High-Gradient Accelerator Development and Applications
Part 2

Vacuum breakdown

You saw in Flyura's lectures an in-depth introduction to vacuum breakdown. Narrative recap:

On the microscopic scale:

High surface electric fields cause field emission of electrons from a cathode surface and transfer of electrode atoms to vacuum. The electrons ionize some of the (copper) atoms, now positively charged, which are accelerated back to the electrode surface. On impact, they eject more copper, that gets ionized, a plasma forms, with it a plasma sheath, more electrons are emitted – avalanche! This all occurs on small surface, something of the order of a few tens of microns across, and it happens quickly, in a few nanoseconds.

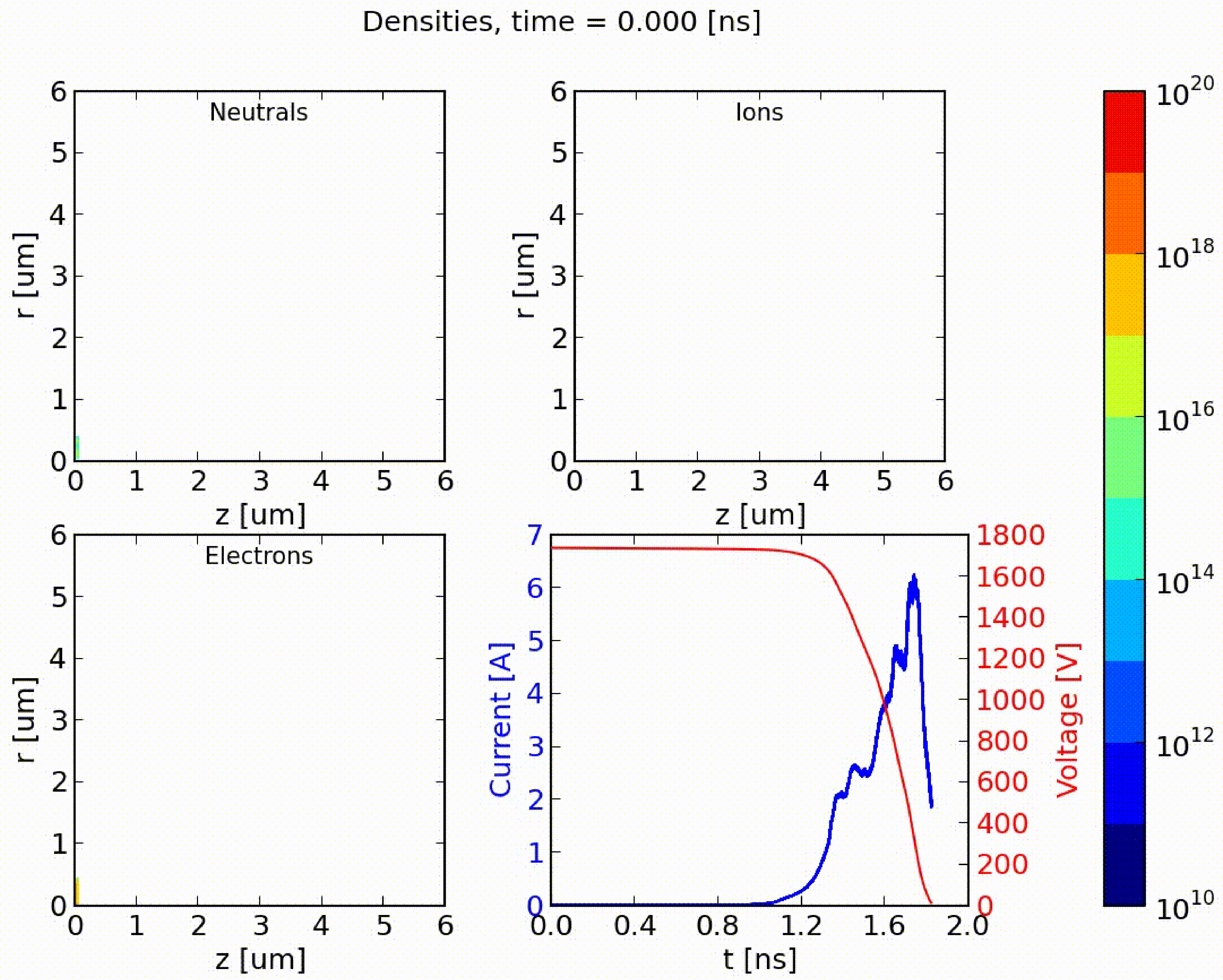
On the macroscopic scale:

A high voltage, or high field in the case of rf, system starts with a lot of electromagnetic energy stored in the fields and power supply of the system. It stays where it is because the vacuum is insulating. A breakdown generates a conducting zone in the vacuum, the high currents that drain the stored energy of the system and cause a sudden and substantial modification of the electromagnetic fields in the system.

Accelerator scale:

The currents and collapsing fields mean that our accelerating structures don't. The collapsed fields give less acceleration and transverse breakdown currents distort and kick the beam.

Microscopic scale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0.4
0.8
1.2
1.6
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10^{10}
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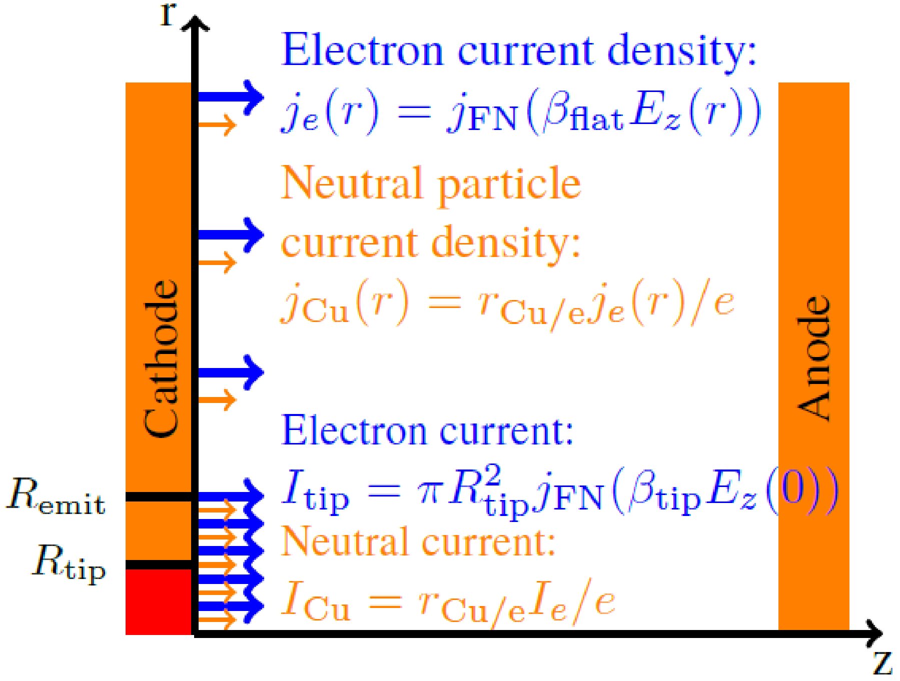
10^{14}
10^{16}
10^{18}
10^{20}

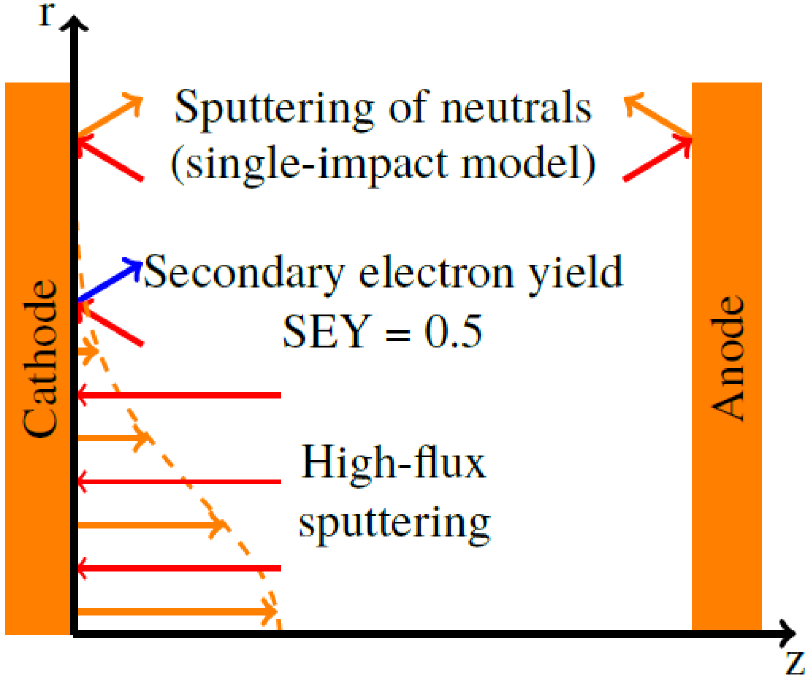
What's going on inside.

ArcPIC simulation of the onset of breakdown, starting from field emission and going through the formation of a plasma, a plasma sheath and dramatically rising emitted current.

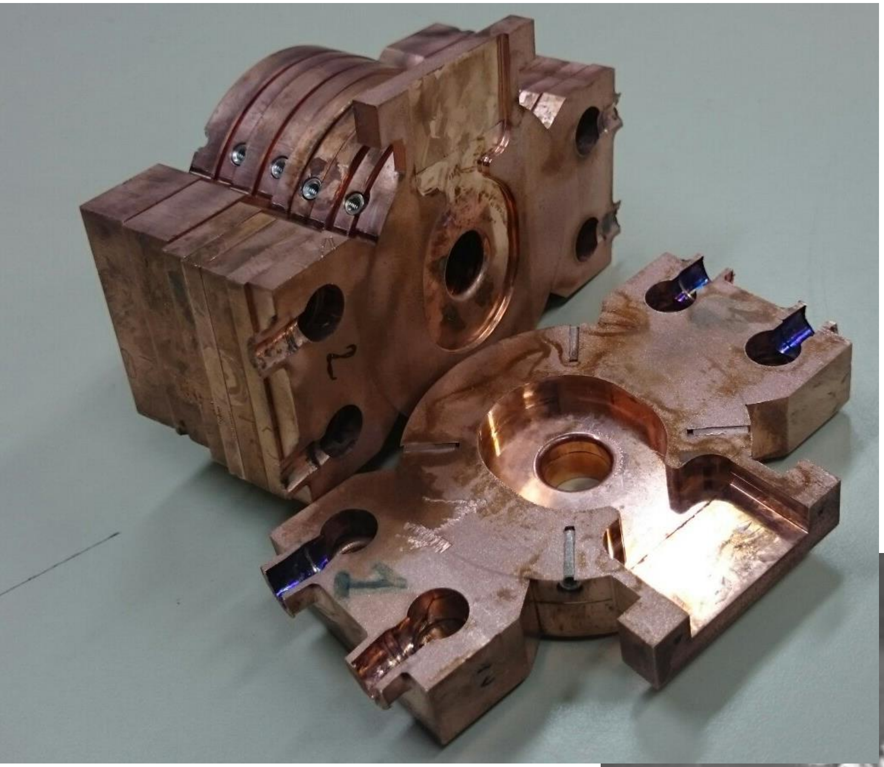
The code is ArcPIC and simulates a 20 micron wide dc gap. https://doi.org/10.1002/ctpp.201400069



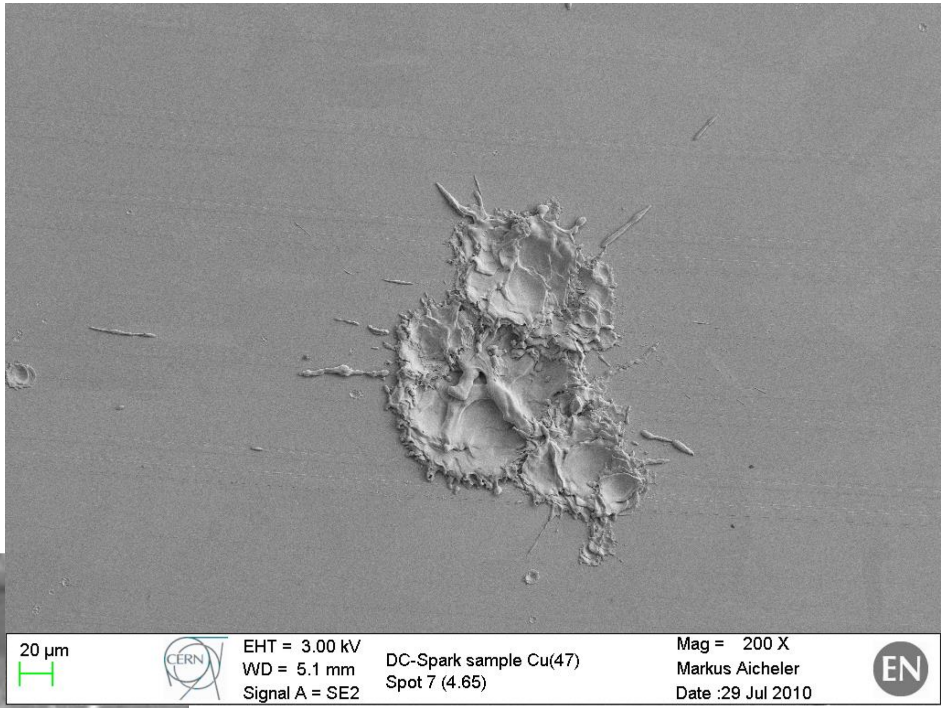
(a) Field emission and neutral evaporation.

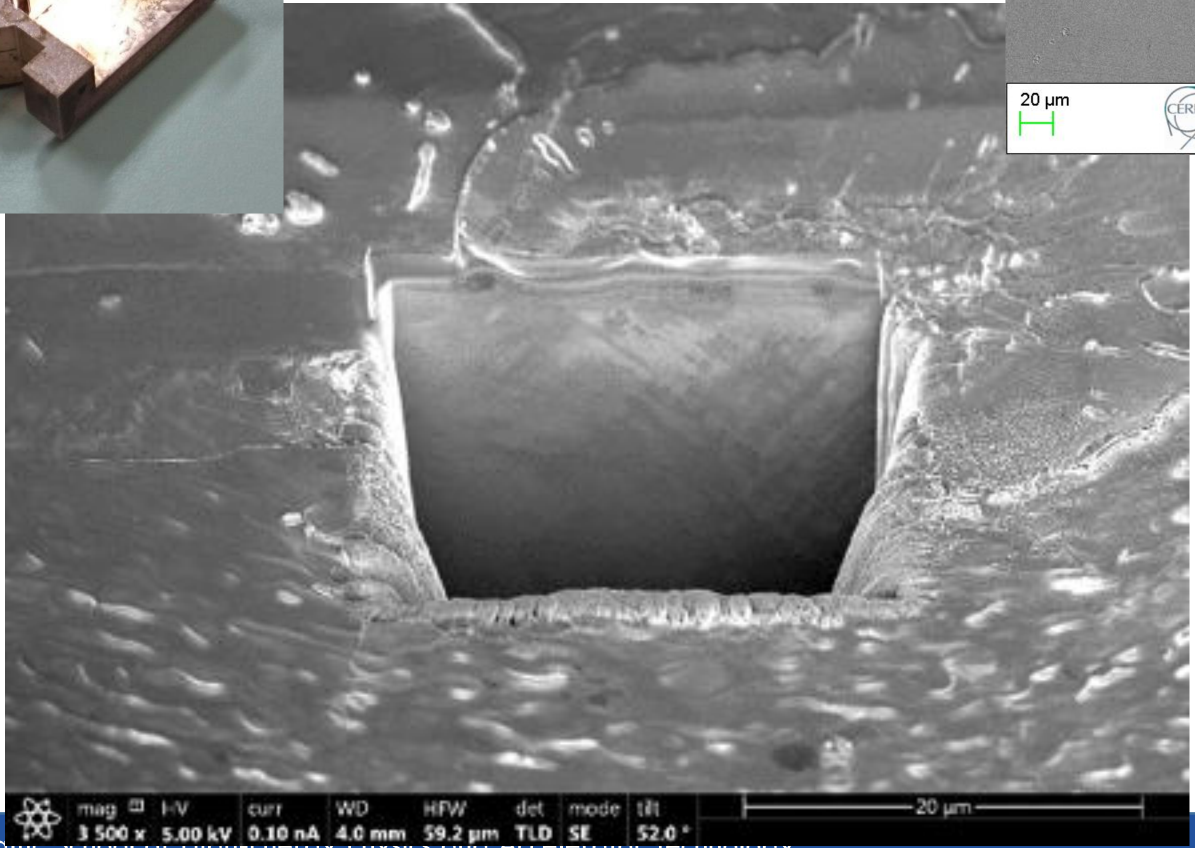


(b) Sputtering and secondary electron yield.



