



Highlights of normal-conducting, high-gradient applications and development



Introduction



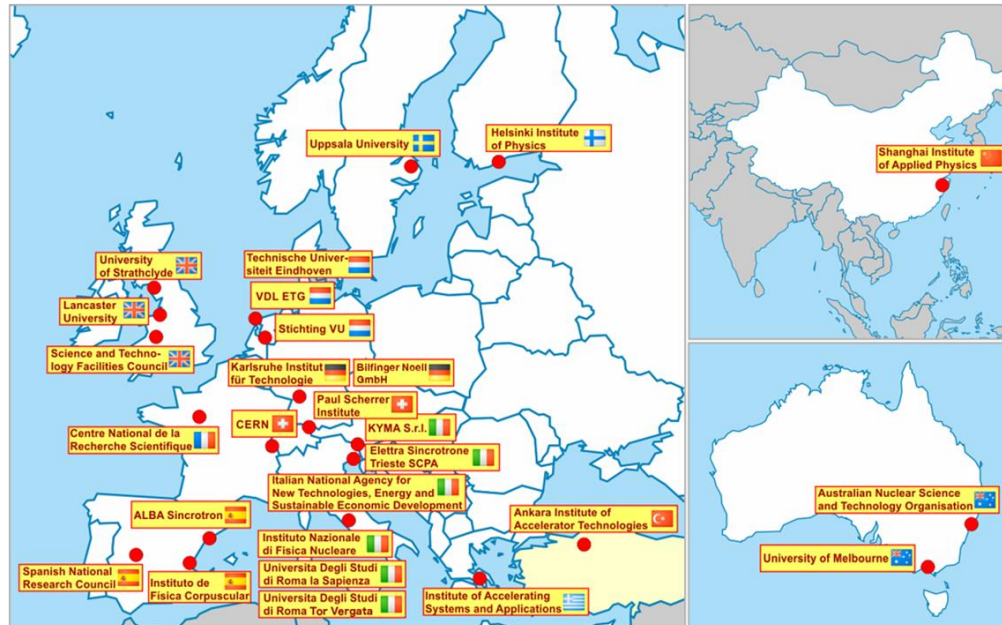
Theme of this presentation - Progress developing normal-conducting, high-gradient linac technology now extends well beyond the CLIC study.

- A selection of applications
 - CompactLight
 - EuPRAXIA@SPARC_LAB
 - FLASH therapy
 - PolariX
- Technology innovations
 - High-efficiency klystrons
- Fundamentals of high fields
 - Just a taste!
 - MeVArc2021 workshop
- HG2021 workshop

EU funded design study of a intermediate-cost, < 250 MCHF, and flexible XFEL facility.
 In fourth and final year, busy now on writing up the design (Deliverables!!).

CompactLight@elettra.eu

www.CompactLight.eu



26 academic and industrial partners

<http://www.compactlight.eu/Main/HomePage>

CompactLight is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.

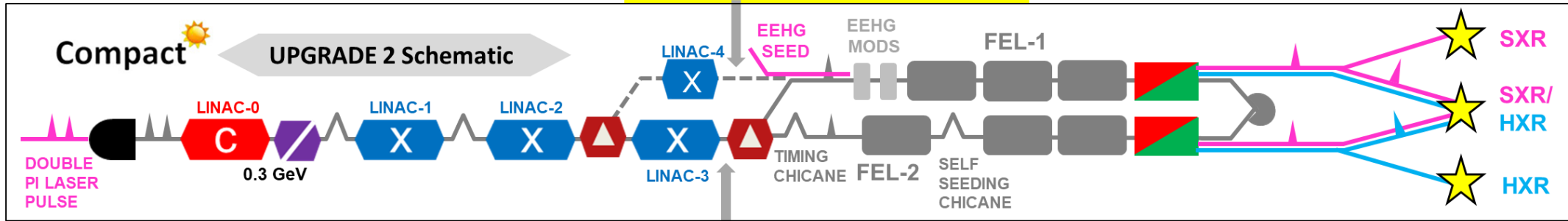


Pump-probe experiments:
Two-bunch linac operation

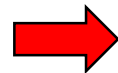
UPGRADE 2

'Dual Source Linac' – single linac, two klystrons

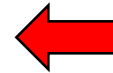
0.97 to 2.4 GeV @ 100 Hz (SXR/HXR)



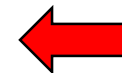
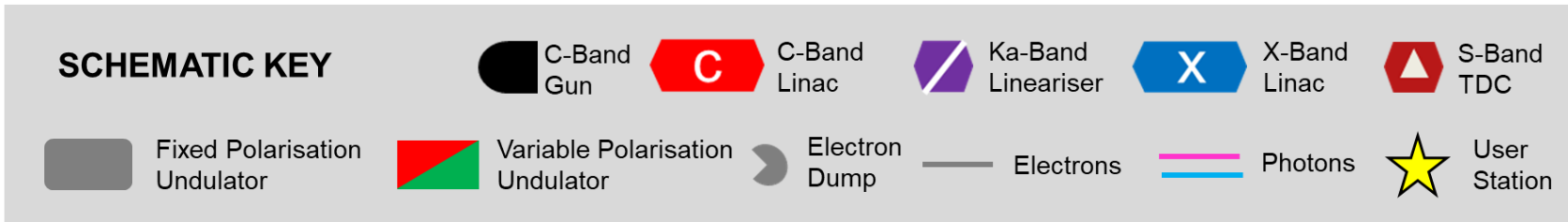
Hard and soft X-ray
operating modes



0.97 to 2.4 GeV @ 1000 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)
2.75 to 5.5 GeV @ 100Hz (SXR/HXR)

