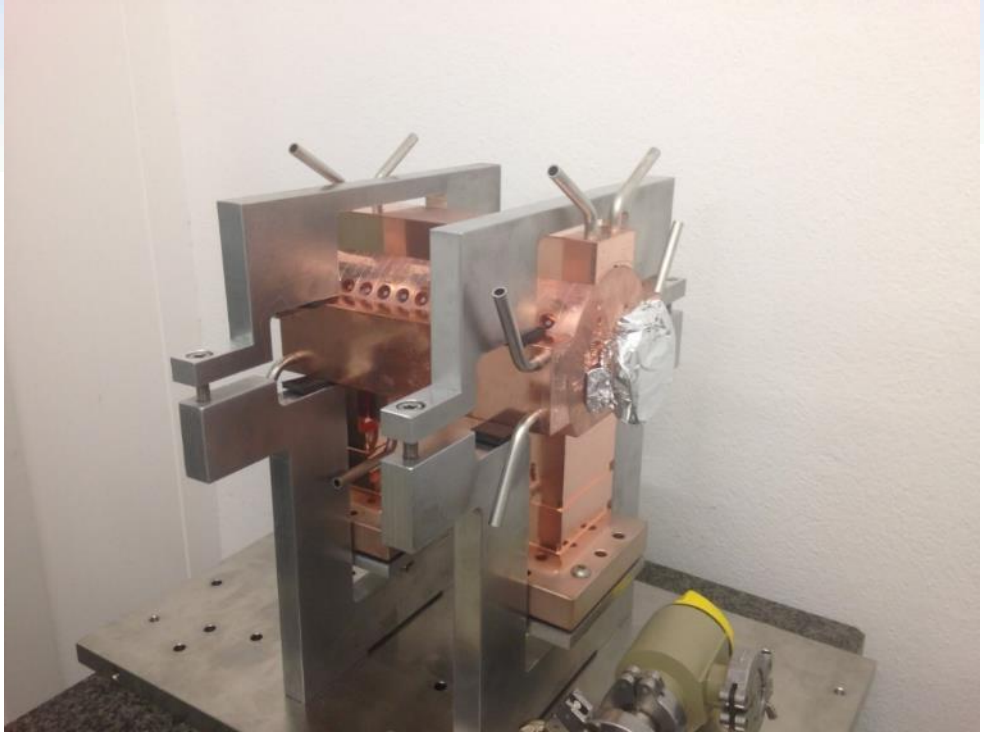
B

Mechanical design







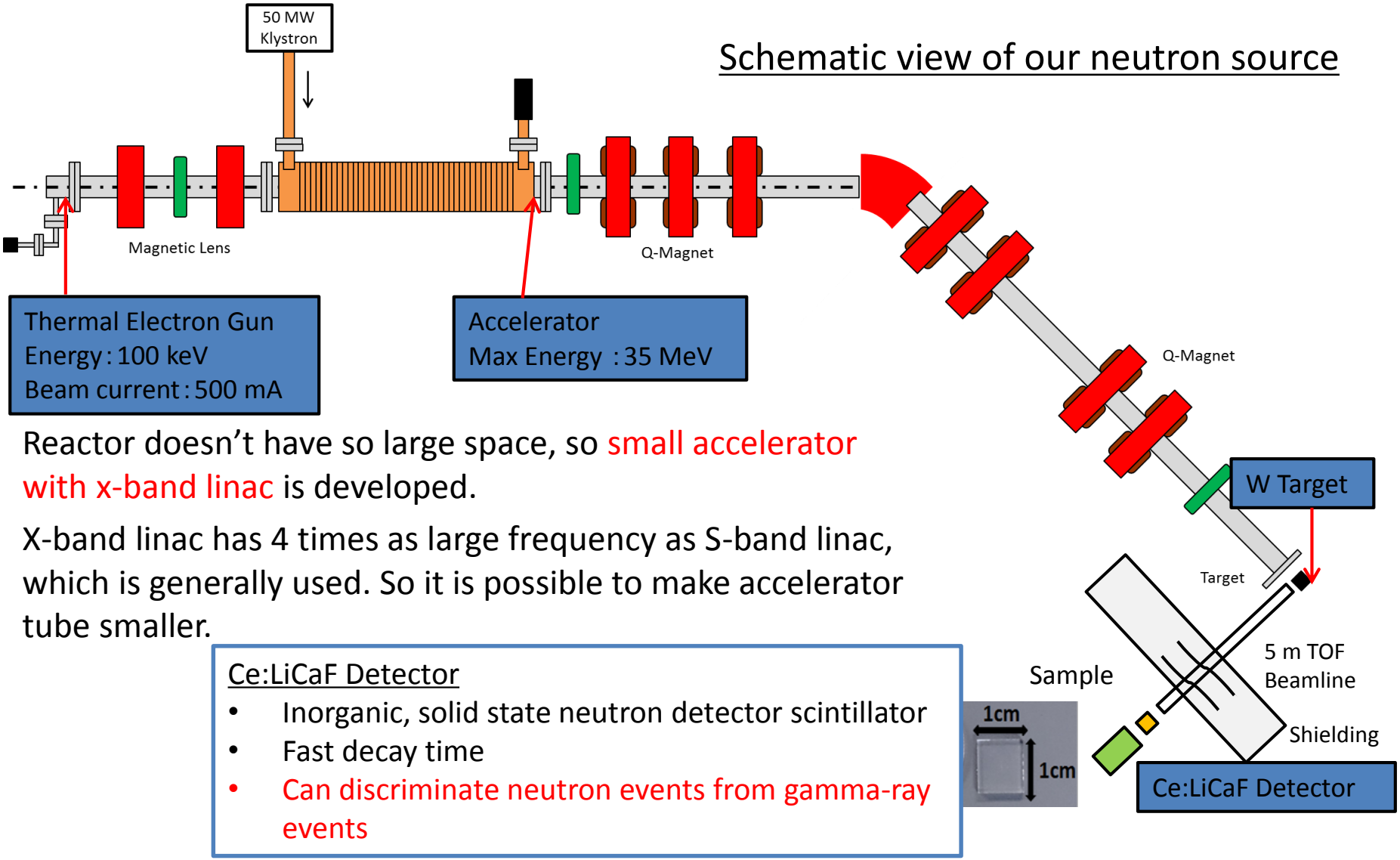


Pulsed neutrons – very short neutron bunches for time-flight-measurements for nuclear physics

Walter Wuensch, CERN

Neutron Source in Univ. of Tokyo

Schematic view of our neutron source



- Reactor doesn't have so large space, so small accelerator with x-band linac is developed.
- X-band linac has 4 times as large frequency as S-band linac, which is generally used. So it is possible to make accelerator tube smaller.