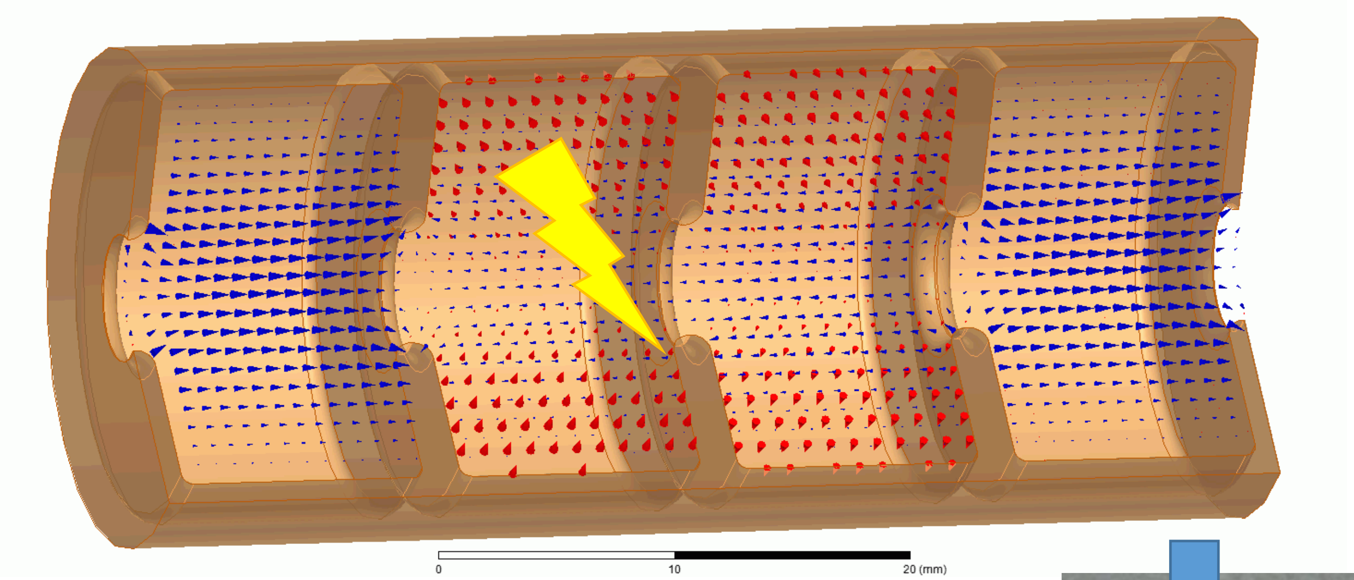
Looking afterwards with an electron microscope