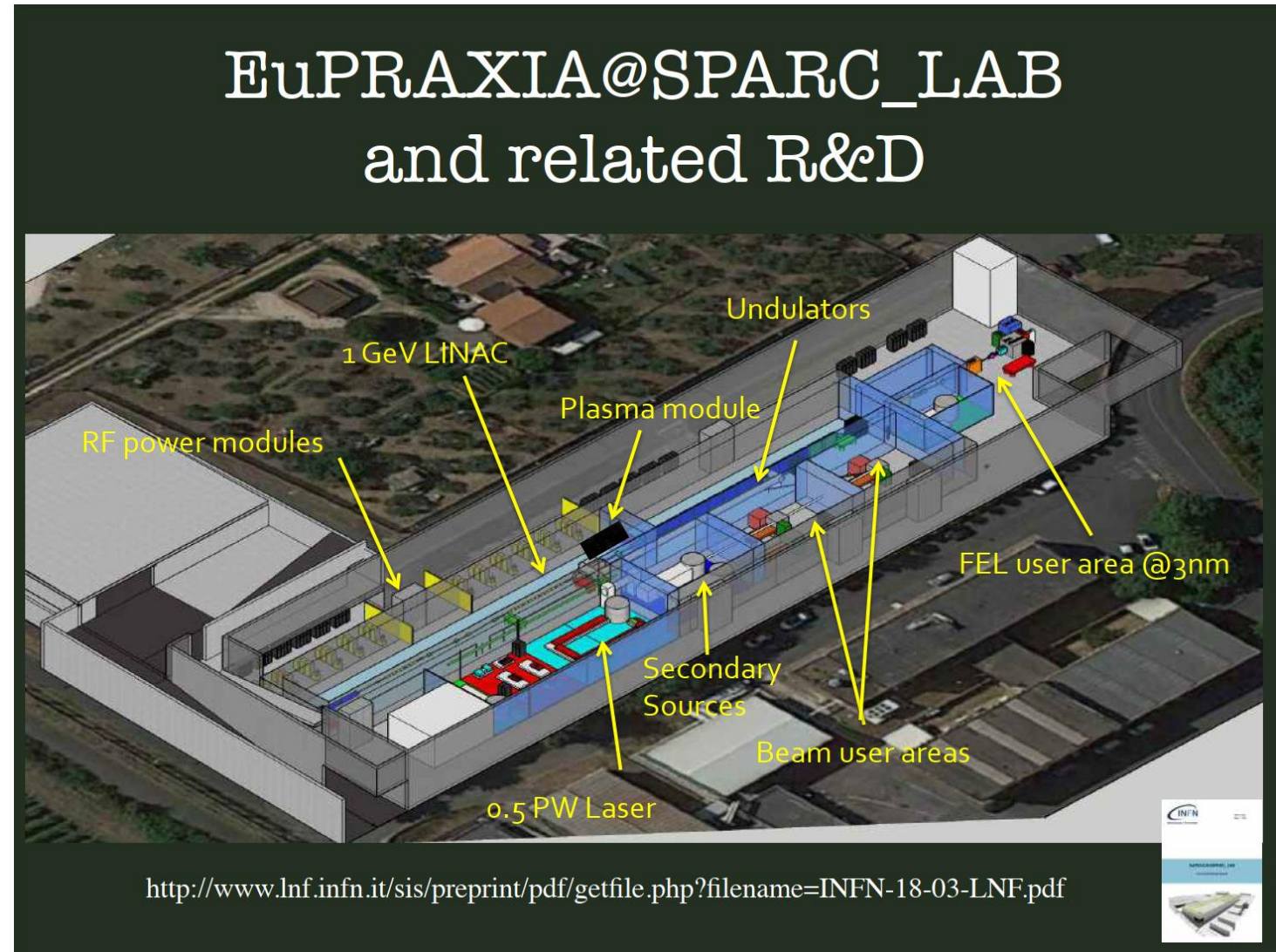
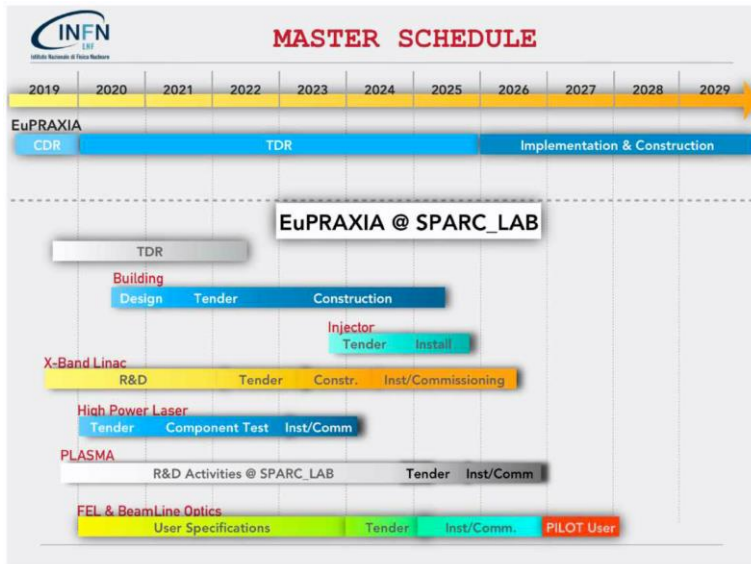


High and low repetition rate
operation



Many frequencies

- Center for research into beam-driven plasma acceleration at INFN Frascati
- Beam will be generated by a 1 GeV high-gradient X-band linac
- Triumph to become “boring” part of a facility
- Shows potential longer-term development of electron linac technology



- X-band linac module design same as CompactLight – a step towards a standardized supply.
- First two accelerating structures to be built by I-FAST (successor to ARIES)

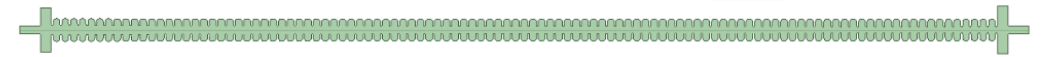


Figure 14: longitudinal cross-section of the structure.

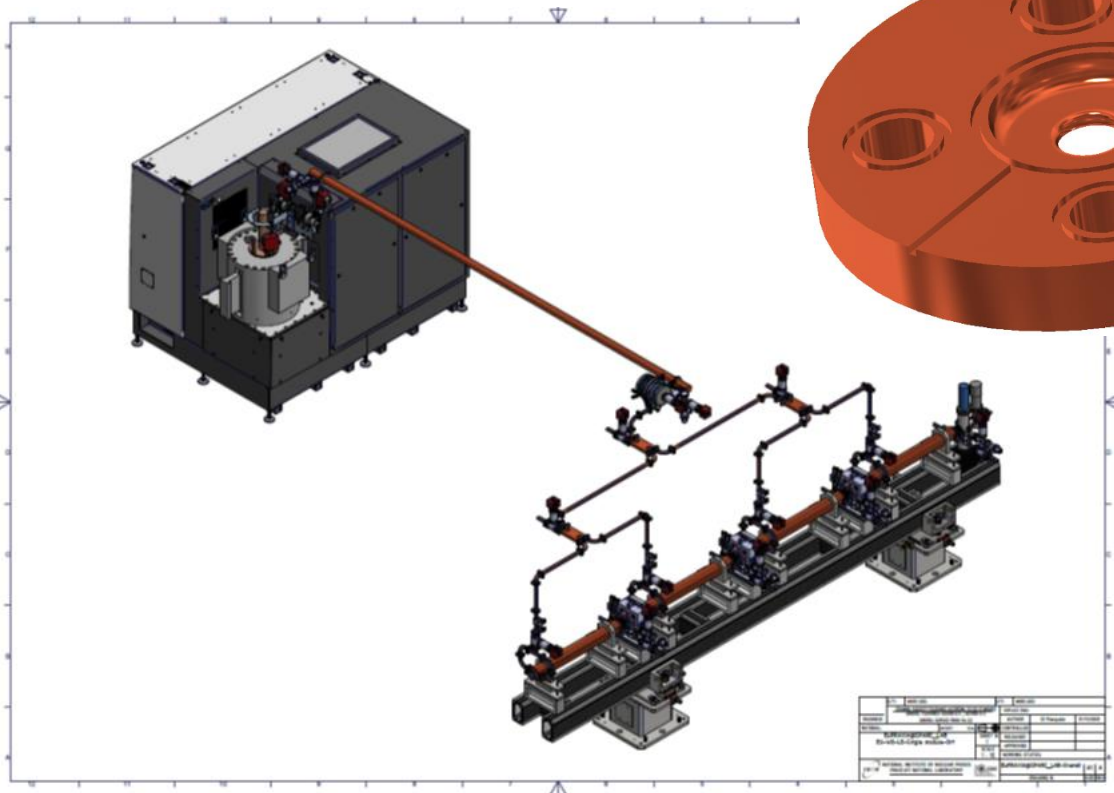
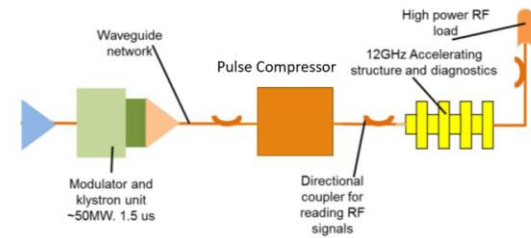
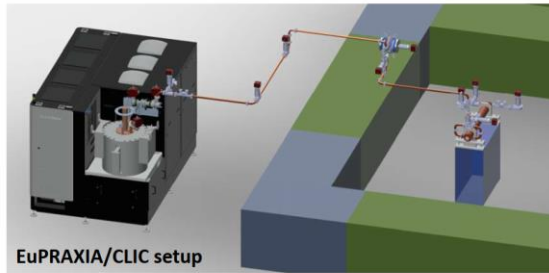