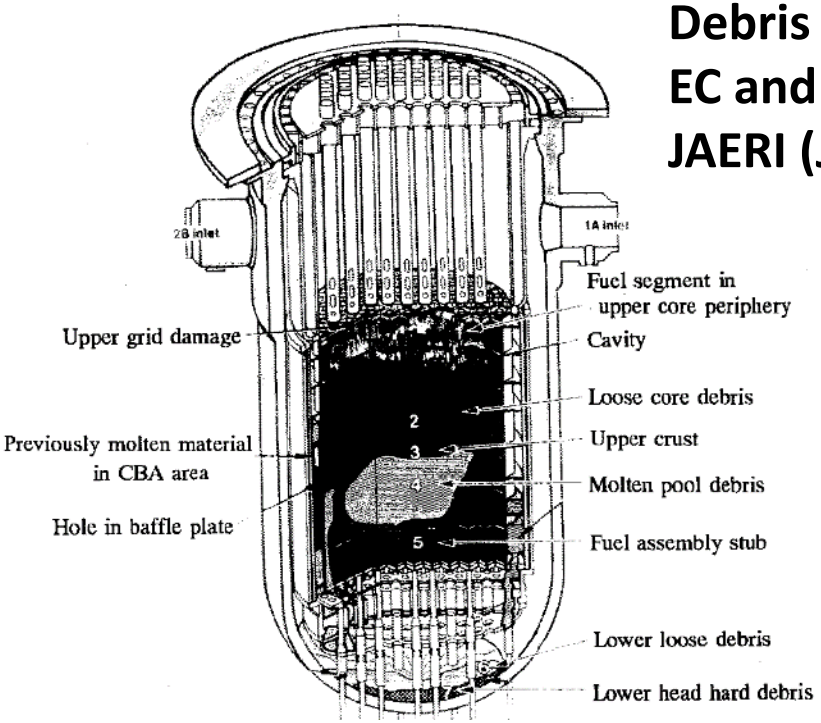
Ce:LiCaF Detector

- Inorganic, solid state neutron detector scintillator
- Fast decay time
- Can discriminate neutron events from gamma-ray events

Hideo Harada (JAEA)

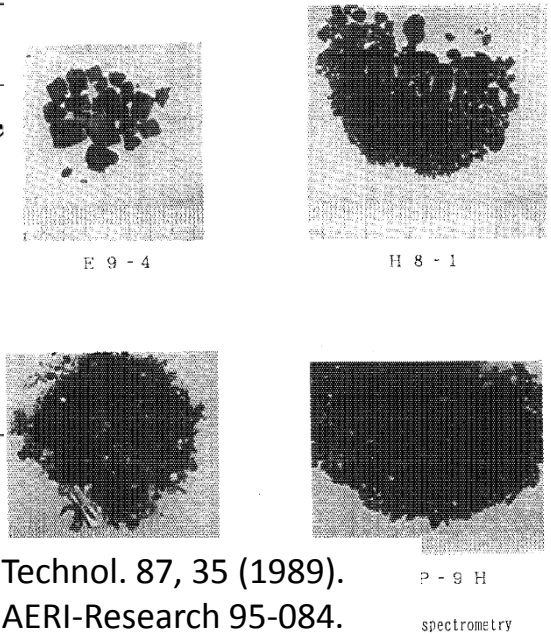
Research Background and Purpose

Debris in TMI-2 have been analyzed by INEL (USA).
EC and Canada also analyzed debris supplied by USA.
JAERI (JAEA) also analyzed debris obtained at 1991.



Sampling Positions

1) Upper core fuel rod segme
2) Upper core loose debris
3) Crust debris
4) Molten pool debris
5) Fuel stab
6) Lower head loose debris
7) Lower head hard debris