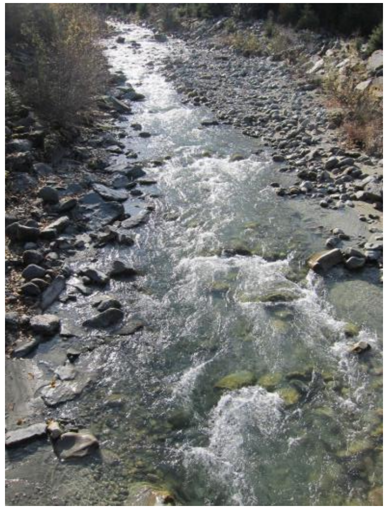


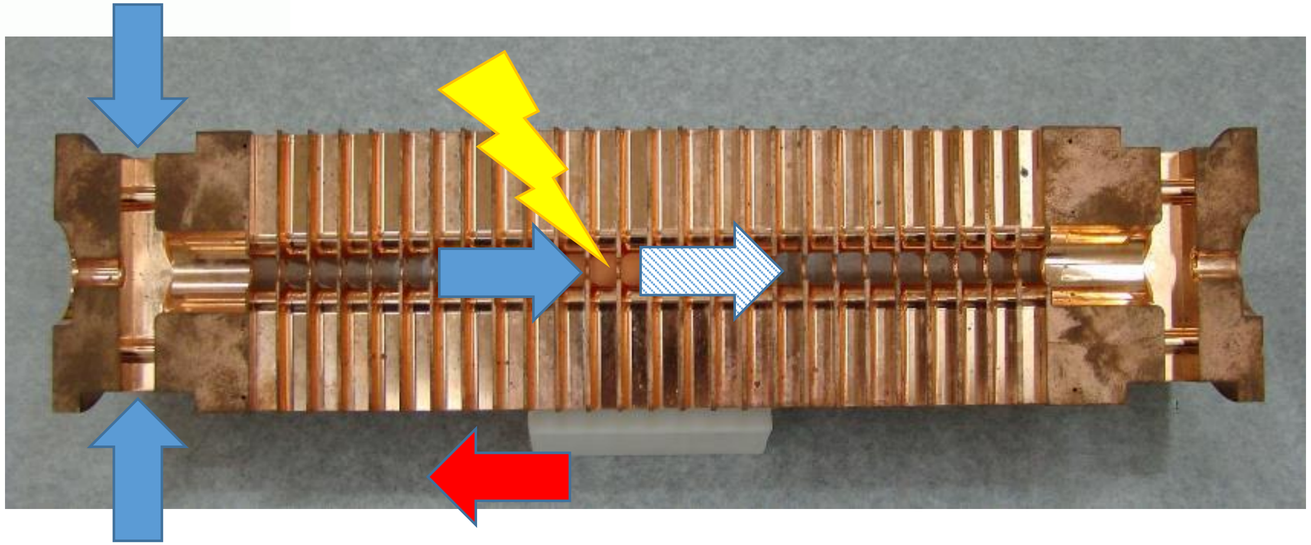


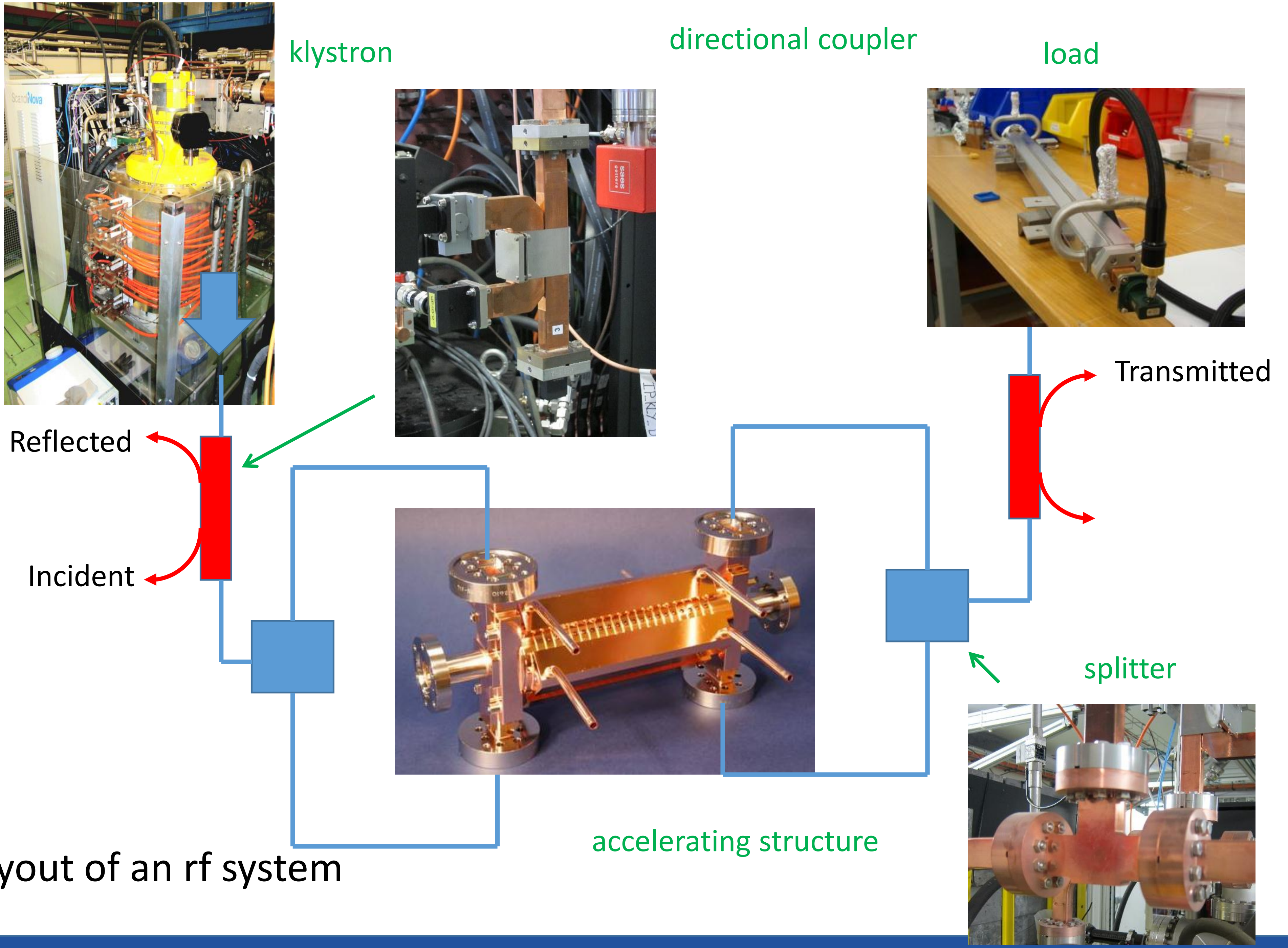
Macroscopic and rf system scale

Vacuum arc in an accelerating structure







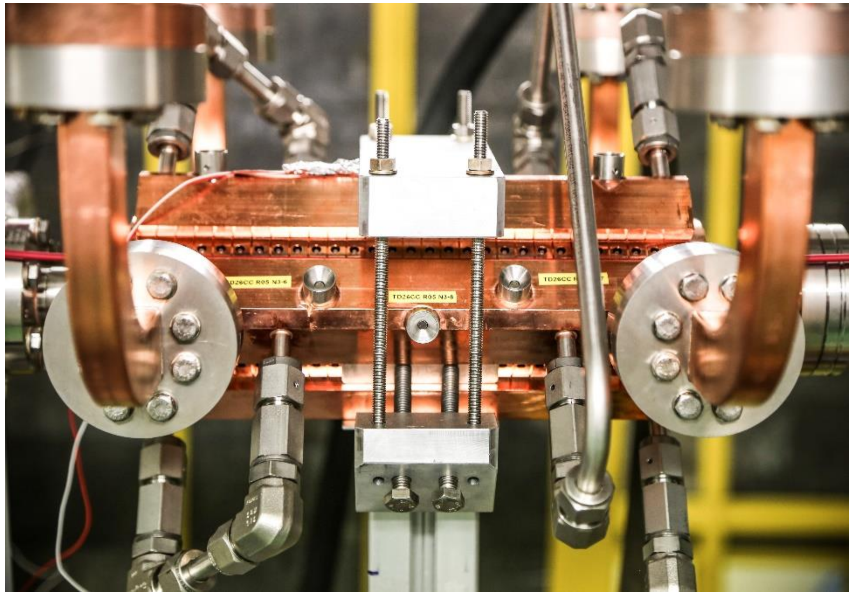


The basic layout of an rf system

rf signals

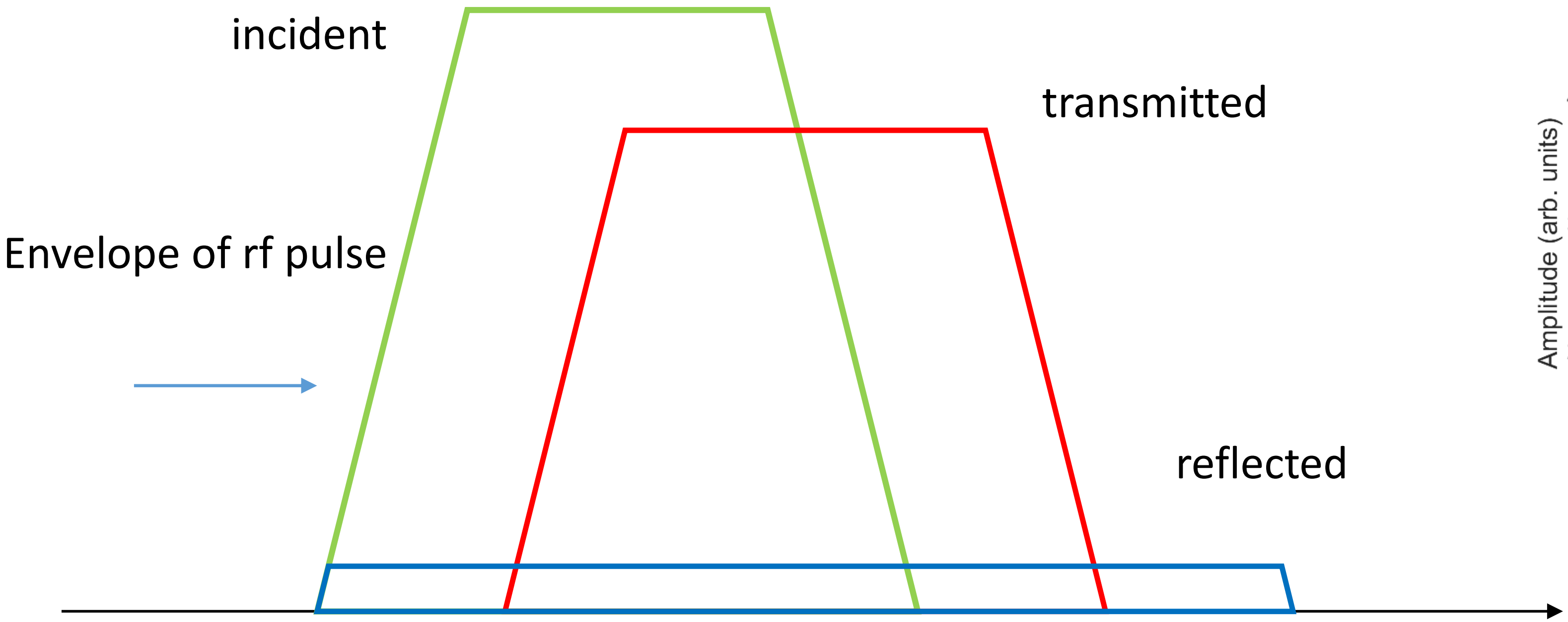
incident power

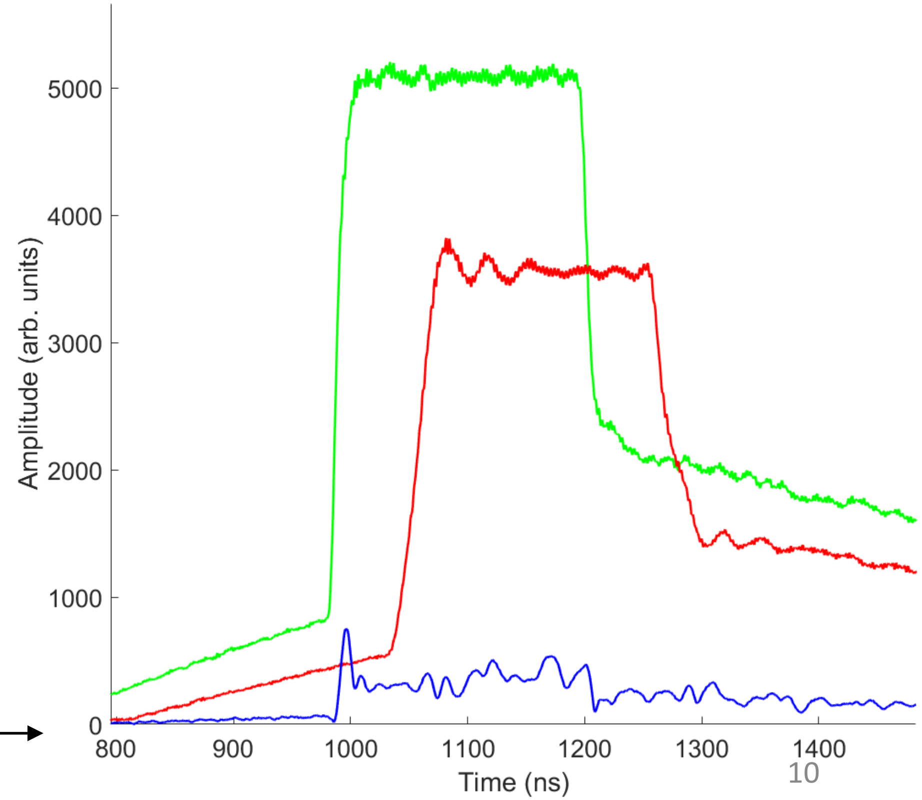
reflected power



transmitted power

From CLIC XBoxes

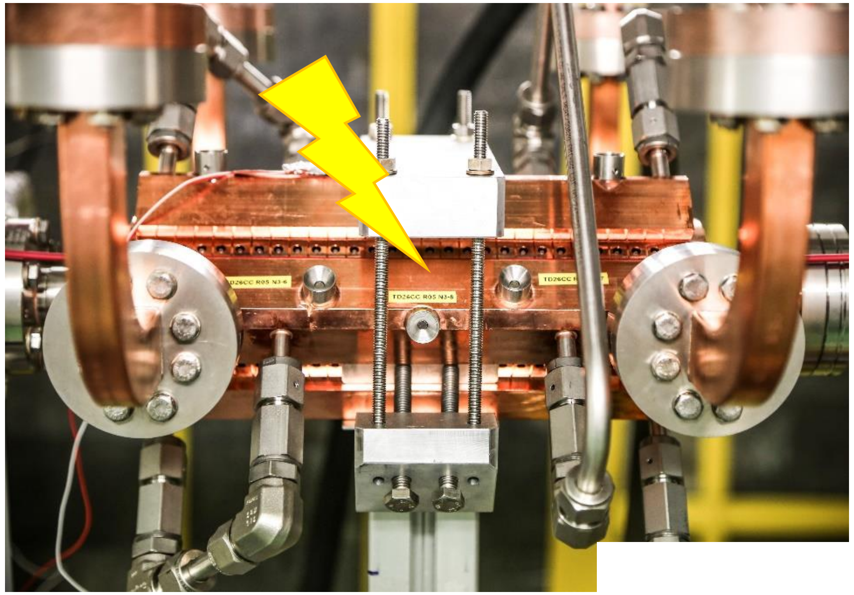




rf signals

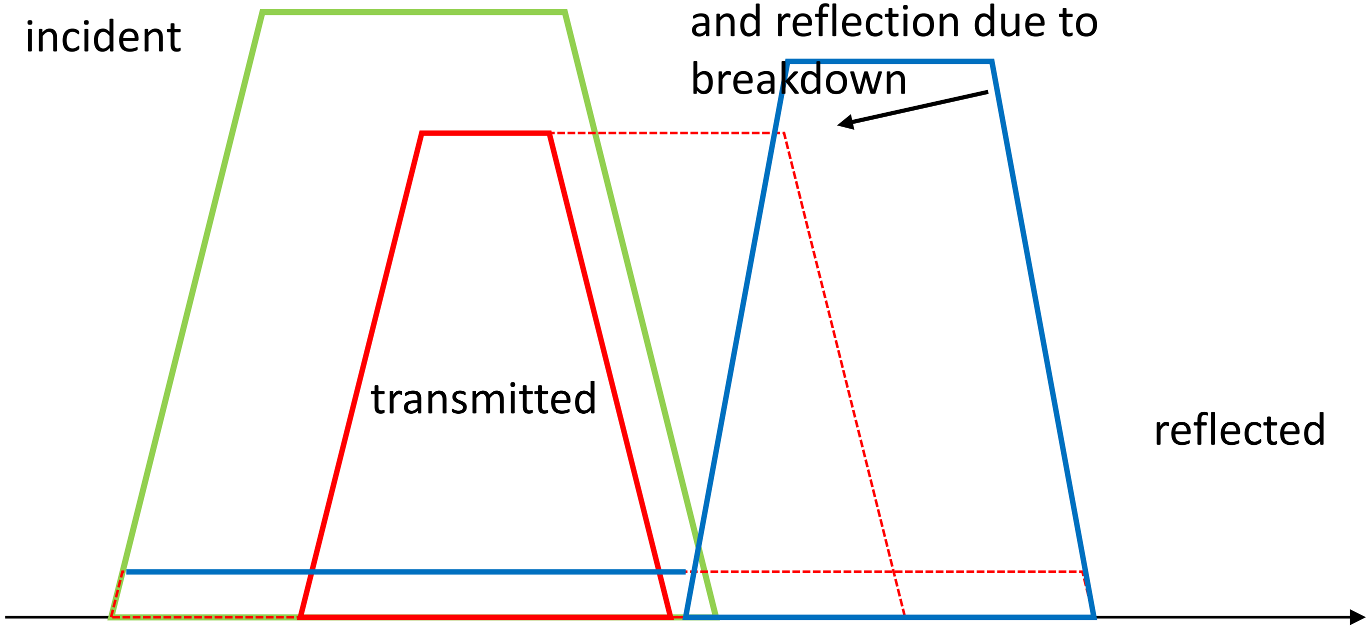
incident power

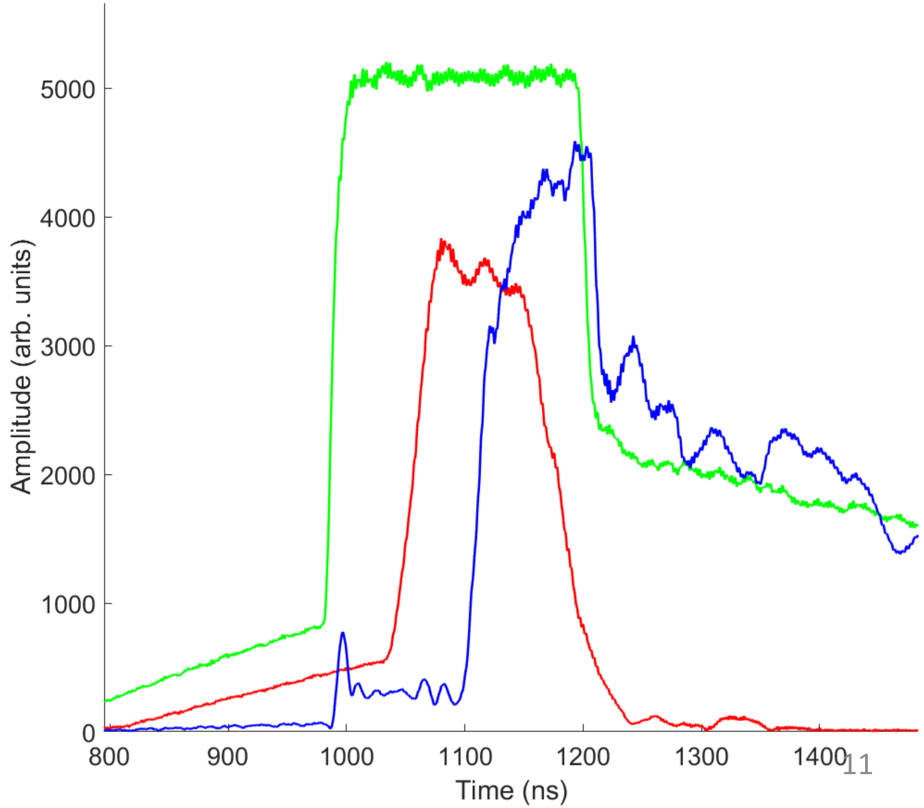
reflected power



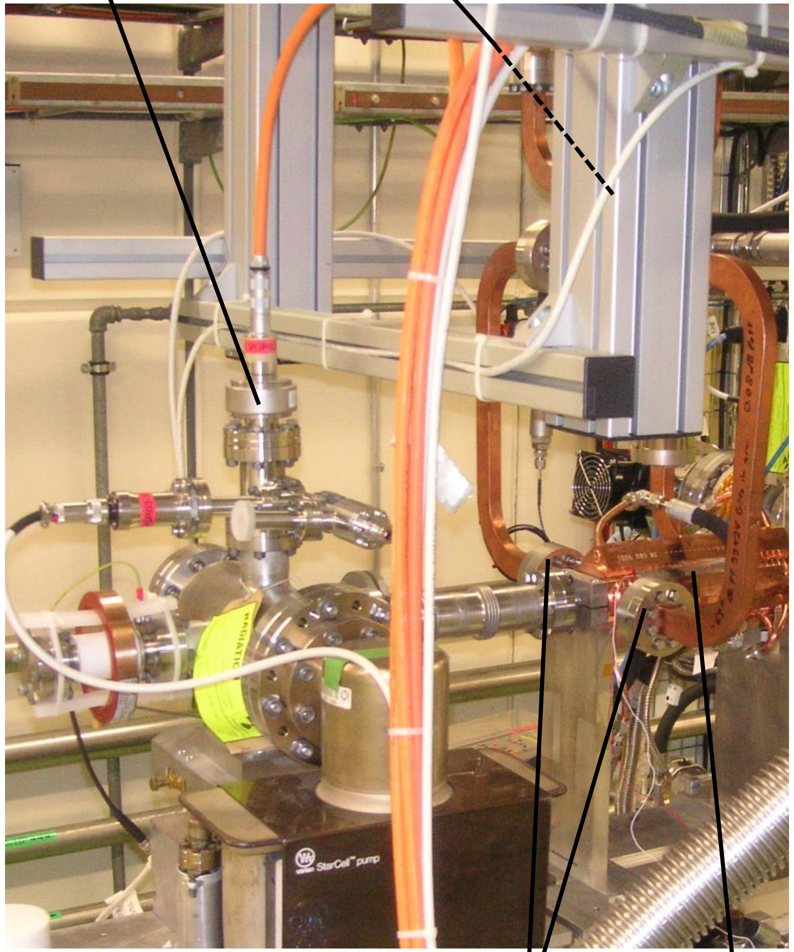
transmitted power

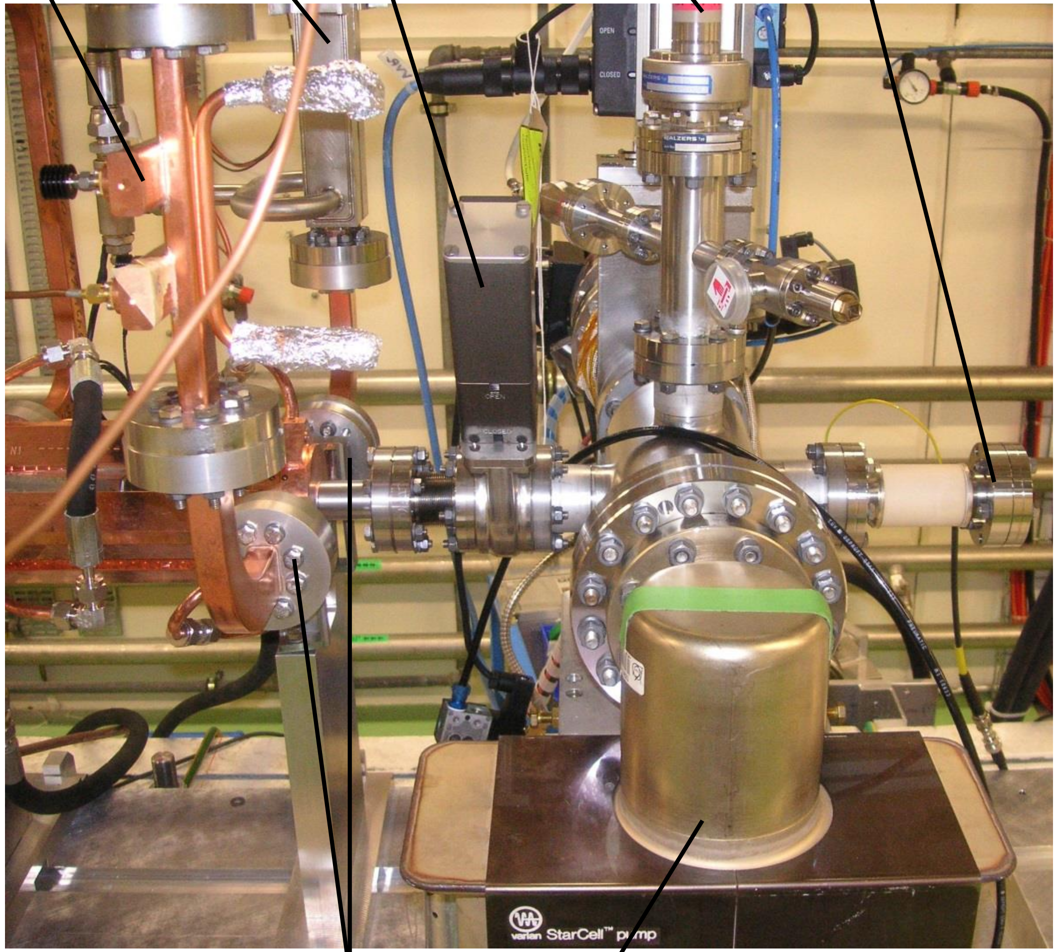
Suppression of transmission and reflection due to breakdown



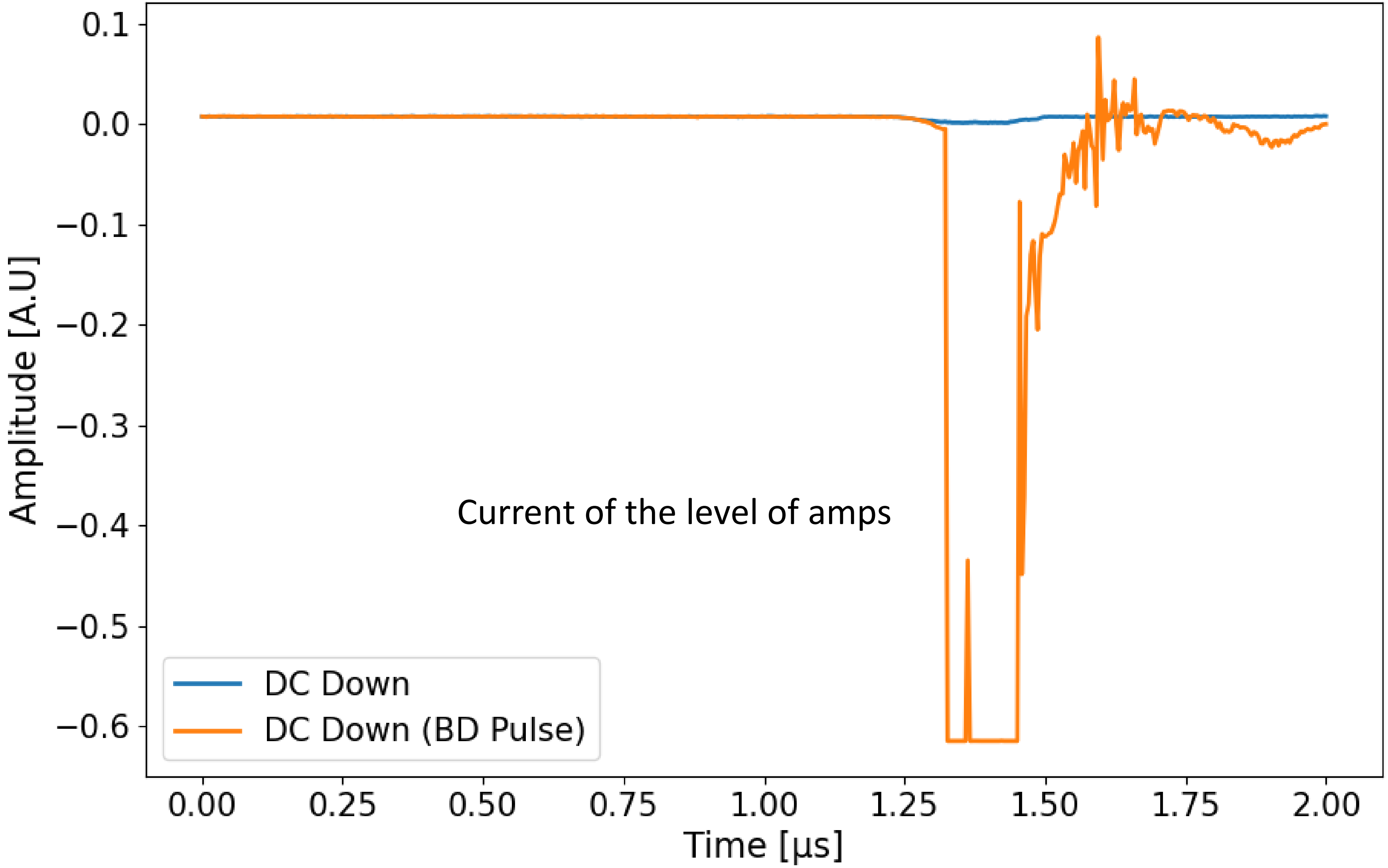


Accelerating Structure Diagnostics



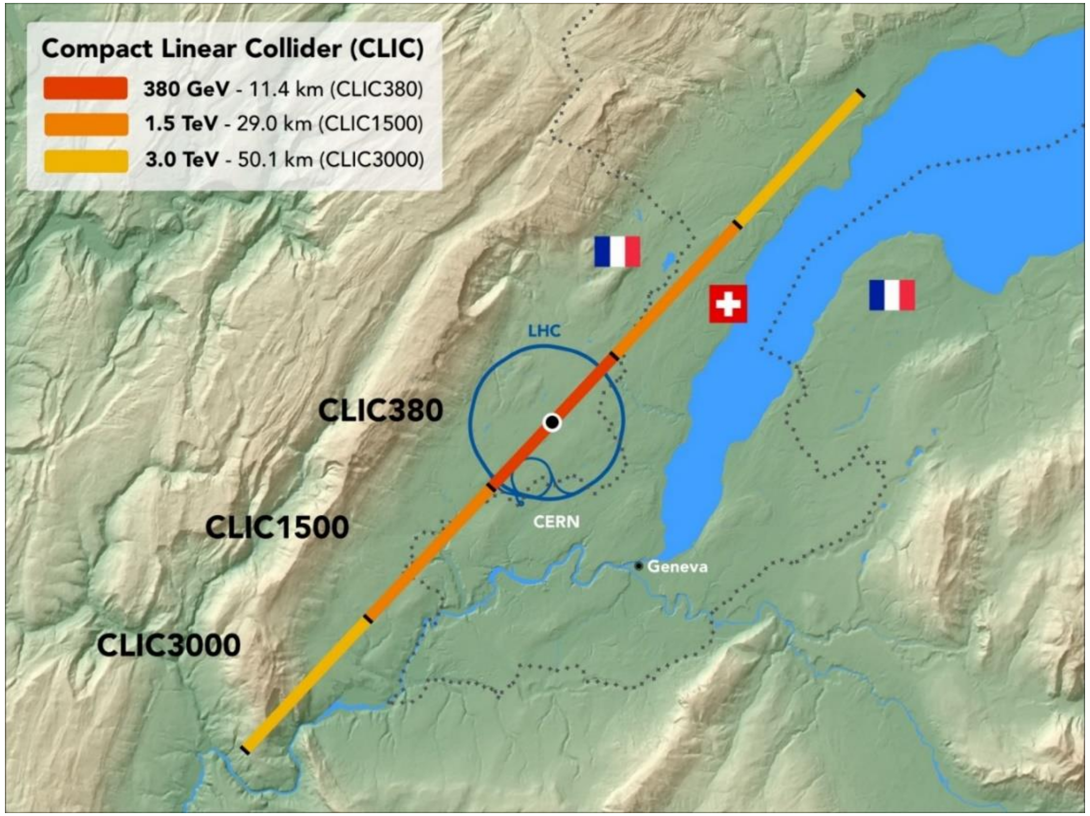


Current in Faraday cup



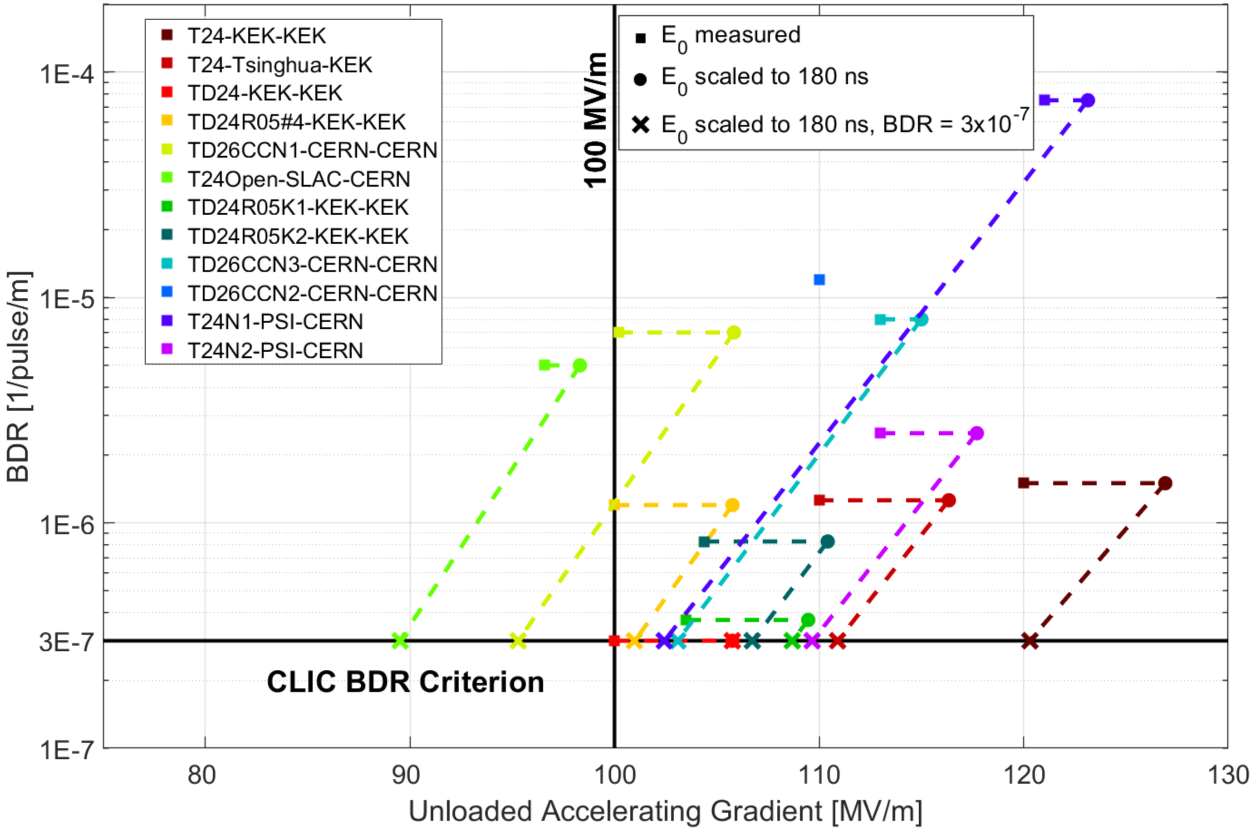
Back to CLIC

BDR (BreakDown Rate) is the fraction of pulses which have a vacuum arc. Arc currents and lost acceleration result in lost luminosity on that pulse.