Table 6: Main parameters of the accelerating structure.

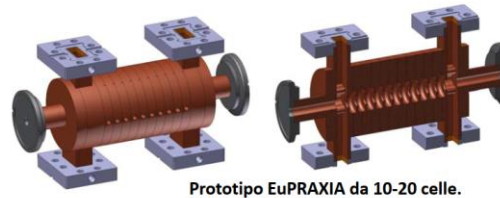
Frequency [GHz]	11.994
Phase advance per cell [rad]	$2\pi/3$
Waveguide power attenuation [%]	≈ 10
Average iris radius $\langle a \rangle$ [mm]	3.5
Iris radius a [mm]	4.3 - 2.7
Iris thickness t [mm]	2.0 - 2.24
Number of cells per structure	109
Accelerating cell length [mm]	8.332
Structure length L_s [m]	0.9
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23200
Shunt impedance R [M Ω /m]	85 - 111
Effective shunt impedance R_s [M Ω /m]	349
Group velocity v_g/c [%]	4.7 - 0.9
Filling time [ns]	146

65 and 30 MV/m accelerating gradient

TEX - RF Source Commissioning



EuPRAXIA Structures Parameter	Value
Frequency [GHz]	11.9942
Average acc. gradient <G> [MV/m]	60
RF pulse [μ s] (before pulse compression)	1.5
Kly. power [MW]	50
Average iris radius <a>	3.5
Iris radius a [mm]	4.3-2.7
Structure length L_s [m]	0.9
No. of cells	109
Shunt impedance R [MQ/m]	85-117

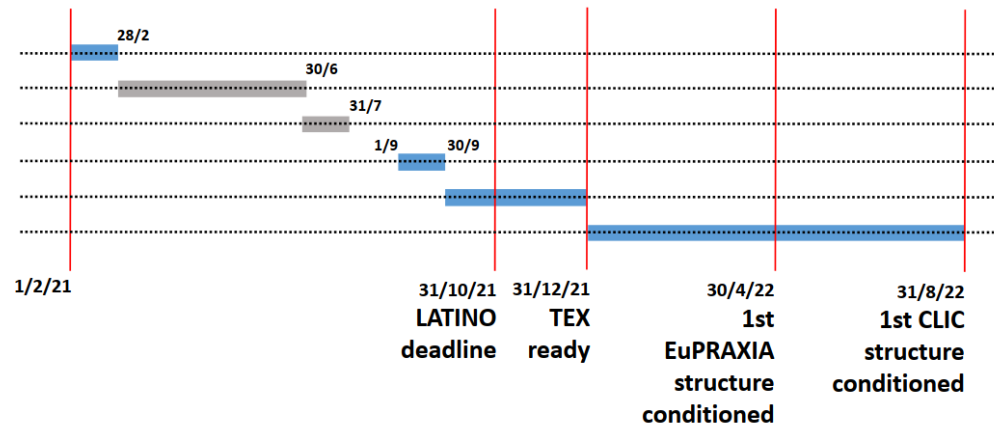


Prototipo EuPRAXIA da 10-20 celle.



Scandinova modulator

- TEX Vac/CS installation
- DT ed.7 refurbishment
- TAV installation
- Modulator SAT
- Sub-systems installation
- TEX operation *



CPI 50 MW klystron

Hot topic in radiation oncology – dose delivered in $\ll 1$ s timescale spares healthy tissue while maintaining effect on tumor.

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



Vozenin et al
Clin Cancer Res
 2018

Contents lists available at ScienceDirect

Radiotherapy and Oncology

journal homepage: www.thegreenjournal.com

Original Article

Treatment of a first patient with FLASH-radiotherapy

Jean Bourhis^{a,b,*}, Wendy Jeanneret Sozzi^a, Patrik Gonçalves Jorge^{a,b,c}, Olivier Gaide^d, Claude Bailat^e, Frédéric Duclos^a, David Patin^a, Mahmut Ozsahin^a, François Bochud^c, Jean-François Germond^c, Raphaël Moeckli^{c,1}, Marie-Catherine Vozenin^{a,b,1}

^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 the 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

PHYSICS TODAY

HOME BROWSE▼ INFO▼ RESOURCES▼ JOBS

During the COVID-19 pandemic, *Physics Today* is providing complimentary access to its entire 72-y...

Home > Physics Today > Volume 73, Issue 12 > 10.1063/PT.3.4631

01 DECEMBER 2020 • page 24

High radiation dose rates may improve cancer therapy

The ill-understood effect is gaining momentum and opening new avenues of research. CERN's Compact Linear Collider and other particle accelerators are contributing.

Toni Feder

PDF COMMENTS

PREV NEXT

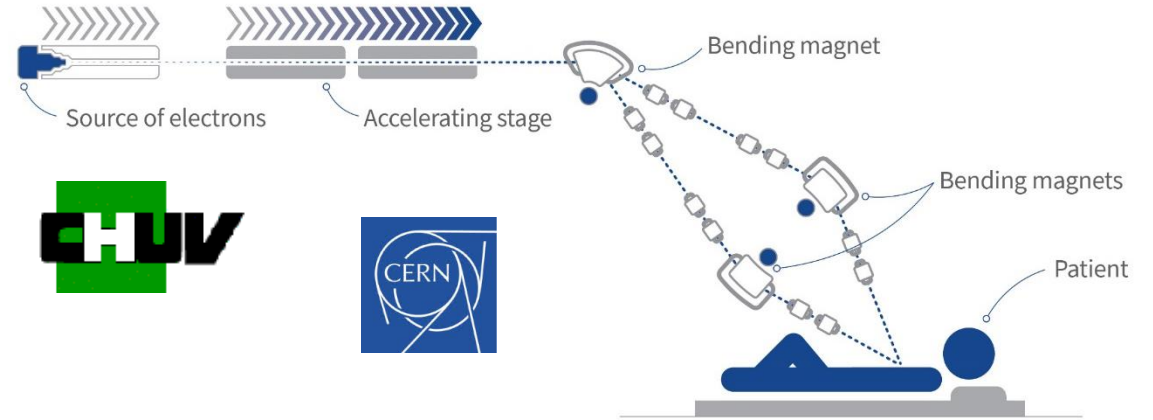
Physics Today 73, 12, 24 (2020); <https://doi.org/10.1063/PT.3.4631>

Dose rates hundreds to thousands of times higher than currently used in clinical treatment show promise for killing tumors while largely sparing healthy tissue. The mechanisms underlying the so-called FLASH effect are not understood, but results so far—in animals and in one human—have invigorated research into what some radiation oncologists and medical physicists say could revolutionize cancer treatment.