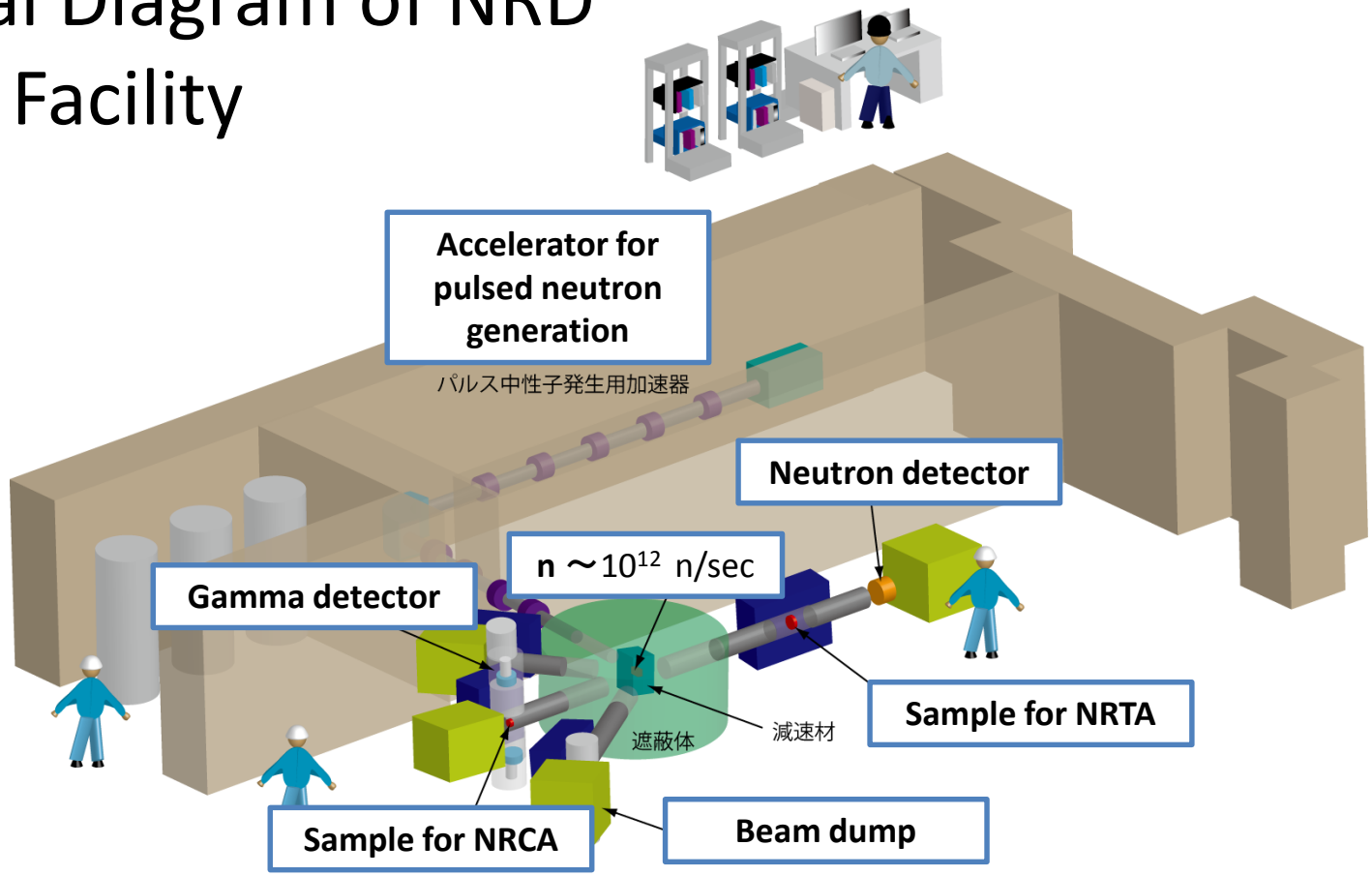
J. M. Broughton, *et al.*, "A Scenario of the Three Mile Island Unit 2 accident", Nucl. Technol. 87, 35 (1989).
H. Uetsuka, *et al.*, "Gamma Spectrometry of TMI-2 Debris" (written in Japanese), JAERI-Research 95-084.

Non-destructive measurement method of nuclear fuels in melted core hasn't been developed yet.

Quantity of nuclear materials in melted cores which are generated in nuclear accident like Fukushima is measured by non-destructive and high accuracy methods

Conceptual Diagram of NRD Facility

Hideo Harada (JAEA)



- **By NRTA, 3-7 kg of small sized MF will be measured within 20 min. (The 3-7 kg: a MF area of 300-700 cm^2 and a thickness of 10 g/cm^2).**
- **By NRCA, 30 g of MF including 10^9 Bq (mainly ^{137}Cs) will be measured within 1 hour for each beam line.**

Conclusions

High-gradient rf is a rapidly maturing technology.
There are a number of applications which are considering its use.
We hope to see it used in many applications in the coming years.

Thank you for your attention!