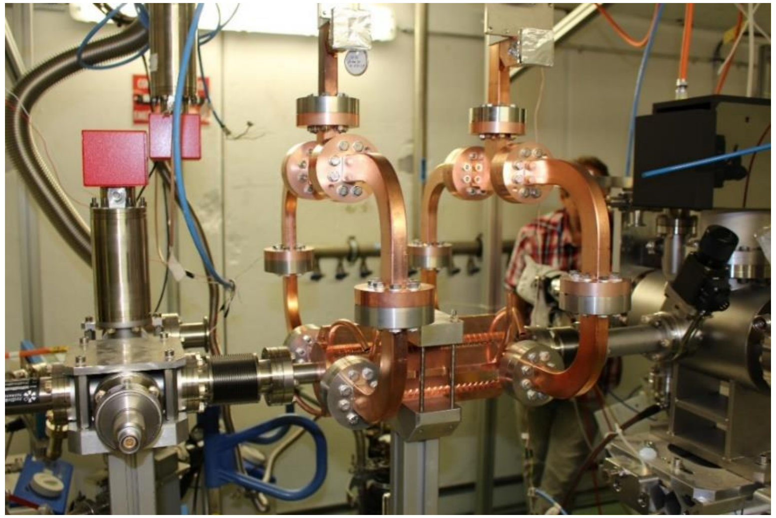


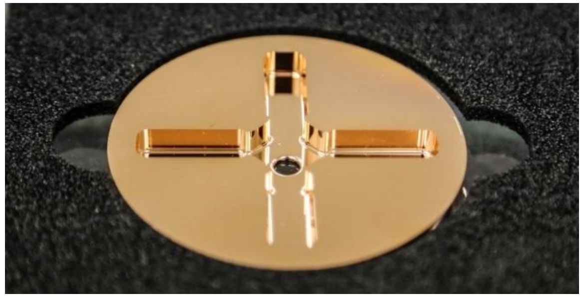
CLIC specification:
$3\text{x}10^{-7}$ 1/pulse/m
At 50 Hz, per structure:
1 BD every 3 days
Per 380 GeV facility:
1 BD someplace every 12 seconds

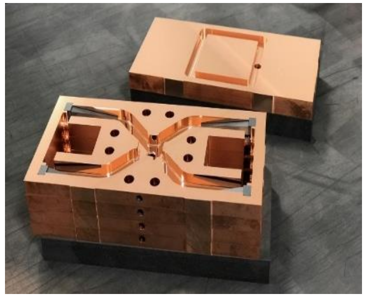
CLIC 12 GHz prototypes – what is possible



Peak surface electric fields about x 2.5 higher







https://doi.org/10.1103/PhysRevAccelBeams.21.061001,
https://doi.org/10.1103/PhysRevAccelBeams.20.052001 etc.

Much of the progress has been in quantifying dependence of gradient on RF design.

A very brief look at some accelerator-specific critical questions in breakdown theory

How does structure geometry affect achievable gradient?

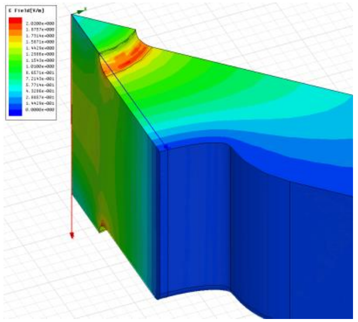
$$\frac{P}{\lambda C} = \text{const}$$

global power flow

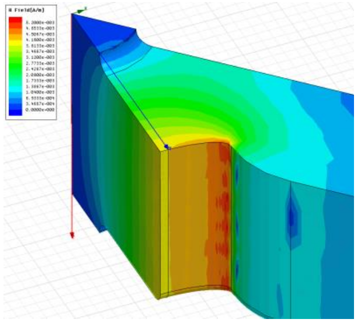
$$S_c = \text{Re}(\mathbf{S}) + \frac{1}{6}\text{Im}(\mathbf{S})$$

local complex power flow

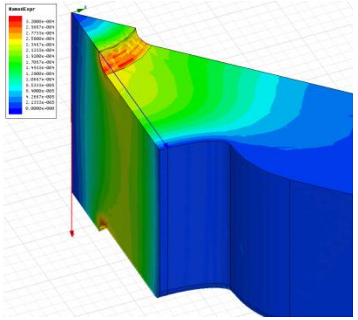
E_s/E_a



H_s/E_a



S_c/E_a^2



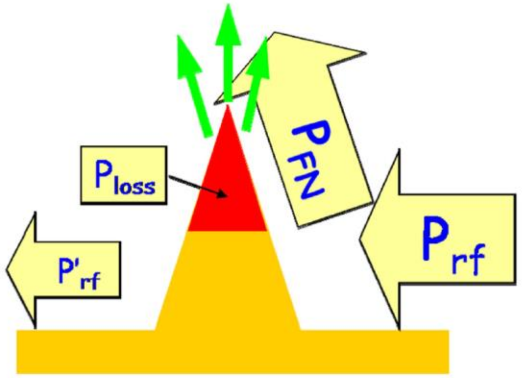
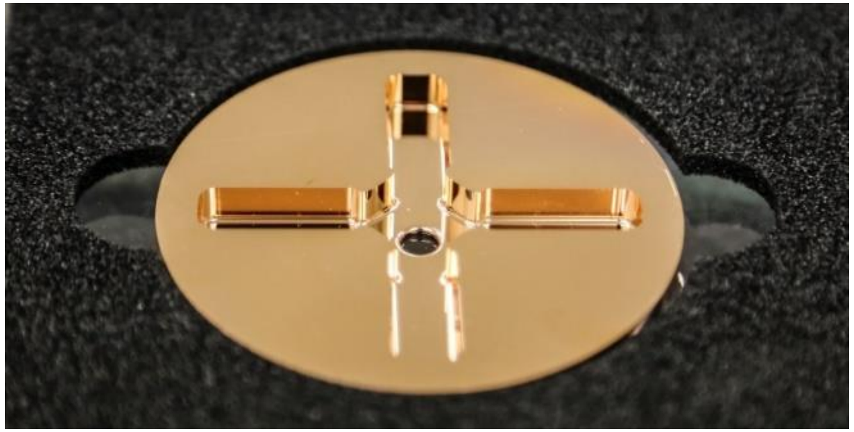


FIG. 9. (Color) Schematic view of the power flow balance near the tip.

S_c is typically the quantity which dominates the design of high-gradient travelling wave structures.



A. Grudiev, S. Calatroni, and W. Wuensch,
New local field quantity describing the high gradient limit of accelerating structures,
Phys. Rev. ST Accel. Beams 12, 102001 (2009)

https://doi.org/10.1103/PhysRevSTAB.12.102001

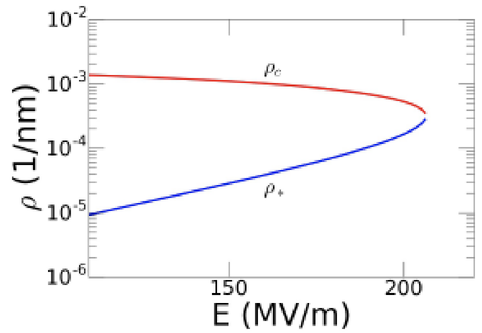
What drives the statistics of breakdown?

Describing mobile dislocation population evolution:

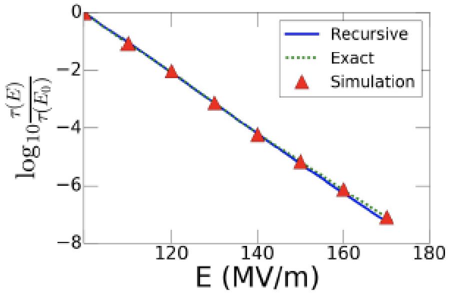
$$\dot{\rho}^+ = \frac{25\kappa C_t}{G^2 b}(\rho + c)\sigma^2 e^{-\frac{E_a - \Omega\sigma}{k_B T}}$$

$$\dot{\rho}^- = \frac{50\xi C_t}{G}\sigma\rho(c+\rho)$$

$$\sigma = \beta\epsilon_0 E^2/2 + ZGb\rho$$

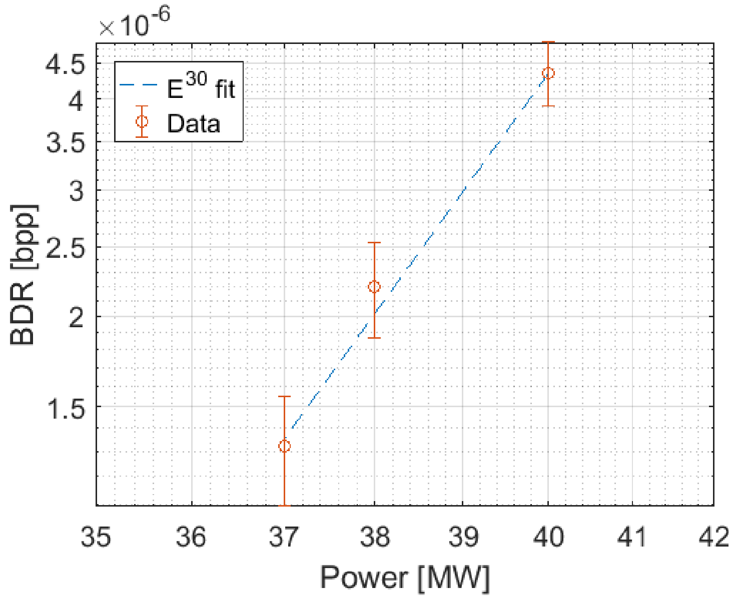


Leads to an exponential decay:



$$\tau \sim e^{-\gamma\frac{E}{E_0}}$$

Eliyahu Zvi Engelberg, Yinon Ashkenazy, and Michael Assaf Phys. Rev. Lett. 120, 124801 (2018) https://doi.org/10.1103/PhysRevLett.120.124801



$$BDR \propto E^{30}\tau^5$$

$$BDR \propto e^{\frac{-E^f + \varepsilon_0 E^2 \Delta V}{k_b T}}$$

Physical model based on defect formation

$$E^f = 0.8\ eV$$

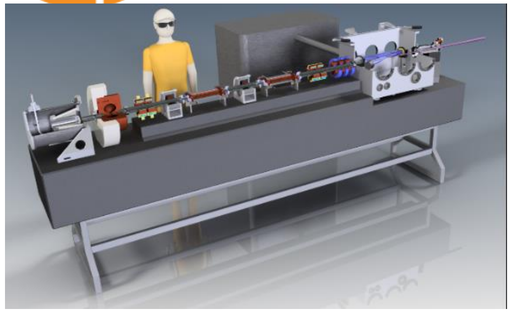
$$\Delta V = 0.8 \times 10^{-24} m^3$$

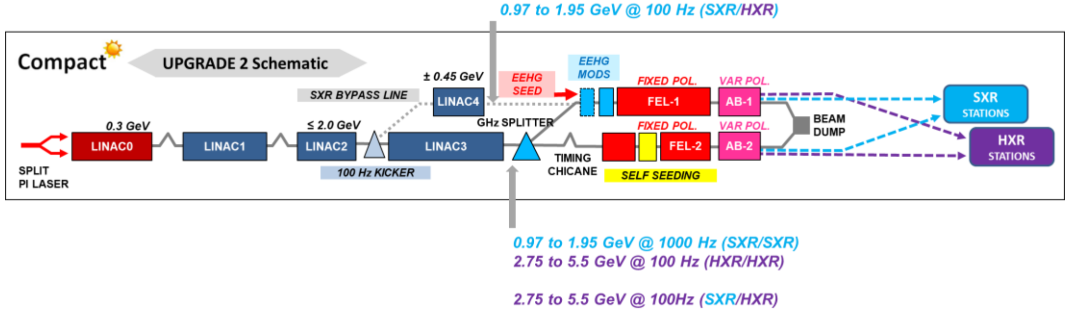
K. Nordlund, F. Djurabekova, *Defect model for the dependence of breakdown rate on external electric fields*, Phys. Rev. ST Accel. Beams 15, 071002 (2012) https://doi.org/10.1103/PhysRevSTAB.15.071002

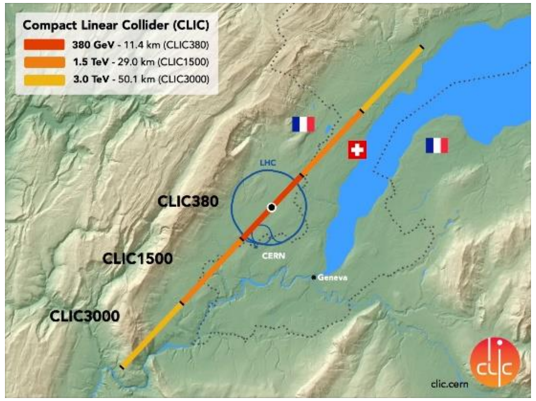
Applications of high gradient accelerators

Having made a significant step in practical accelerating gradient for CLIC, we looked more broadly to see if there are applications that could benefit, or become realistic, due to this step in performance.

X-band and high-gradient applications overview



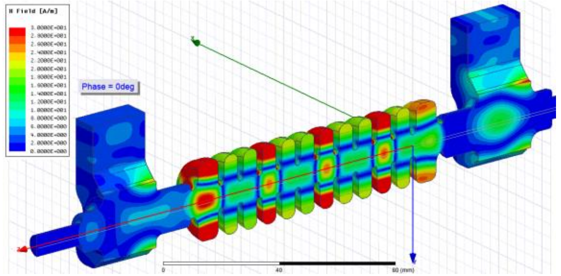


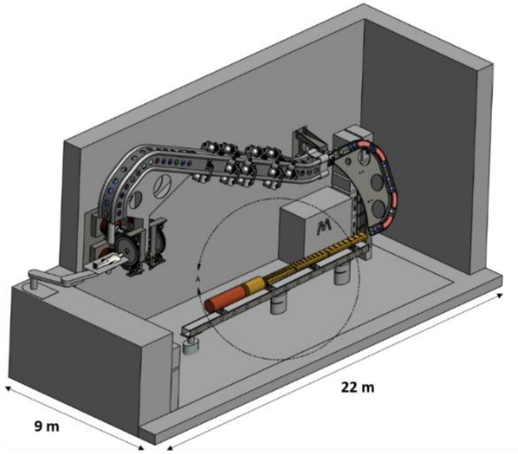


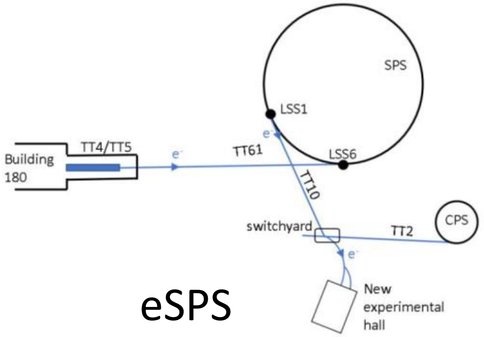
Linear collider

Light source - Inverse Compton Scattering Source

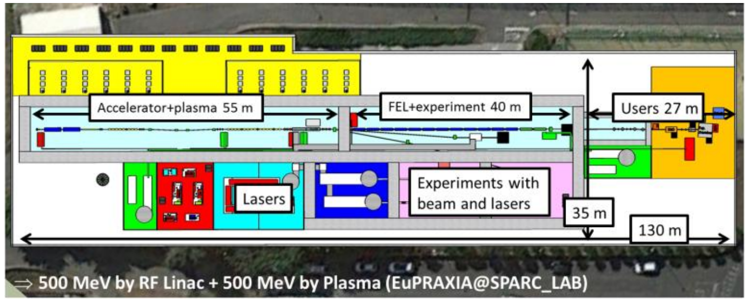
Light source - XFEL



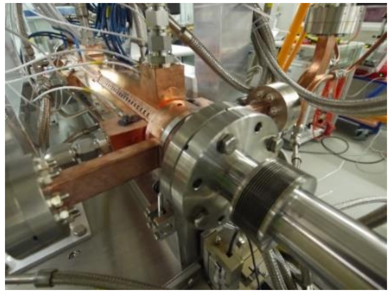




eSPS



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

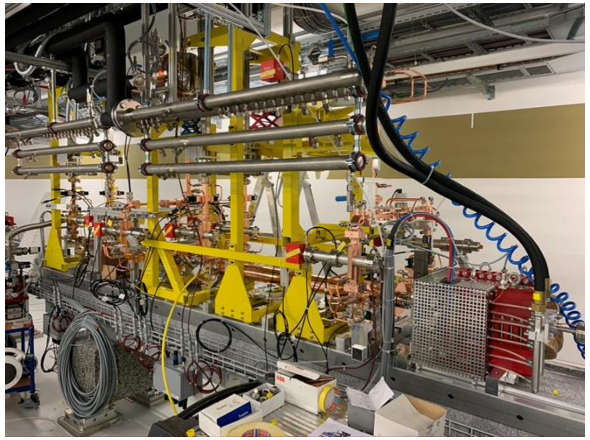
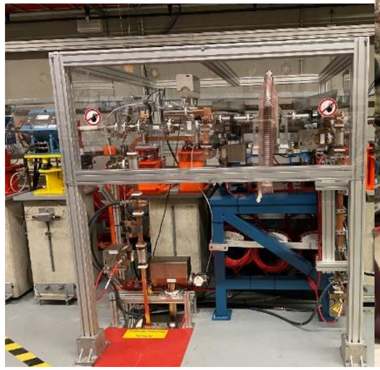
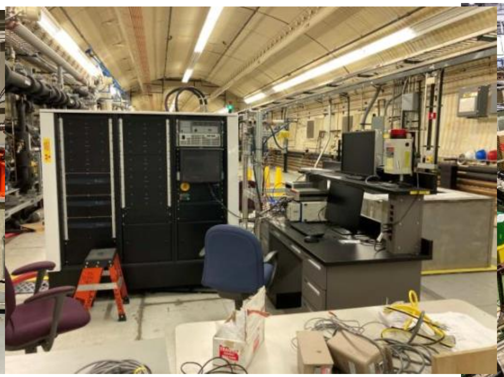
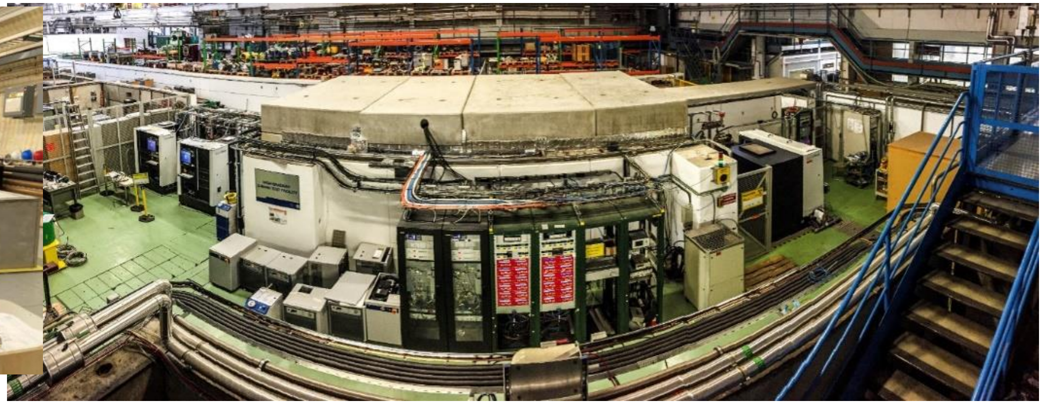