Scientists at medical and high-energy-physics research centers worldwide are tweaking existing accelerators to study and characterize the FLASH effect, named for the brevity of radiation exposure. The total dose is comparable to conventional therapy, but it is delivered in intense, subsecond single pulses or pulse sequences. Last month Varian launched a clinical trial that is treating bone metastases with proton FLASH therapy. Other companies are also getting involved.

In Switzerland, medical researchers at the Lausanne University Hospital (CHUV) are collaborating with physicists from the Compact Linear Collider (CLIC) project at CERN on a new accelerator to produce high-energy electrons for the first FLASH radiotherapy clinical trials on deep-seated tumors. They plan to begin the trials by 2024.

<https://physicstoday.scitation.org/doi/10.1063/PT.3.4631>



Clinical trials:

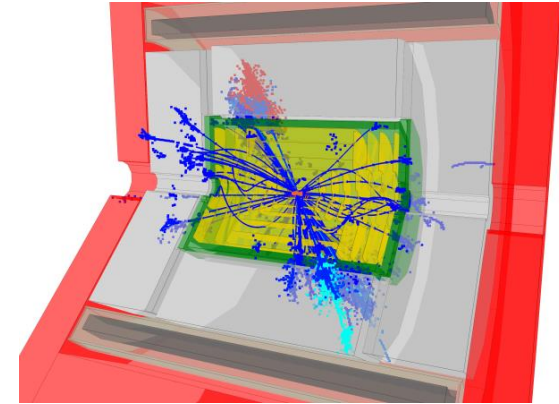
- Skin cancer using 10-MeV range electrons starting at CHUV (University hospital Lausanne).
- Palliative care of metastasis in bone marrow using protons by Varian

- Facility under study to treat large, deep-seated tumors in FLASH conditions
- Uses 100 MeV-range electrons, high current beam and optimized dose delivery
- Compact to fit on a typical hospital campus
- Based on CLIC technology!
- Design well advanced

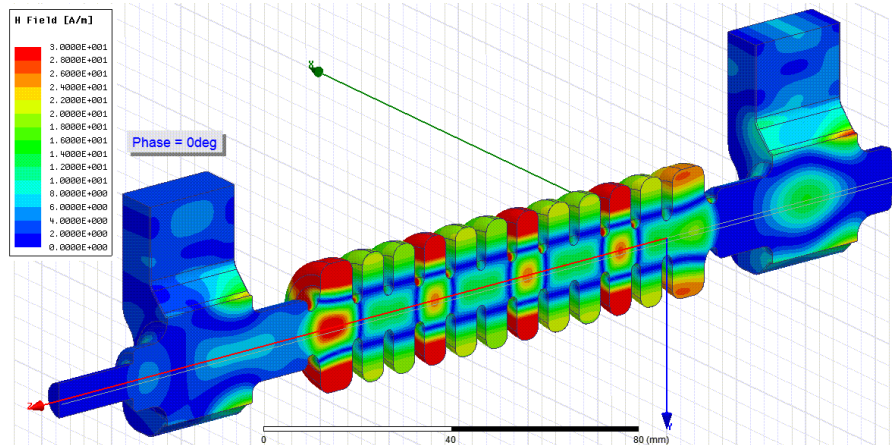
The remarkable connection between CLIC and FLASH

Both need:

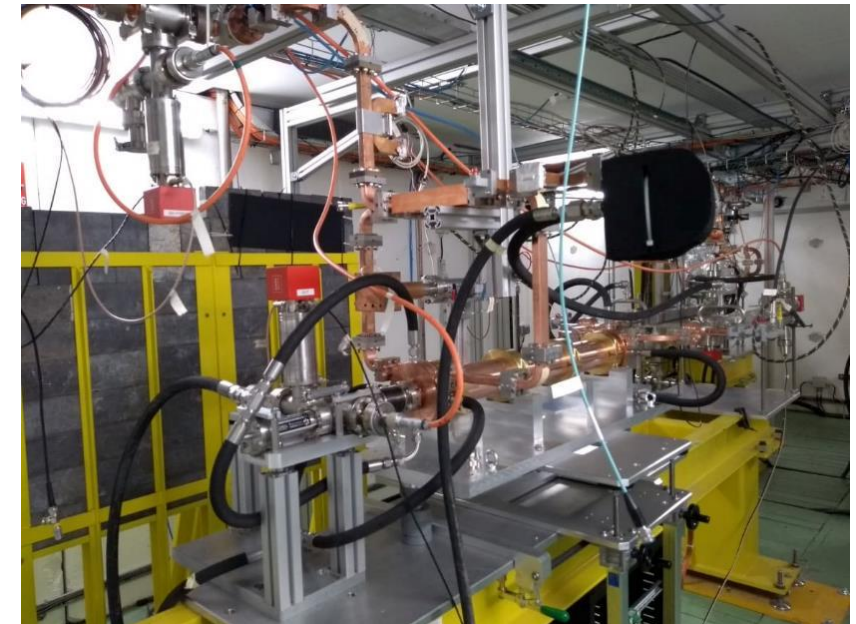
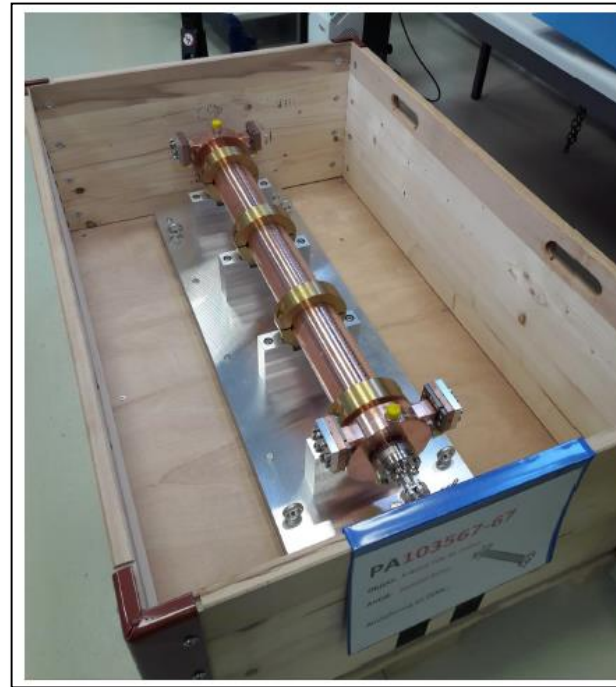
- Very intense electron beams
 - CLIC – to provide luminosity for experiments
 - FLASH – to provide dose fast for biological FLASH effect
- Very precisely controlled electron beams
 - CLIC – to reduce the power consumption of the facility
 - FLASH – to provide reliable treatment in a clinical setting
- High accelerating gradient
 - CLIC – fit facility in the Geneva area and limit cost
 - FLASH – fit facility on a typical hospital campus and limit cost of treatment