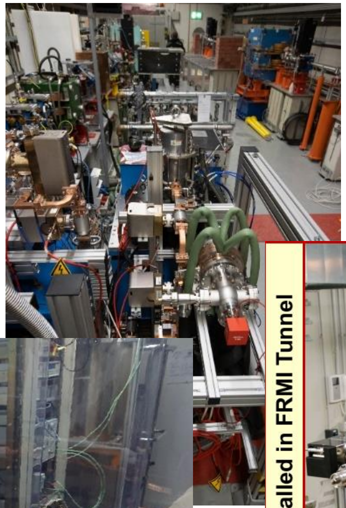
Medical applications

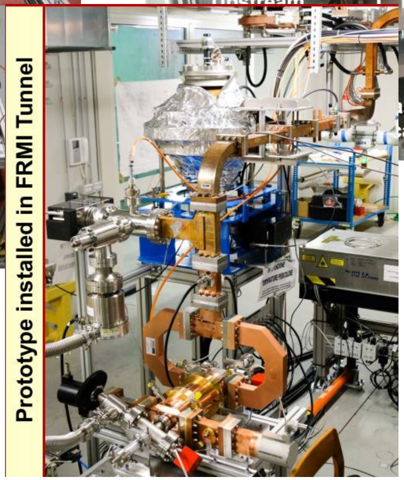
GeV-range research linacs

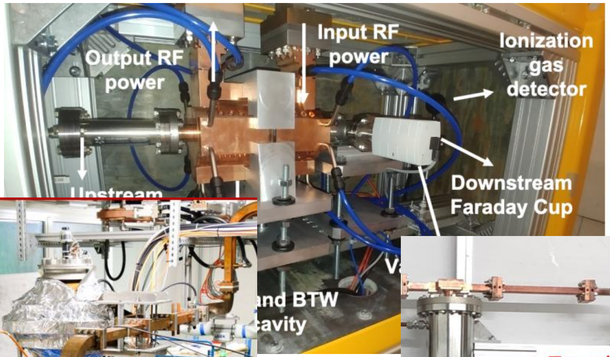
Beam manipulation

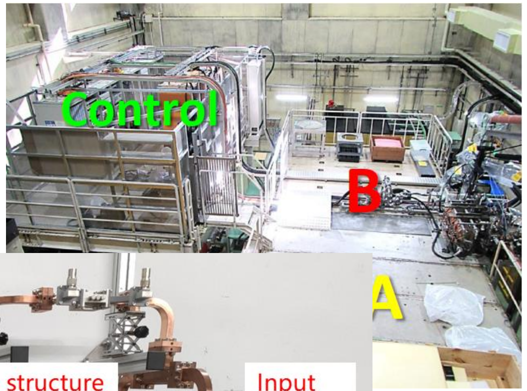
X-band and high-gradient infrastructure worldwide

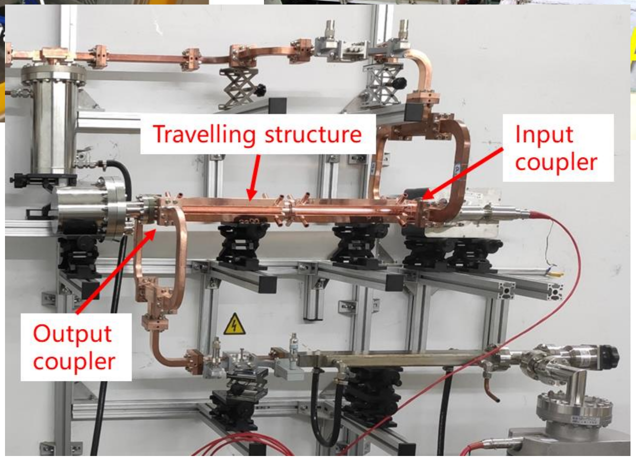













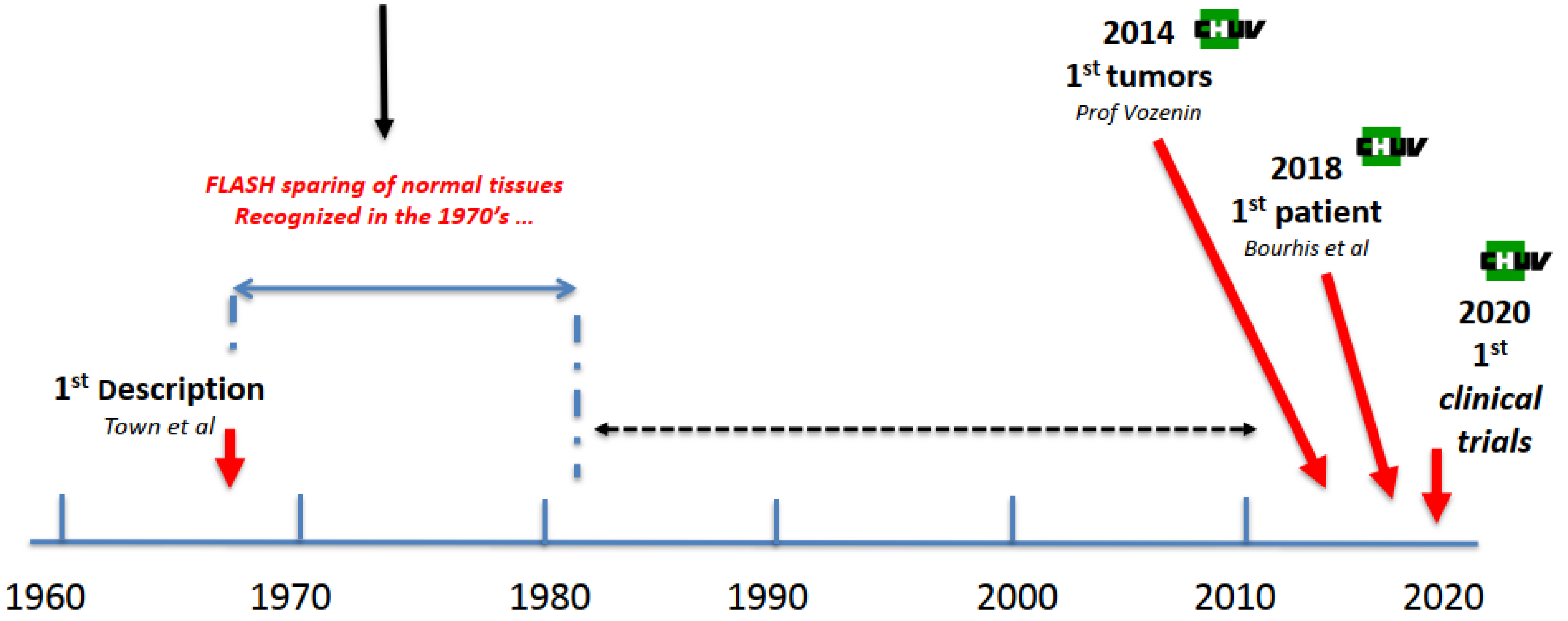
Focusing on one application – FLASH radiation therapy

Introduction

- A very hot topic in radiation oncology is so-called FLASH therapy which involves delivering an entire radiation treatment in a few hundred ms or less, as opposed to minutes, and in one or few fractions.
- This fast delivery can reduce toxicity to healthy tissue while maintaining tumor control expanding the parameter space for treatment – more in a moment.
- Another trend in radiation oncology is a renewed interest in VHEE (Very High Energy Electron) therapy.
- In a parallel universe, major developments in accelerator technology have occurred in linear collider projects, relevant for this story, CLIC…

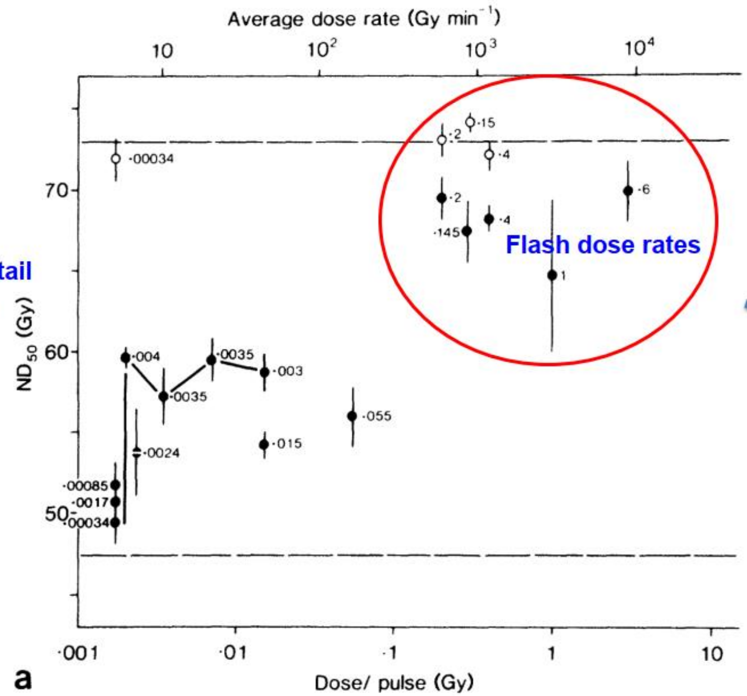
FLASH goes way back

Historical perspective



What oncology data can look like

Until 1982 :




Jolyon H. Hendry
1982

FLASH sparing effect on normal tissues was recognized

2014 Re-discovery …

1) Sparing normal tissues

2) No sparing of tumors


Favaudon & Vozenin

RESEARCH HIGHLIGHTS


IN BRIEF

RADIOTHERAPY

FLASHing tumours

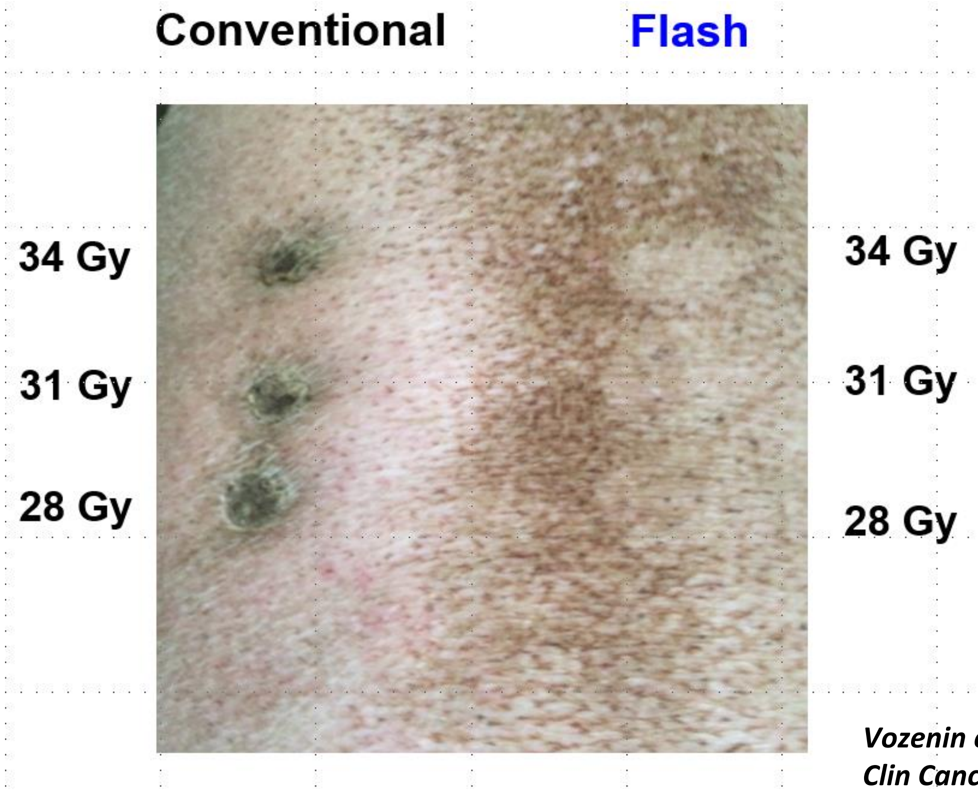
A new study in mice suggests that radiation delivered in short pulses at ultrahigh dose rates (FLASH) is as effective against lung tumours as conventional protracted single lower dose rates and has fewer side effects. Using both orthotopic lung tumours in immunocompetent mice and human lung tumour xenografts in nude mice, Favaudon *et al.* showed that FLASH irradiation caused less lung fibrogenesis and less apoptosis in normal tissue than conventional radiation. Although this technique was only tested in one tumour type, it suggests that delivery methods are crucial to minimizing radiation treatment side effects, and it has implications for therapeutic protocols.

ORIGINAL RESEARCH PAPER Favaudon, V. *et al.* Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice. *Sci. Transl Med.* **6**, 245ra93 (2014)

NATURE REVIEWS | CANCER VOLUME 14 | SEPTEMBER 2014

Visually

Illustration of the Flash-RT effect in pig :
A major decrease of radiation side effects



Vozenin et al Clin Cancer Res 2018

ELSEVIER
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Radiotherapy and Oncology
journal homepage: www.thegreenjournal.com

Original Article

Treatment of a first patient with FLASH-radiotherapy

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[a] Department of Radiation Oncology, Lausanne University Hospital and University of Lausanne; [b] Radiation Oncology Laboratory, Department of Radiation Oncology, Lausanne University Hospital and University of Lausanne; [c] Institute of Radiation Physics, Lausanne University Hospital and University of Lausanne; and [d] Department of Dermatology, Lausanne University Hospital and University of Lausanne, Switzerland

Fig. 1. Temporal evolution of the treated lesion: (a) before treatment; the limits of th PTV are delineated in black; (b) at 3 weeks, at the peak of skin reactions (grade 1 epithelitis NCI-CTCAE v 5.0); (c) at 5 months.

First human patient – skin cancer treated with 10 MeV-range electrons

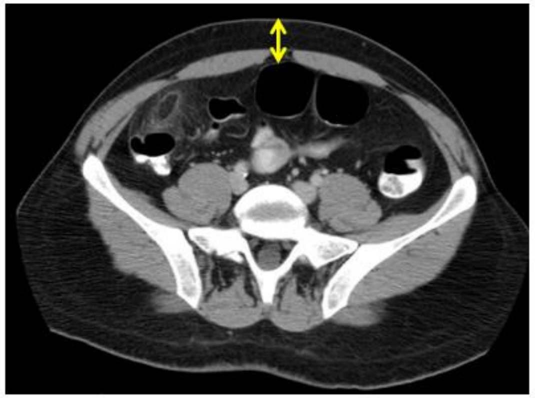
First clinical translation with low energy electrons

CHUV

Transfert clinique au CHUV (I)

FLASH-Mobetron

Only for superficial skin cancers



Unil | Université de Lausanne

Press release — Lausanne, Switzerland & Sunnyvale, USA , June 18 2020

IntraOp and Lausanne University Hospital Announce Collaboration in FLASH

A collaborative R&D agreement will advance FLASH radiotherapy for cancer patients

The Lausanne University Hospital (CHUV) and IntraOp Medical Corporation have announced a research and development collaboration to accelerate the development of FLASH radiotherapy toward first human trials.

CHUV

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Transfert clinique @ CHUV (II) : intra-operative FLASH-THERAPY

With
Pr Simon,
Pr Demartines,
Pr Mathevet

For cancers not amenable to
A complete resection

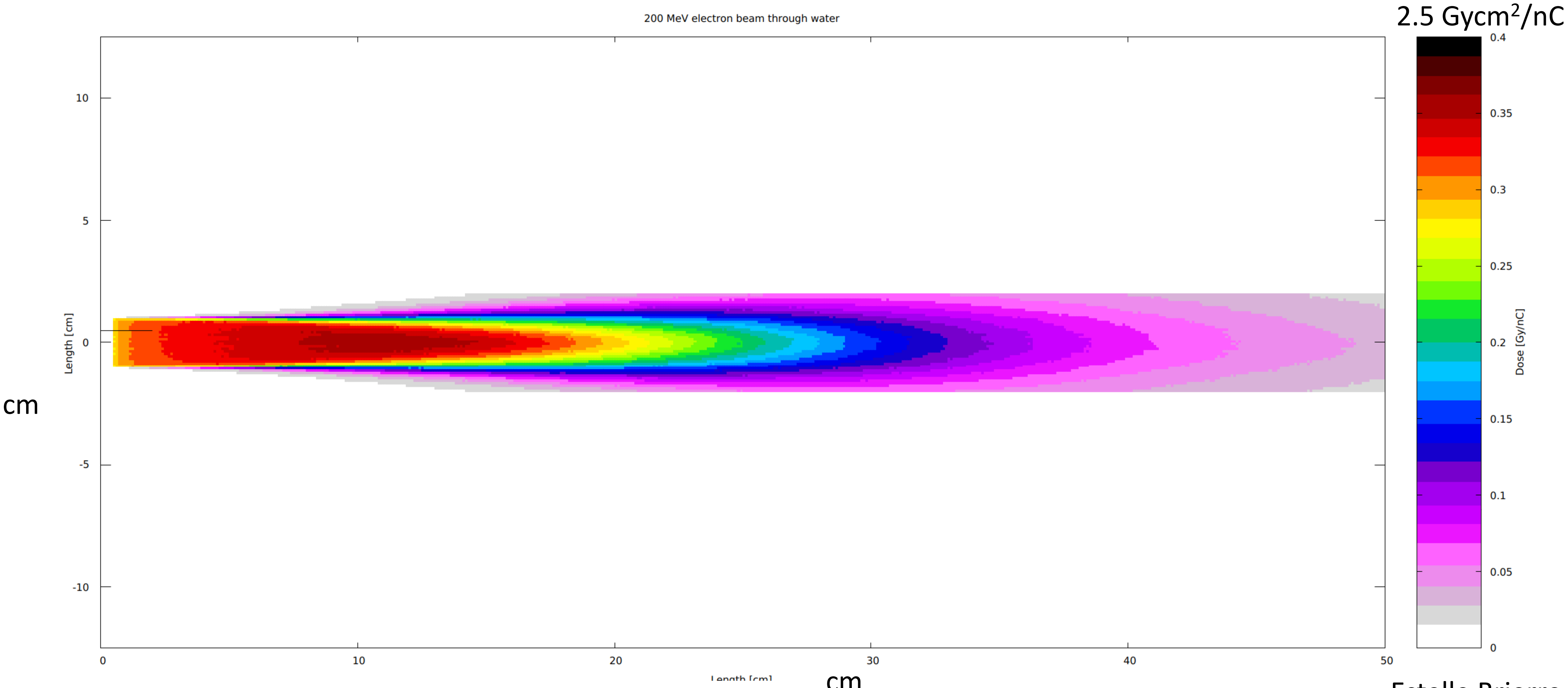
t-

What about large tumor volumes and deep seated tumors ?

- **Unmet clinical need :** this is where we have most of the tumor failures …
- **So far no FLASH** pre-clinical data mimicking these clinical situations
- **No FLASH** irradiating device is currently **available** : technical challenges
- **FLASH characteristics may not help for its use in such large volumes ?**

What a high-energy electron beam can do

200 MeV electrons in water

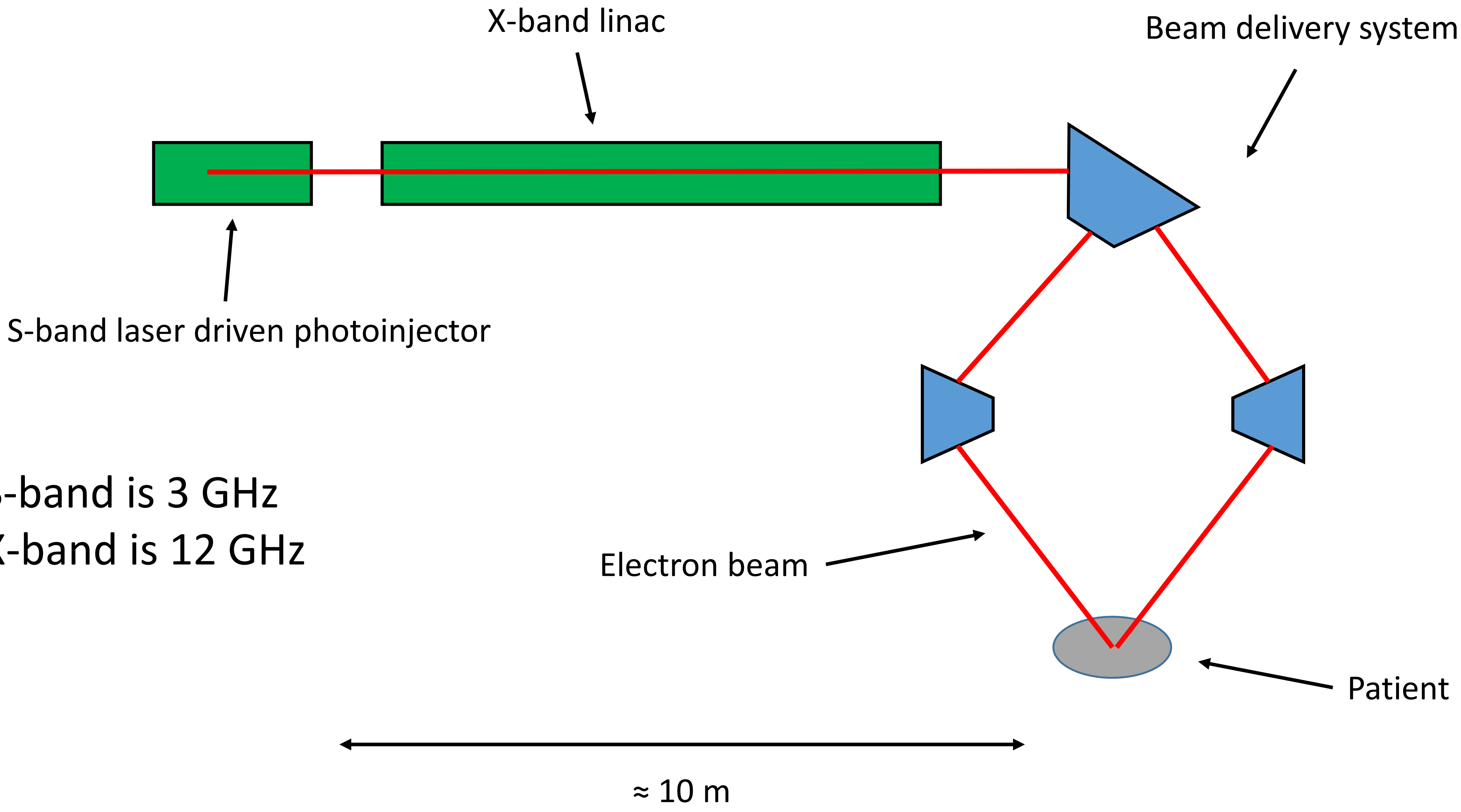


Estelle Brierre

The CHUV-CERN collaboration

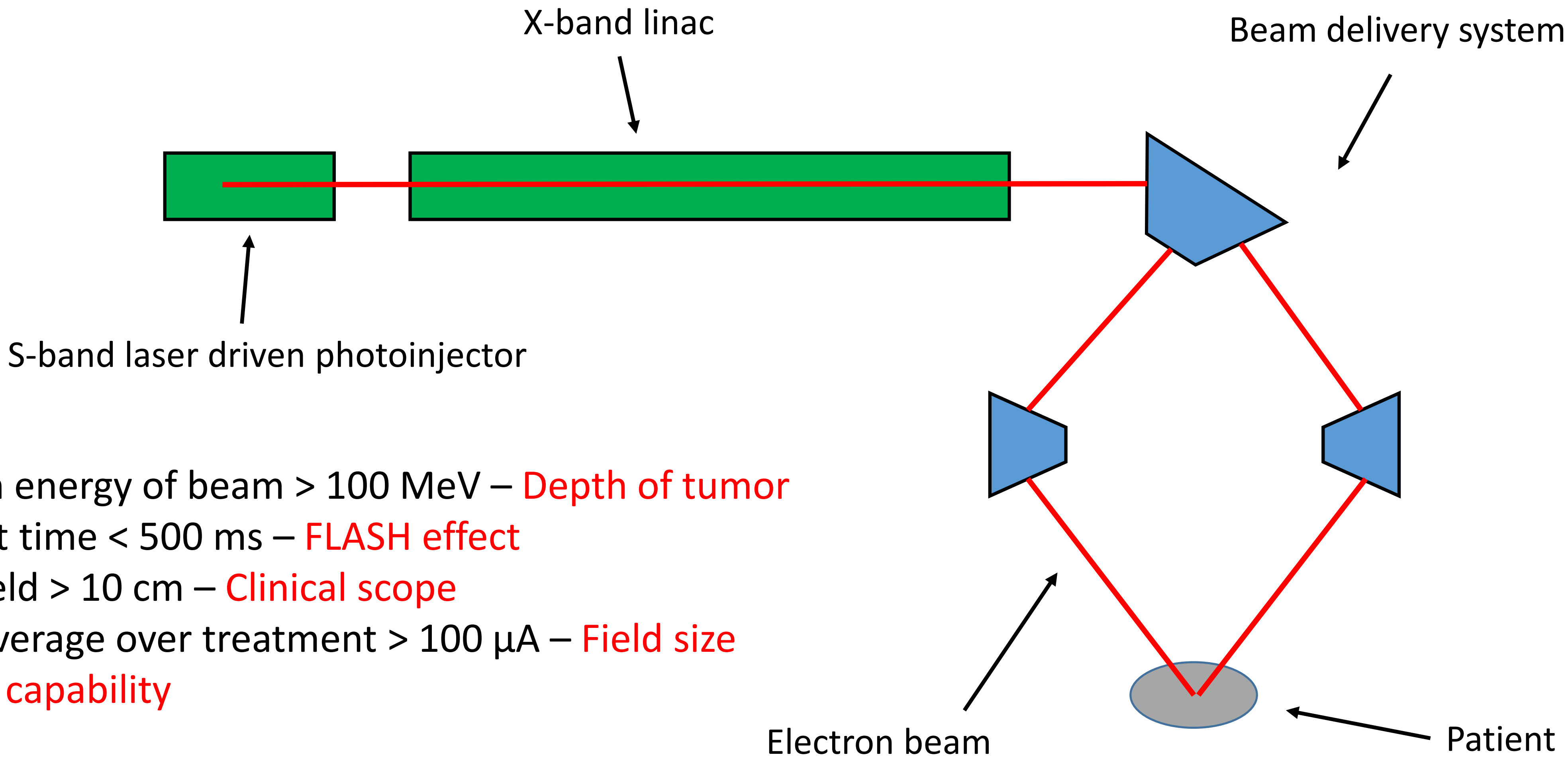
- From a few coincidences then follow up discussions (a story for another day) CHUV and CERN realized that electron linac technology developed for CLIC could be the basis for a facility for treating large, deep-seated tumors in FLASH timescales – extending CHUV's clinical translation program.
- An extremely dynamic collaboration started in early 2019 to make a conceptual design of such a facility. This design is now done, feasibility OK and we have a good idea of the critical areas.
- CHUV succeeded in finding a donor to fund the construction of the facility.
- The project officially started on 1 September 2022, and ramp-up – as a collaboration, at CHUV and at CERN – is now underway.
- Participation of an industrial partner is planned and investigation and discussions are underway.

Layout



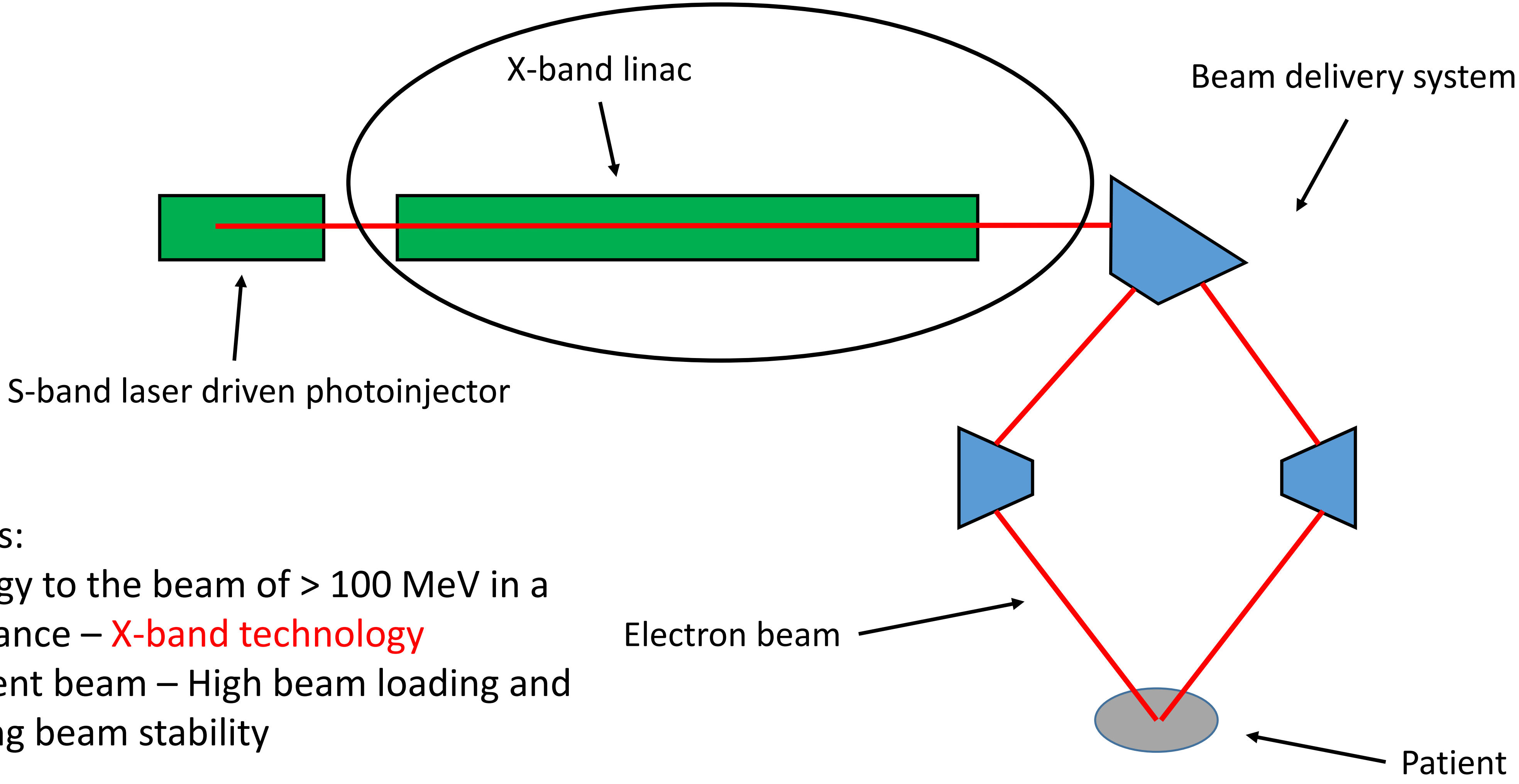
S-band is 3 GHz
X-band is 12 GHz

Basic parameters



- Maximum energy of beam > 100 MeV – Depth of tumor
- Treatment time < 500 ms – FLASH effect
- Largest field > 10 cm – Clinical scope
- Current average over treatment > 100 μA – Field size over time capability

Starting in the middle – the X-band linac

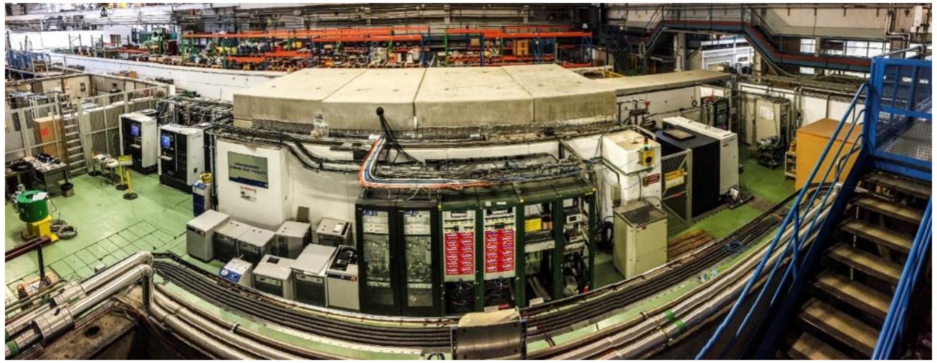


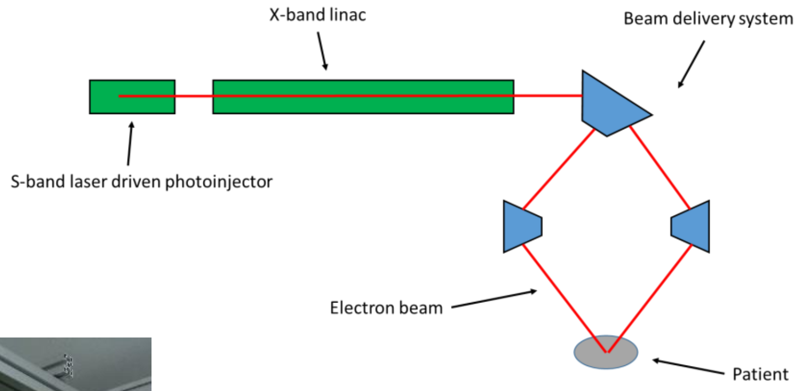
Critical issues:

- Give energy to the beam of > 100 MeV in a short distance – X-band technology
- High current beam – High beam loading and challenging beam stability

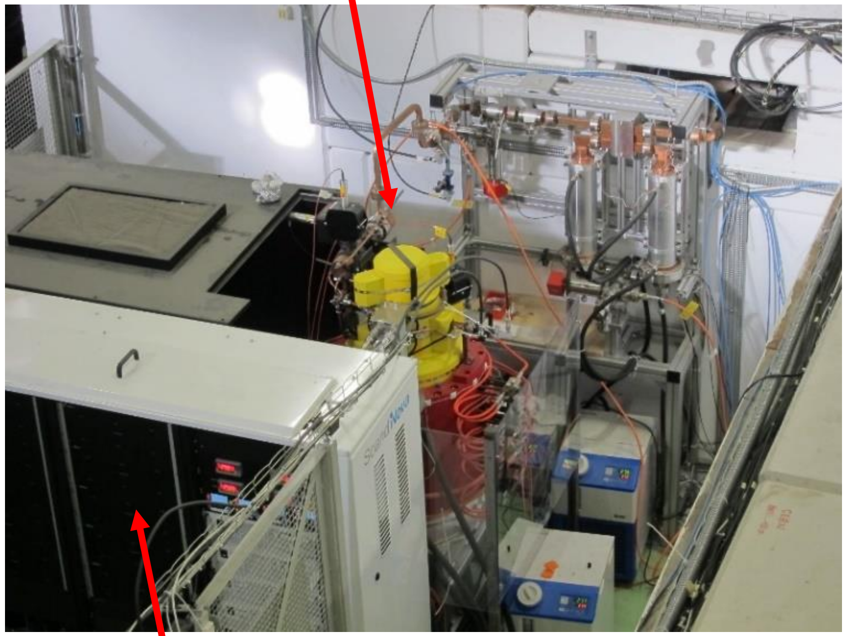
X-band linac hardware

Based on CLIC accelerating structures and XBox test stands.