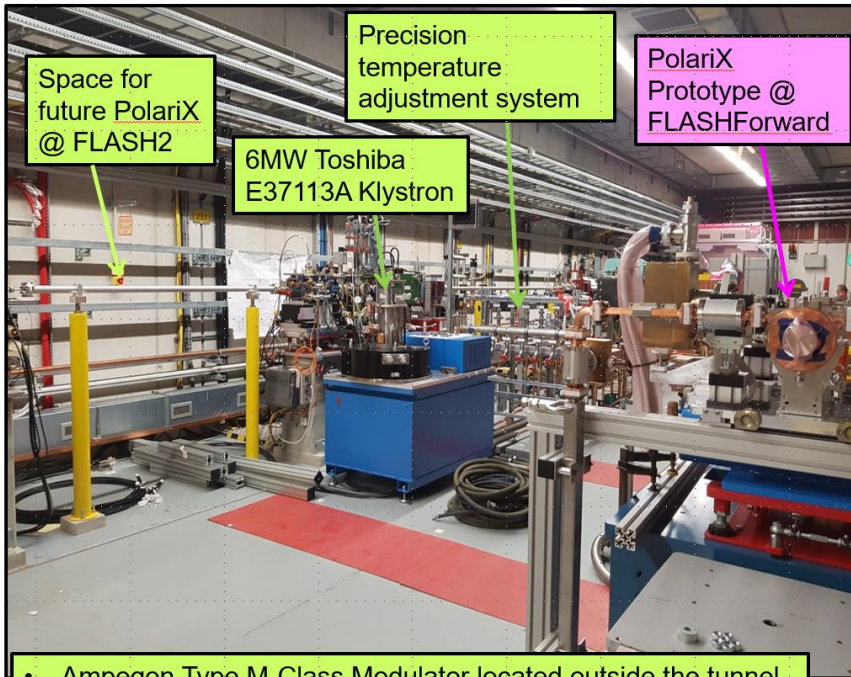
- Longitudinal profile measurements of short bunches based on RF deflector and screen
- High-gradient and X-band both contribute to performance of such devices.
- A CERN, DESY and PSI collaboration has designed, built, tested a novel variable-polarization rf deflector. Multiple units are being put into operation at DESY and PSI.



A. Grudiev



Installation of the Prototype PolariX TDS at DESY – FLASHForward



- Ampegon Type M-Class Modulator located outside the tunnel
- Connected to the klystron via a ~12 m long high power cable



Prototype PolariX TDS installed

DESY | PolariX TDS | Barbara Marchetti, IPAC 2020

Page 15

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23**, 112001 (2020)

Editors' Suggestion

Novel X-band transverse deflection structure with variable polarization

P. Craievich¹, M. Bopp, H.-H. Braun, A. Citterio, R. Fortunati, R. Ganter, T. Kleeb, F. Marcellini, M. Pedrozzi, E. Prat, S. Reiche, K. Rolli, and R. Sieber
PSI, 5232 Villigen, Switzerland

A. Grudiev¹, W. L. Millar², N. Catalan-Lasheras, G. McMonagle, S. Pitman, V. del Pozo Romano, K. T. Szypluła, and W. Wuensch
CERN, 1211 Geneva 23, Switzerland

B. Marchetti³, R. Assmann, F. Christie, B. Conrad, R. D'Arcy, M. Foese, P. Gonzalez Caminal, M. Hoffmann, M. Huening, R. Jonas, O. Krebs, S. Lederer, D. Marx⁴, J. Osterhoff, M. Reukauff, H. Schlarb, S. Schreiber, G. Tews, M. Vogt, A. de Z. Wagner, and S. Wesch
Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany

<https://doi.org/10.1103/PhysRevAccelBeams.23.112001>

Experimental Demonstration of novel Beam Characterization using a Polarizable X-Band Transverse Deflection Structure

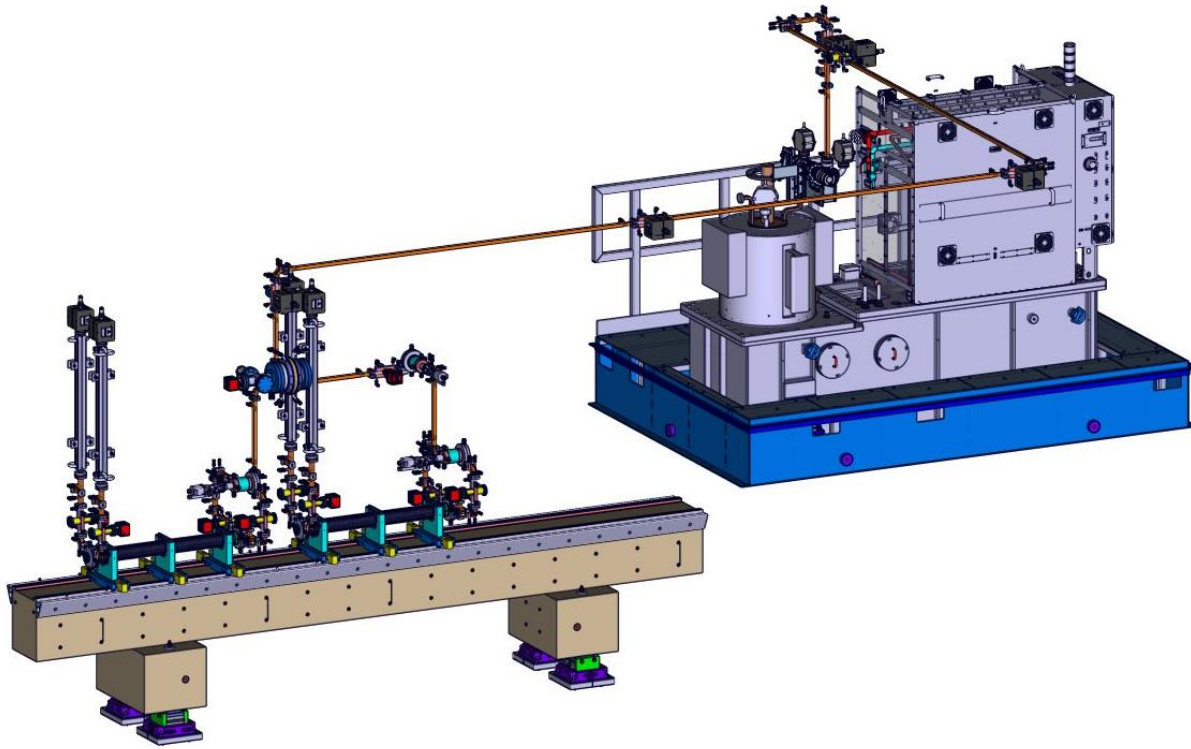
B. Marchetti³, R. Assmann, F. Christie, R. D'Arcy, P. González Caminal, M. Hoffmann, M. Huening, S. M. Jaster-Merz, R. Jonas, D. Marx⁴, J. Osterhoff, M. Reukauff, S. Schreiber, G. Tews, M. Vogt, and S. Wesch
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PSI, 5232 Villigen, Switzerland