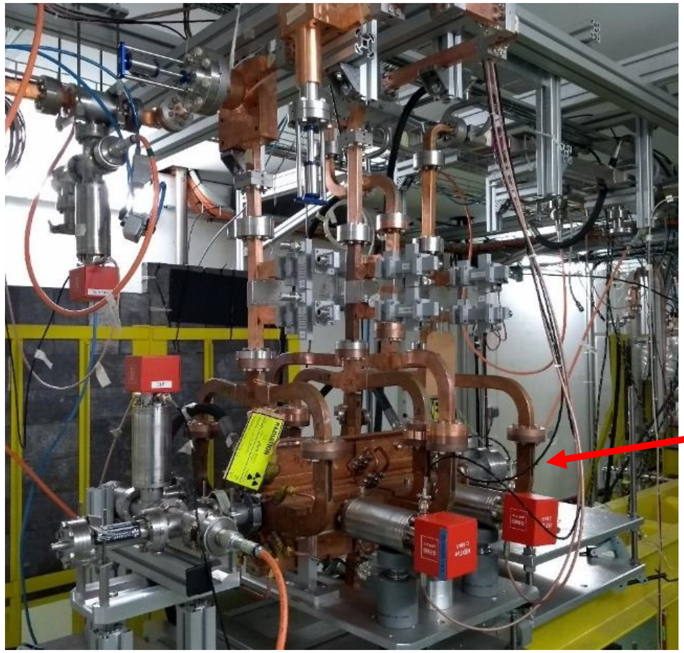




CPI 50 MW klystron

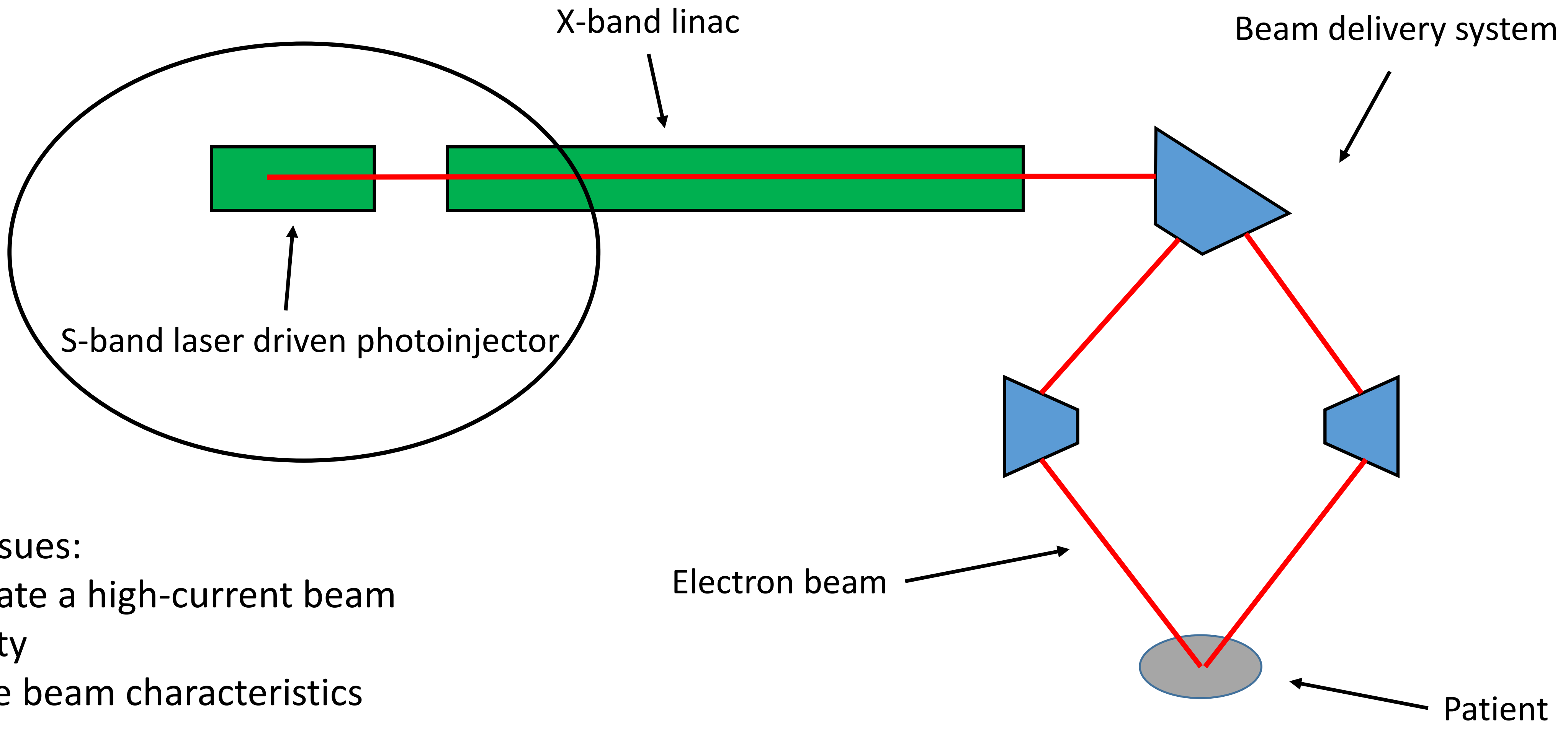


Scandinova solid state modulator



Prototype CLIC accelerating structure

The S-band photoinjector



Critical issues:

- Generate a high-current beam
- Stability
- Precise beam characteristics

Laser-driven RF photoinjectors

Laser-driven RF photoinjectors are a commonly used device to provide well controlled electron bunches in a wide variety of linacs including XFELS, Inverse Compton Sources, ERLs, linear collider related test facilities etc.

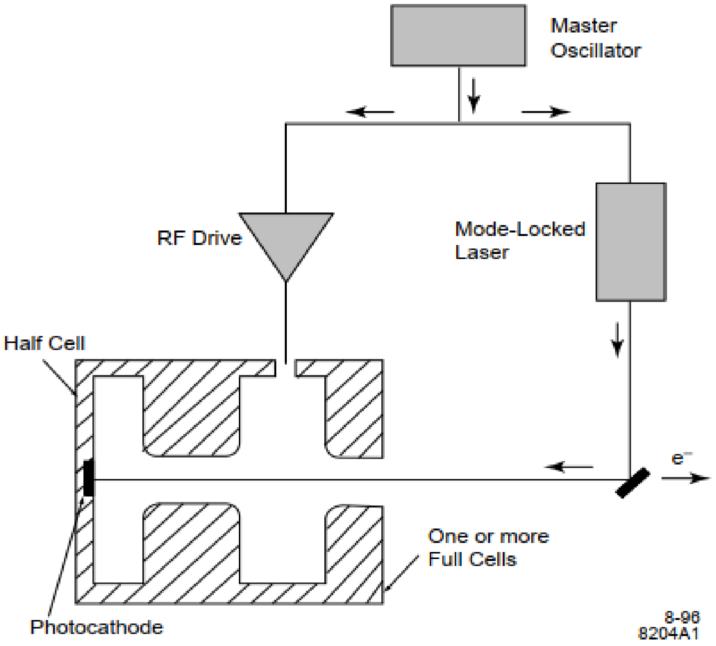
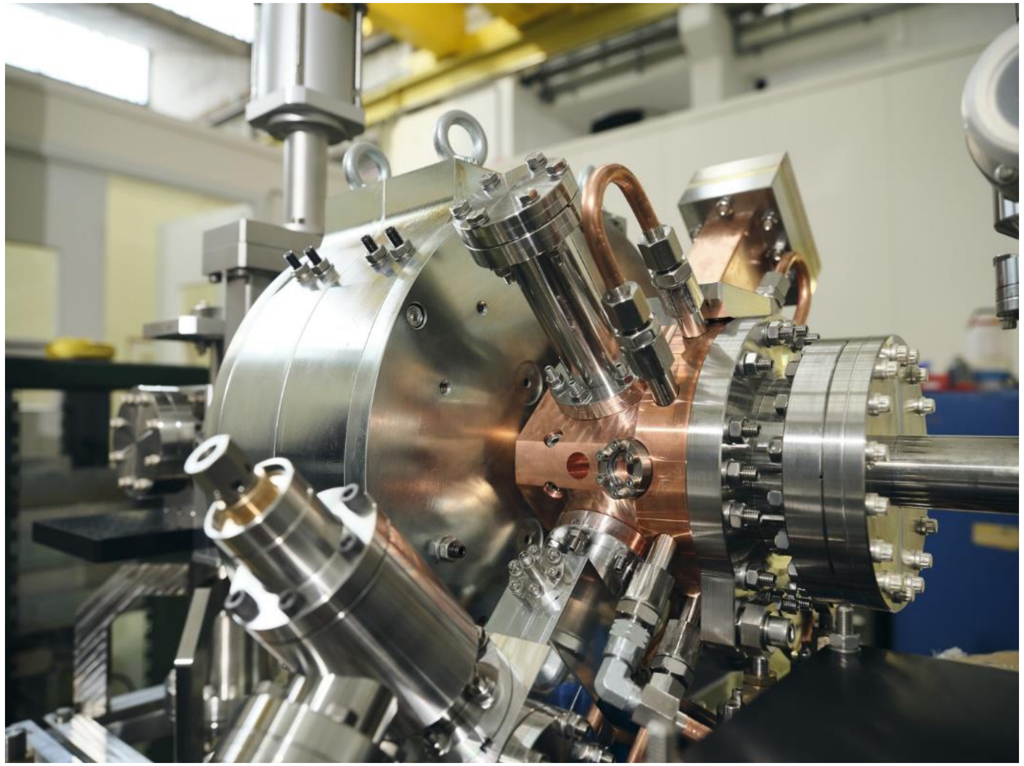


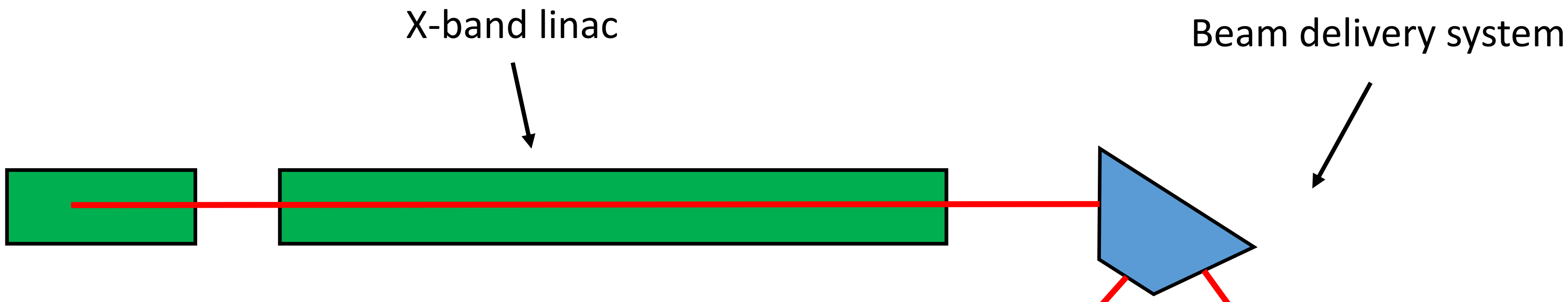
Fig. 1. Principal components of an rf photoinjector.

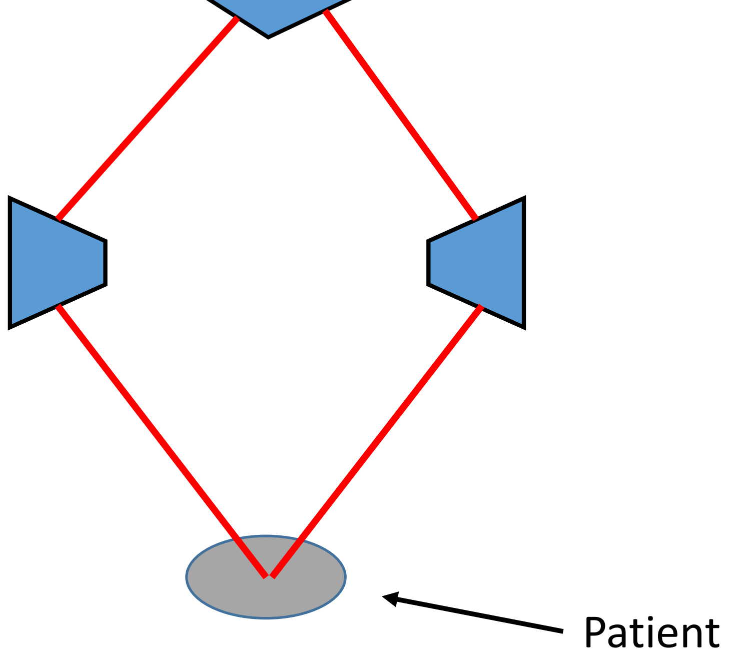
From J.E. Clendenin, LINAC96

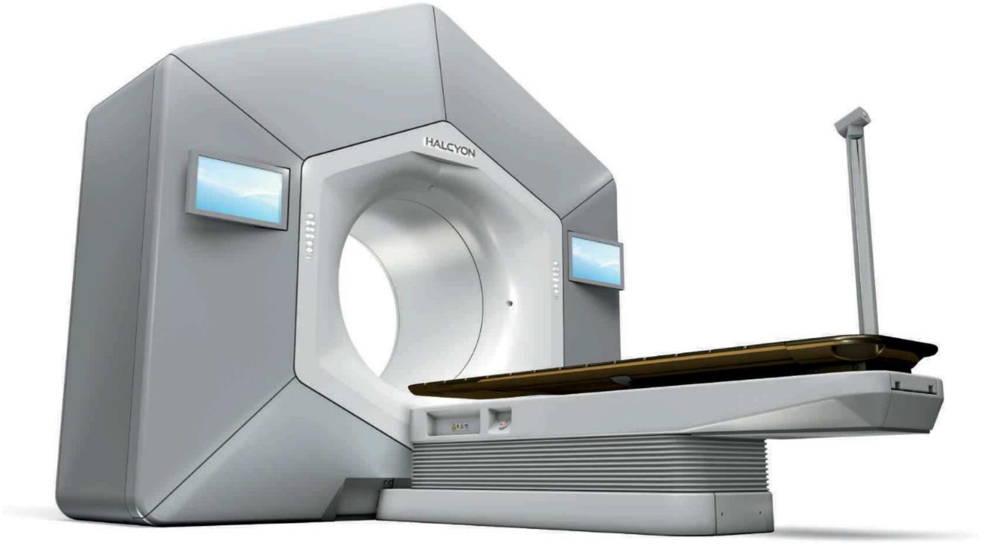


2021 - New CLEAR gun from INFN Frascati

The beam delivery system



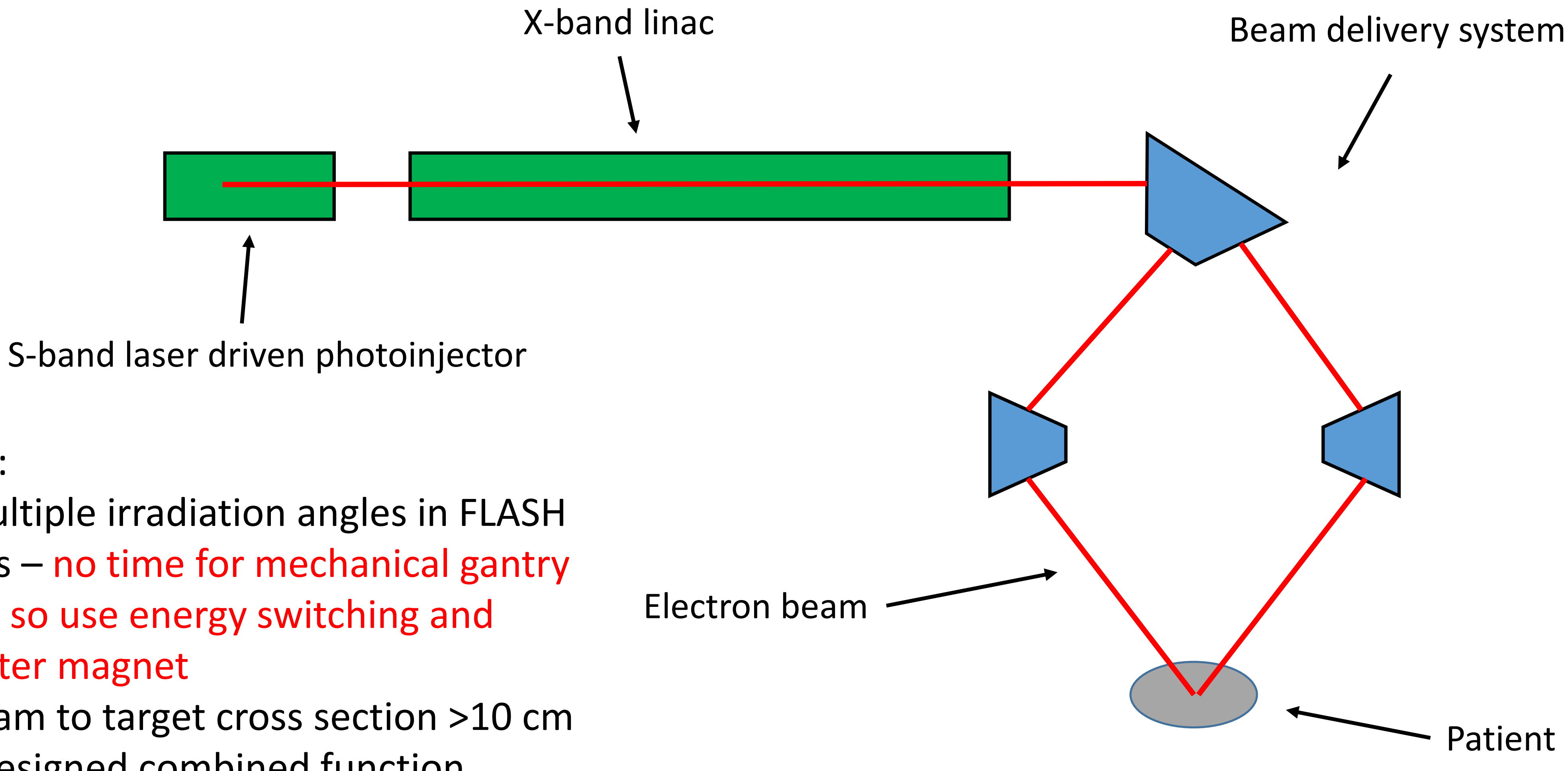




XRay therapy system
from https://www.varian.com/en-ch

(not same scale)

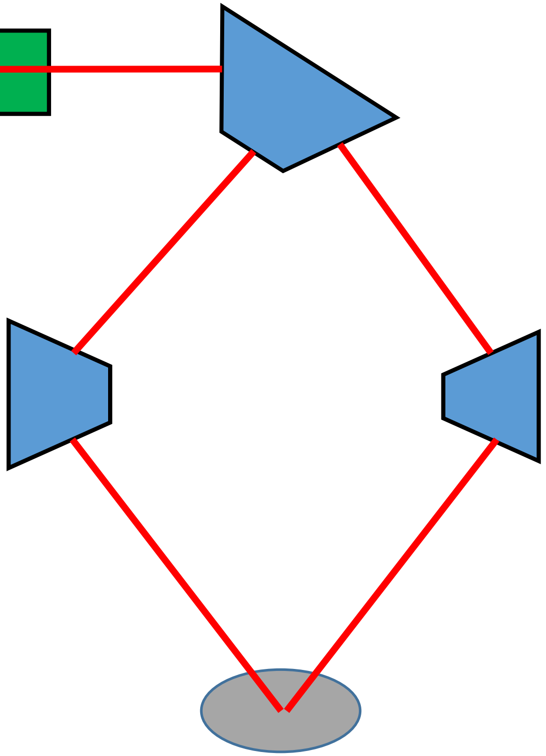
The beam delivery system



Critical issues:

- Provide multiple irradiation angles in FLASH sub-100 ms – no time for mechanical gantry movement so use energy switching and spectrometer magnet
- Expand beam to target cross section >10 cm
- Specially designed combined function separator magnet.