Scientific Reports **volume 11**, Article number: 3560 (2021)

<https://doi.org/10.1038/s41598-021-82687-2>

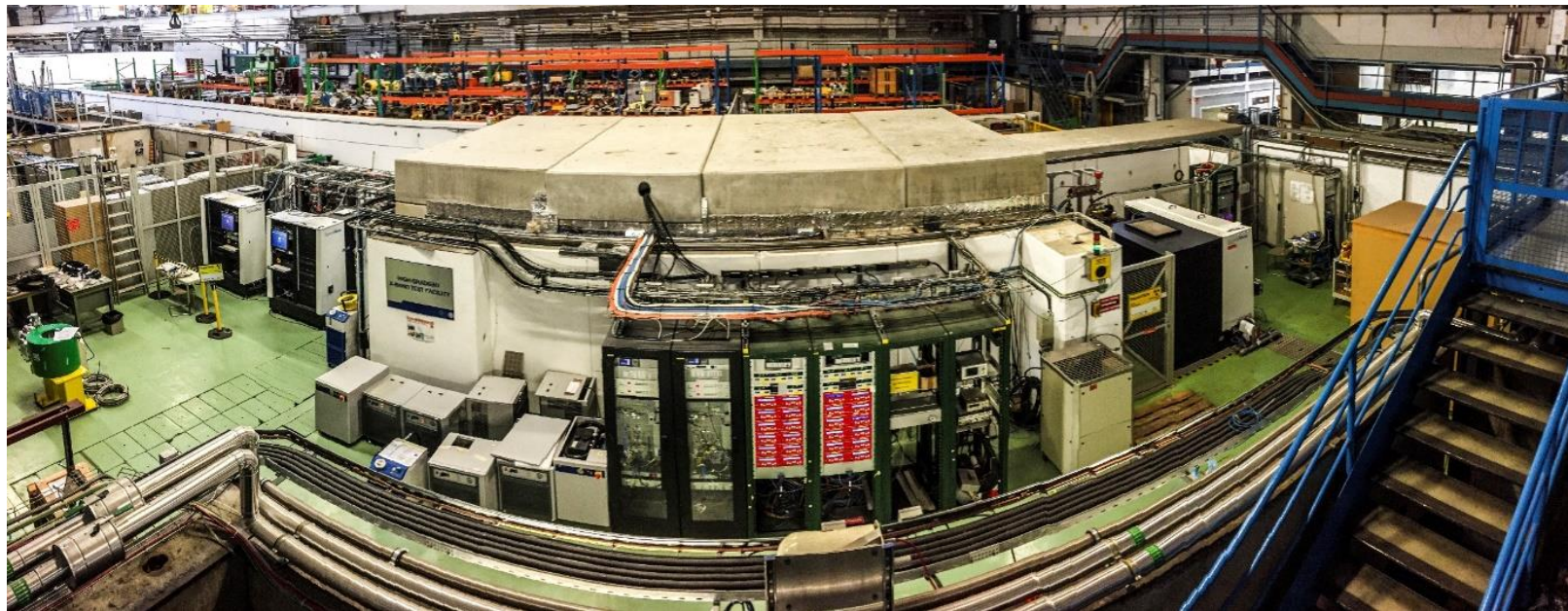


P. Craievich

- HV klystron modulator under development at PSI
- XBOCs developed at PSI, tested at CERN and now in operation at DESY
- Phase shifters (CERN concept), directional couplers, waveguide components developed at PSI and presently installed in the tunnel – ready for RF conditioning
- RF conditioning should start in summer
- Goal: achieve the deflecting voltage for sub-fs resolution for user operation

The CLIC linac baseline power source is two-beam, but X-band klystrons are crucial for test stands, series-level conditioning, fine-tuning the beam in CLIC and are essential for applications.

High-efficiency means lower power consumption but also a smaller and less expensive installation, e.g. modulator.



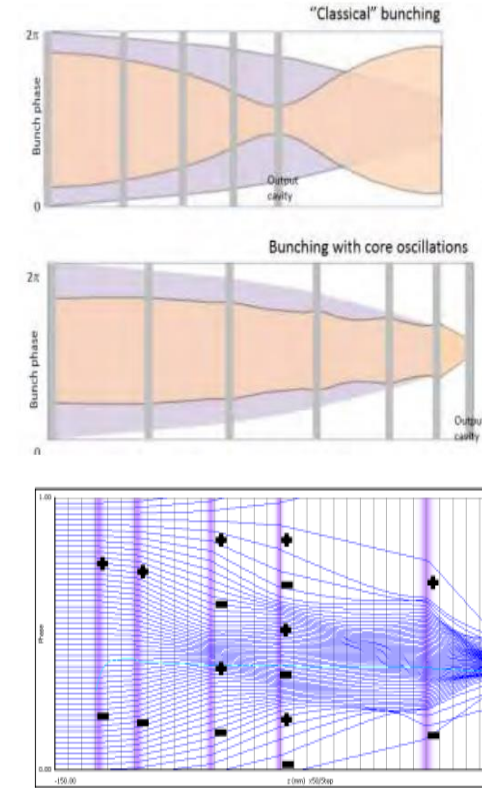
6 MW klystron pairs

50 MW klystron

XBox-3

XBox-2

- The CERN high-efficiency klystron program develops klystrons for numerous accelerators including LHC, CLIC, FCC-ee and ILC.
- For CLIC, this includes the L-band and X-band sources.

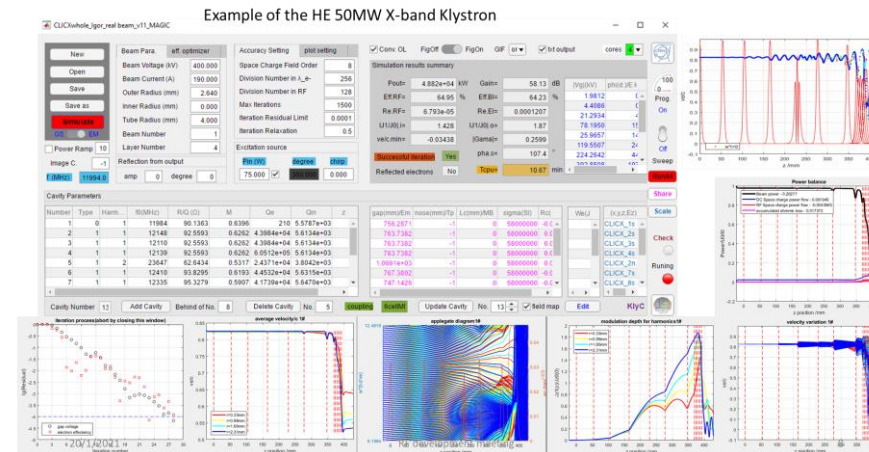


Classic

COM

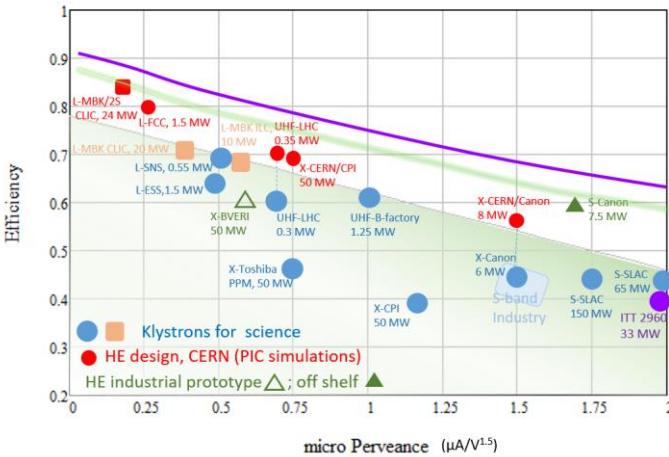
CSM

Wave-beam interaction module (GUI and Design report module)