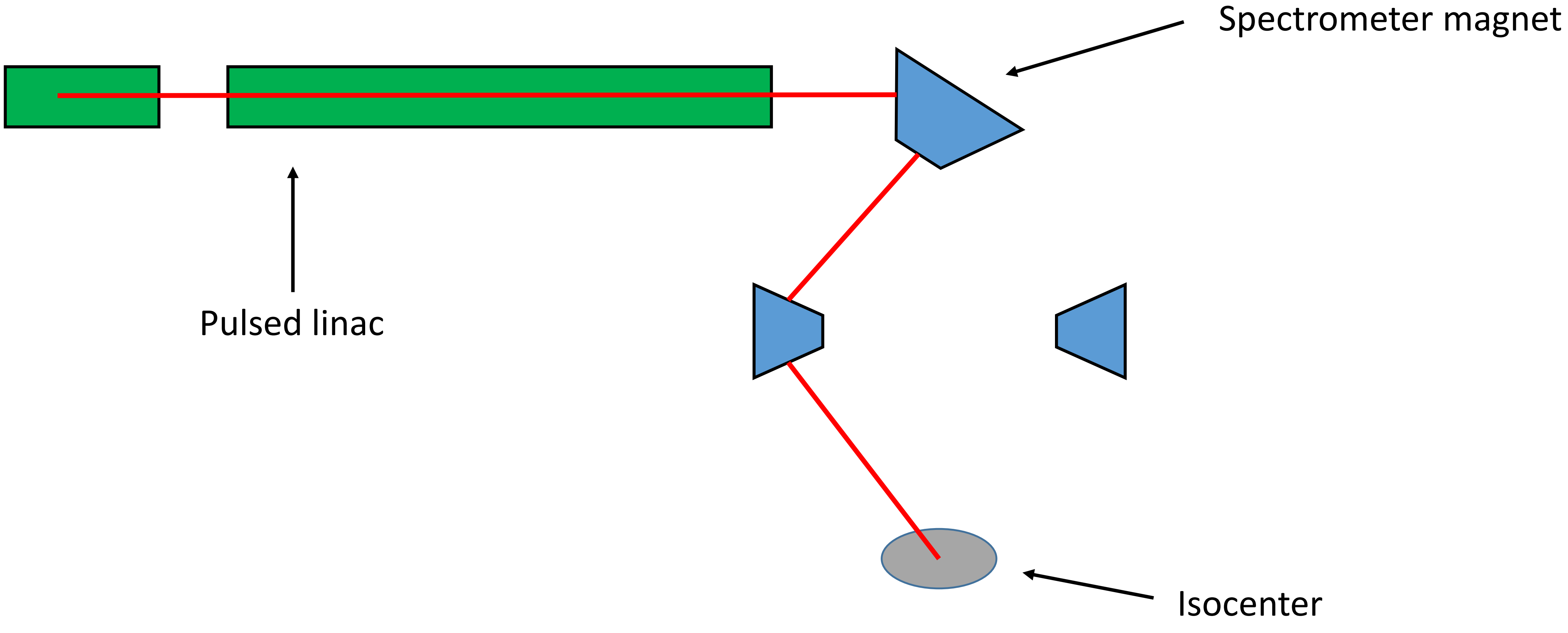
Pulsing and energy modulation



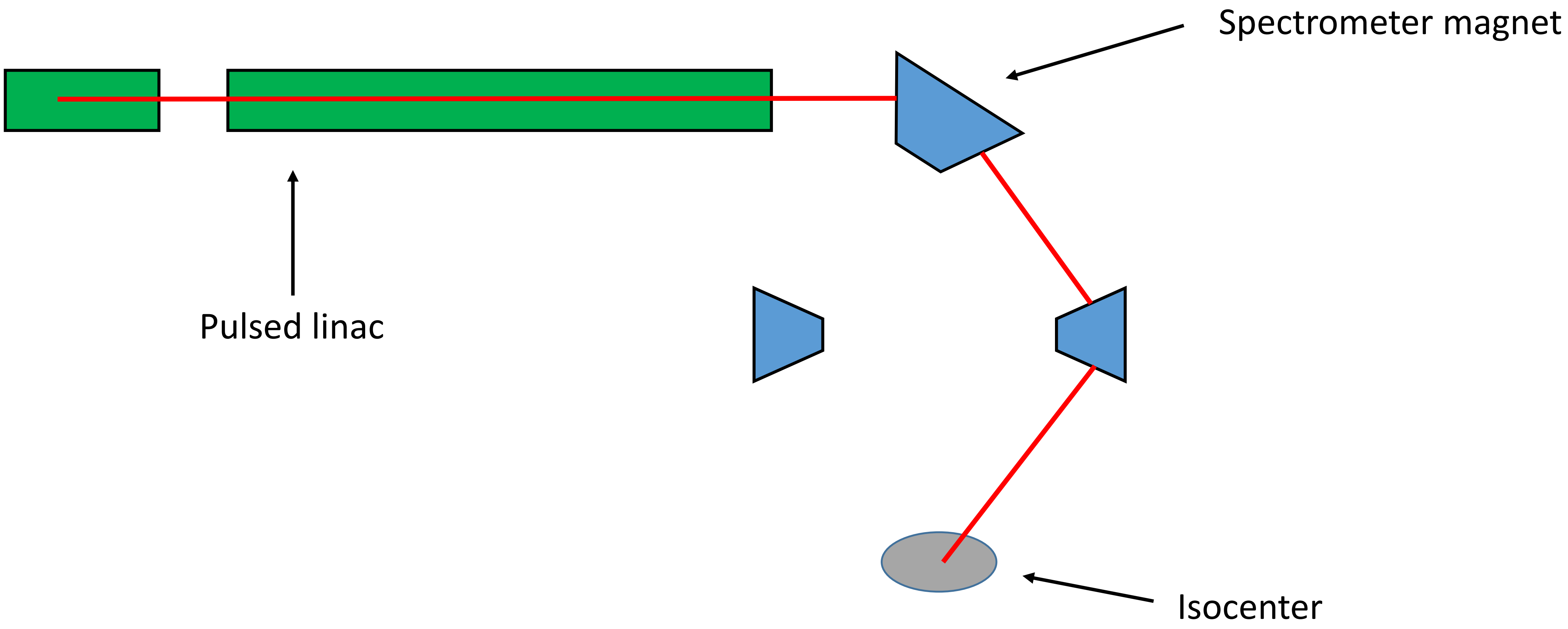
LINAC2

XBox-3 high-gradient test stand. Klystrons operate at 400 Hz, alternatively powering two test slots at 200 Hz.

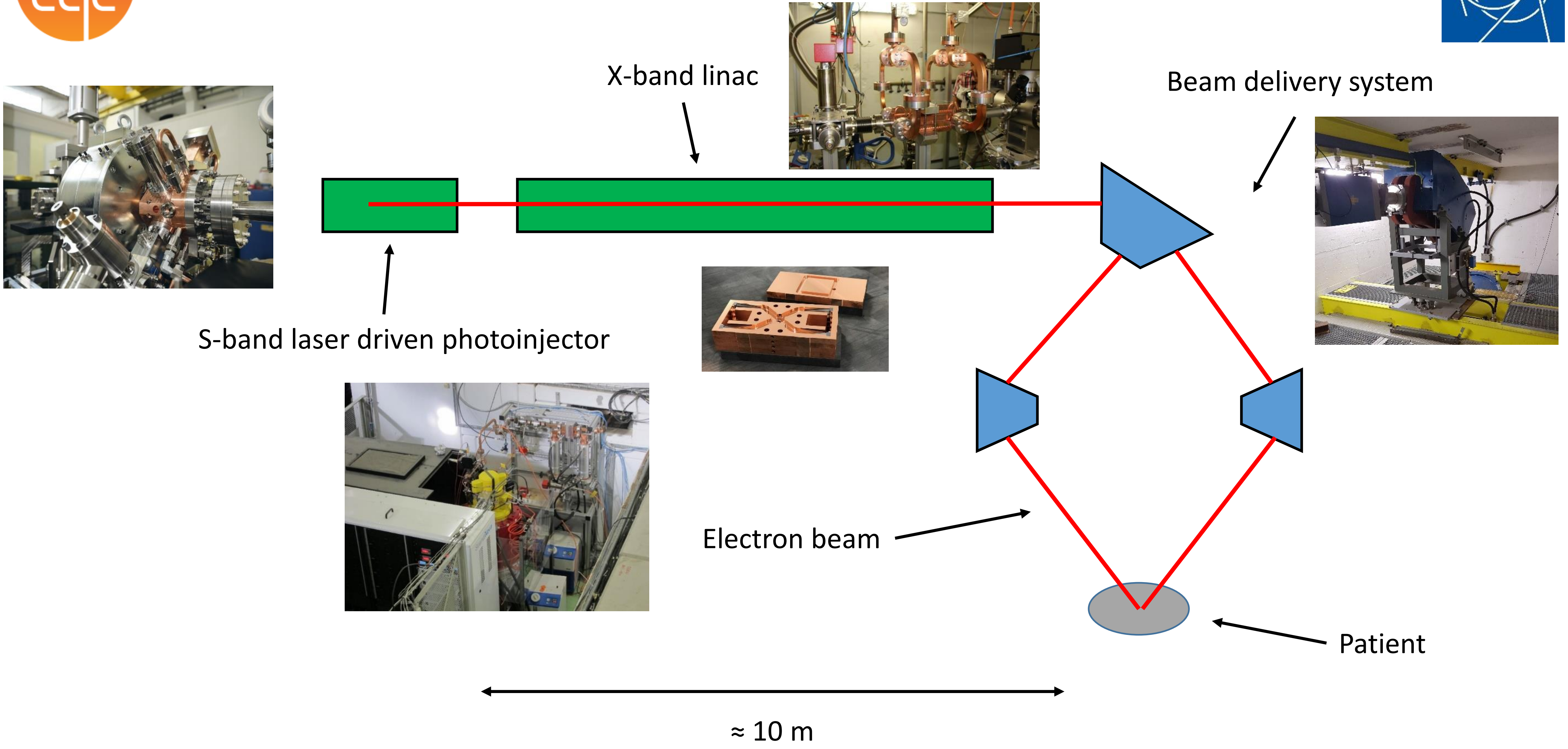
Energy E_1



Energy E_2



The overview again



More information

Fundamental processes of high-fields

Dynamic and growing community of university, laboratory and industrial groups.
Fields include accelerators, fusion devices, satellites, vacuum interrupters, electron sources, photo-switching nano-devices, high-voltage systems etc.
Next meeting https://indico.cern.ch/event/1099613/ in person hosted by the University of Tartu!

The High-Gradient RF Workshop Series

Our last in-person meeting, Chamonix, summer 2019

International Workshop on Breakdown Science and High Gradient Technology (HG2022)

May 16 – 19, 2022

Europe/Paris timezone

Enter your search term

- Overview
- Timetable
- Participant List
- Registration
- Previous workshops
- Privacy Notice - HG2022
- Privacy Notice - Zoom

We are pleased to announce the 14th workshop on breakdown science and high gradient technology, HG2022, will be held virtually on Zoom from May 16-19, 2022.

The HG workshop series dedicate to the discovery and advancement of high gradient technologies for advanced beam applications to both magnificent fundamental researches and civil life. As the idea of X-band technologies was born out of the demand of compact collider, it is naturally boned with the high gradient conception and has been substantially discussed in previous HG workshops. At all times, with the participation of material science, our vision on breakdowns has been expanded to a more microscopical area. By the tight collaborations worldwide, we have climbed to peaks that no one has ever reached before: accelerators with gradients over 100 MV/m and less breakdown probability have been achieved, and the gradient limitation has been pushed to over 200 MV/m. Such achievement has pushed the application of high-gradient technologies to scientific facilities and to both electron and proton radiotherapy equipment.

In previous HG workshops, from large collider to desktop light, from room-temperature to cryogenic, from new structures to high power-sources, from horizons under microscope to simulations with enormous particles, voice of discussions rises one after another, benefits far beyond the high gradient community.

HG2022 will continue our adventures. The workshop will share the latest advancements in, but not limited to, breakdown theory, low breakdown rate high-gradient accelerators, novel structure designs, low-cost accelerator fabrication technologies, accelerator applications to light source, medical, and industrial technologies, high efficiency high power RF sources, etc. Although this workshop will be hold virtually, the format of HG2022 follows the format of preceding workshops, including oral presentations and poster sessions and discussions.

We look forward to seeing you again.

Local Organizing Committee:

Jiaru Shi (Tsinghua University)

Hao Zha (Tsinghua University)

Qiang Gao (Tsinghua University)

Last meeting, remote, hosted by Tsinghua University.

https://indico.cern.ch/event/1080222/

More on FLASH therapy

Academic Training Lecture Regular Programme

REMOTE - Mechanisms of the FLASH effect (1/4)

by Marie-Catherine Vozenin (CHUV)

Tuesday 15 Mar 2022, 11:00 → 12:00 Europe/Zurich

Zoom

Description A re-emergence of research implementing radiation delivery at ultra-high dose rates (U
sciences and has opened a new field of investigation in radiobiology. Much of the pro
vivo biological response observed to maintain anti-tumor efficacy without the normal
dose rate. The FLASH effect has been validated primarily, using intermediate energy e
short period of time (<200 ms), but has also been found with photon and proton beam
highly significant and as pioneers in this field, our group has developed a multidisciplin
mechanisms and clinical translation of the FLASH effect. Here, I will give an overview
involved in the FLASH effect.

Short bio:

Marie-Catherine Vozenin is head of radiobiology at Lausanne university hospital (CHU
Lausanne University Hospital and University of Lausanne- Switzerland.

Her research projects aim at finding innovative tools to protect normal tissue and enh
Vozenin has developed a novel modality of radiation therapy called FLASH-RT that mi
various organs including the brain, lung and skin and in various species including mice
by FLASH-RT was termed the FLASH effect, resulting in a series of investigations to c
Vozenin and her team are investigating the entirely different biological response induc
translation of FLASH-RT to cancer patients.

MCVozenin_CERN1... | Recording | Video preview

From the same series 2 3 4

Organised by Manuela Cirilli / Participants 167

Videoconference Academic_Training 0522

Organiser Manuela.Cirilli@cern.ch

Academic Training Lecture Regular Programme

REMOTE - Towards clinical use of FLASH therapy (2/4)

by Jean Bourhis (CHUV)

Wednesday 16 Mar 2022, 11:00 → 12:00 Europe/Zurich

Zoom

Description Delivering radiation therapy in milliseconds (FLASH therapy) instea
tissues, while the effect on tumor is maintained the same. The ma
translation.

Among the pre-requisite for clinical transfer are the robustness and
potential clinical use will be envisaged addressing some key quest
volumes of tissues, together with fractionated and high precision r

All these aspects will be addressed during the presentation and rep
that need to be solved to optimally translate this outstanding biolo

Short bio:

Jean Bourhis was appointed head of radiation oncology at CHUV i
radiation oncology Department of the Institut Gustave Roussy of U
active in promoting translational and applied research, between 19
sensitivity of tumours and healthy tissues.

Jean Bourhis is among the top international experts in radiation on
d'Oncologie Radiothérapie Tête Et Cou or Head and Neck Oncology
between 2008 and 2011 of the ARCHADE (Advanced Resource Cen
ESTRO (European Society of Radiation Oncology) from 2009 to 20

Prof. Bourhis' research aims at innovating and testing new therapie
lowering the damage to the healthy tissues. In particular, he is at th
with radiotherapy and with FLASH therapy. Most of this research is
of irradiation modes are available and can be tested on different ex
innovation from the laboratory to the clinical practice.

Recording | Video preview

From the same series 1 3 4

Organised by Manuela Cirilli / Participants 89

Videoconference Academic_Training 0522

Academic Training Lecture Regular Programme

REMOTE - Medical physics of ultra-high dose rate electron beams (3/4)

by Raphael Moeckli (CHUV)

Thursday 17 Mar 2022, 11:00 → 12:00 Europe/Zurich

Zoom

Description The dose delivered to tissues induces a spec
high dose rates (UHDR; > ~40 Gy/s in averag

Biological experiments were performed on p
validated to reach a reasonable accuracy, be
the challenging work to provide adequate be
necessary to produce a large homogeneous
UHDR for clinical treatments is obviously the

I will present the characteristics of available
tumors, and describe the challenges that we

Short bio:

Raphaël Moeckli completed his MSc degree
Lausanne in 2001. He is certified Swiss med
head physicist in the Radio-Oncology Depart

He is associate professor in Lausanne Unive
optimisation. He is and has been director an
papers in peer-reviewed journal.

He is past president of the Swiss Society of I
Swiss recommendations about good practic
well as other Swiss and international meetin

Physics_FLASH_CE... | Physics_FLASH

From the same series 1 2 4

Organised by Manuela Cirilli / Participants 80

Videoconference Academic_Training 0522

Organiser Manuela.Cirilli@cern.ch

Academic Training Lecture Regular Programme

REMOTE - An accelerator system for the FLASH treatment of large deep-seated tumors (4/4)

by Walter Wuensch (CERN)

Friday 18 Mar 2022, 11:00 → 12:00 Europe/Zurich

Zoom

Description The potential benefits of radiation treatment in FLASH timescales have been clearly demonstrated in experiments and clinical trials are underway for specific cases such as skin and intraoperative treatment using low energy electrons. Generalizing FLASH therapy to large, deep-seated tumors requires new radiation delivery infrastructure. A collaboration between CHUV and CERN is now developing an accelerator system for such a facility which is scheduled to be used for first clinical trials in 2025. The facility uses > 100 MeV electrons and draws heavily on technology developed by the CLIC project. The major features and critical issues of the accelerator, as well the status of the project are described.

Short bio:

Walter Wuensch is a principle applied physicist in the Radio-Frequency group at CERN currently leading the development of high-performance linac technology for multiple applications including CLIC and a broad range of next-generation compact accelerators including XFELs, Inverse Compton Sources and medical linacs. The accelerator technology development is complemented by both theoretical and experimental investigations of the fundamental processes which occur at high-gradients including field emission and breakdown. The investigations are illuminating long-standing mysteries and the newly gained understanding are being applied to a range of applications the electron linacs, RFQs and high-voltage systems.

DEFT training 2022-... | DEFT training 2022-... | Recording | Video preview

From the same series 1 2 3

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Organiser Manuela.Cirilli@cern.ch

https://indico.cern.ch/event/1131207/

Animation

https://www.youtube.com/watch?v=87JLhcsuIao