Crucial development – simulation code KlyC

Bunching concepts – dealing with a strongly non-linear system



J. Cai, I. Syratchev

High-efficiency X-band klystrons

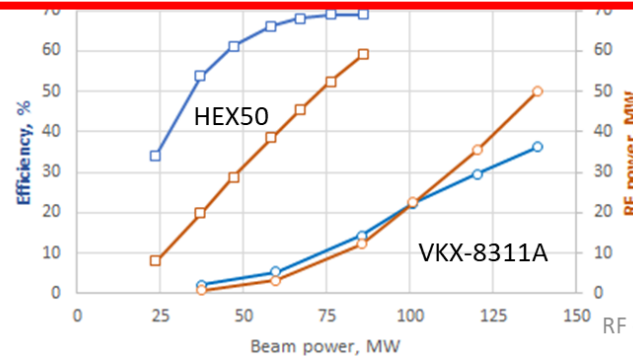
High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).



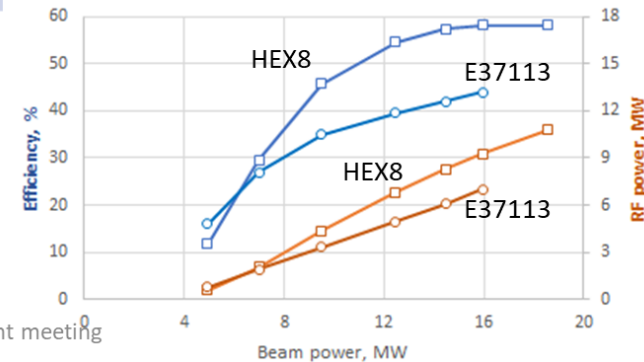
50 MW	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / klyc
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	0.32	0.32



8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	0.127	0.127



20/1/2021



15



Fundamental processes of high-fields



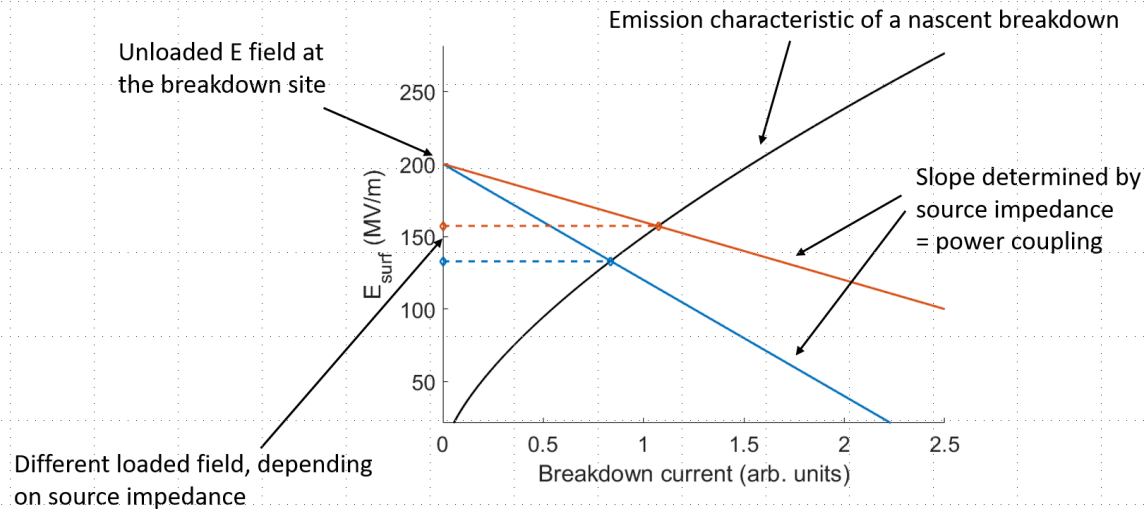
Normal conducting accelerating structures are limited in gradient by three main effects (setting aside input power):

- Field emission,
- Vacuum arcing (breakdown),
- Fatigue due to pulsed surface heating

Understanding these processes gives important input into:

- RF design – Optimizing structures also coupled with beam dynamics
- Technology – Material choice, process optimization
- Operation – Conditioning and recovery from breakdown

Breakdown current-loaded field limit

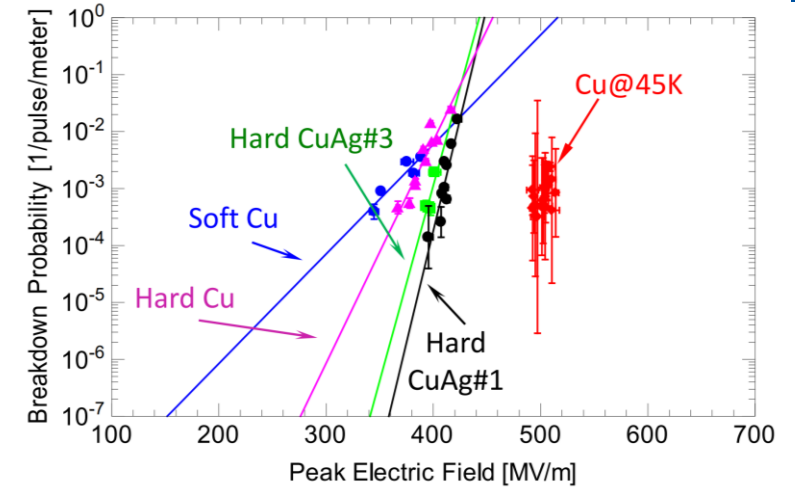
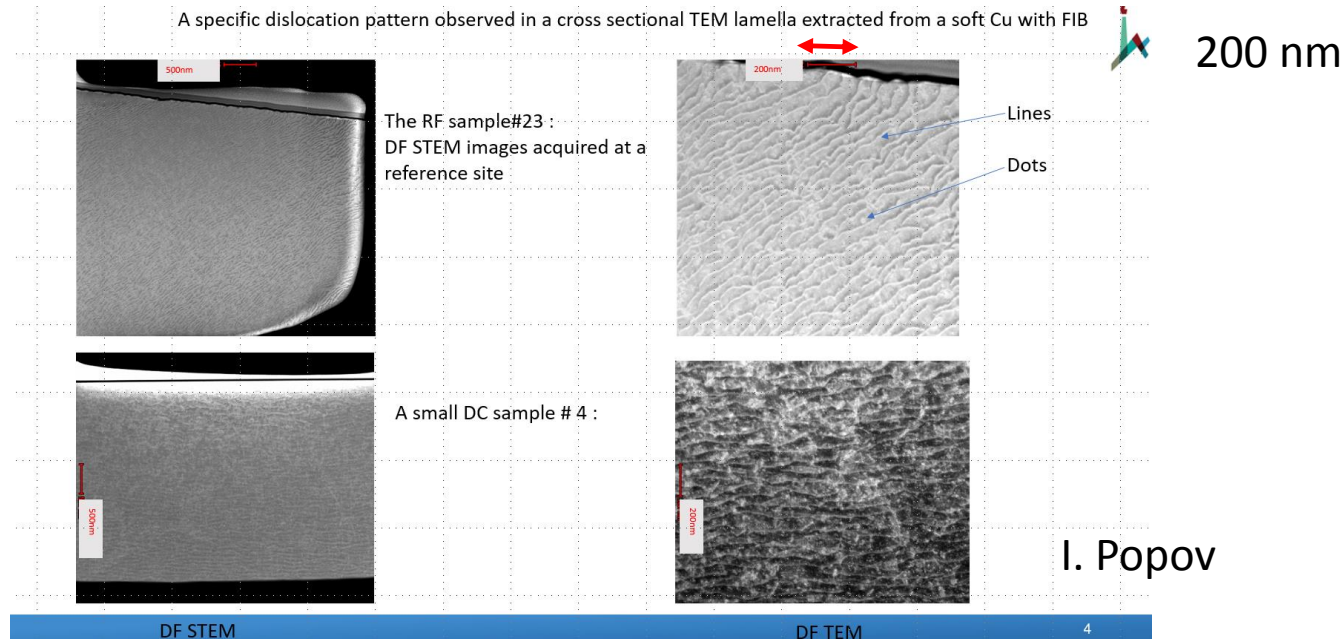


- The ultimate achievable gradient is a function of available power, like with S_c .
 - $S_c = Re\{E \times H\} + \frac{1}{6}Im\{E \times H\}$
 - Consider power during BD onset, not before!
- The current emitted by a nascent breakdown is a function of the surface E field.
- But the local surface E field decreases under BD loading, caused by the emitted current.
- Higher sustained E field under loading = higher BDR.
- Maximum gradient depends on both the unloaded E field, and how well power can be supplied to sustain the field.

PhD thesis J. Paszkiewicz <https://cds.cern.ch/record/2749494?ln=en>

Basic question – At which gradient will a specific design of a structure run for a given fabrication technology?

Role of dislocation dynamics



SLAC

<https://doi.org/10.1103/PhysRevAccelBeams.21.102002>

Stochastic Model of Breakdown Nucleation under Intense Electric Fields

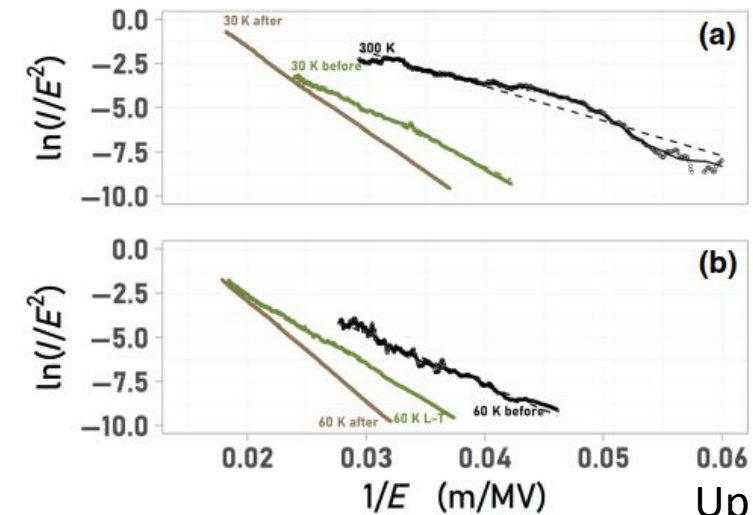
Eliyahu Zvi Engelberg, Yinon Ashkenazy, and Michael Assaf
Phys. Rev. Lett. **120**, 124801 – Published 20 March 2018

<https://doi.org/10.1103/PhysRevLett.120.124801>

And following;

<https://doi.org/10.1103/PhysRevAccelBeams.22.083501>

<https://doi.org/10.1103/PhysRevAccelBeams.23.123501>



30 K

60 K

Uppsala, CERN

<https://doi.org/10.1103/PhysRevApplied.14.061002>

9th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2021)

8-12 March 2021
Online
Europe/Zurich timezone

Overview

LATEST NEWS!

Key Dates

Topics

Timetable

Contribution List

Instruction for oral and poster presentation

Videoconference Rooms

Zoom instructions

Registration

Participant List

MeVArc 2021 contact

- ✉ andreas.kyritsakis@ut.ee
- ✉ fyura.djurabekova@hel...
- ✉ marek.jacewicz@physic...
- ✉ anton.saressalo@helsinki...

MeVArc 2021 (remote) group picture



Overview

Vacuum arcs are a concern in nearly every vacuum device under electric field; consequently they are present in a very wide range of applications. Sometimes vacuum arcs form the basis for device operation, but all too often they are the primary failure mode.

Understanding the physical processes of a vacuum arc requires expertise from many disciplines – material science, surface physics, and plasma physics. Applications include high-voltage electronics, RF accelerators, electrostatic accelerators and vacuum interrupters. The purpose of this workshop series is to bring together scientists and engineers from many different disciplines and application areas to discuss the latest efforts in understanding vacuum arcs. We cover theory, simulation and experiments.

This year, due to the COVID-19 pandemic, the workshop will be held remotely. The workshop will last 5 days, with a 3-4h session each day, in order to cover all time zones. There will be no participation fee.

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.

<https://indico.cern.ch/event/966437/>



Sandia
National
Laboratories



Our last meeting, Chamonix, summer 2019

International Workshop on Breakdown Science and High Gradient Technology (HG2021)

19-22 April 2021
Europe/Zurich timezone

- Overview
- Timetable
- Speaker List
- Registration
- Participant List
- Previous Meetings

Support

✉ traci@slac.stanford.edu

We are pleased to (re)announce the 13th workshop on breakdown science and high gradient accelerator technology, HG2021, will be held virtually on Zoom from April 19-21, 2021.

Clearly the identification and advancement of high gradient accelerator technologies for a linear collider have been the main goal since the inception of the High Gradient workshop series. Historically, the workshop has heavily concentrated on progress of X-band accelerator technologies, the area in which the most recent research results have been shared and discussed. The tight collaborations among the participants have pushed practical accelerator technologies to a level that has never been achieved before. Knowledge gained through the HG workshops in the past, like the current depth in understanding RF breakdown, the procedure of fabricating and conditioning high gradient accelerators, and the novel designs of high power rf components, etc., have benefits far beyond the X-band accelerator community.

Besides the intensive focus on X-band high gradient accelerator technologies, the workshop has always made efforts to broaden the spectrum of technologies discussed and attract more talent in related fields. In recent years, the workshop has successfully recruited theorists in material science and experts in accelerator applications, whose participation has significantly enriched the program and generated mutual benefits. HG2021 will continue this journey. The workshop will share the latest advancements in, but not limited to, breakdown science, high efficiency high power RF sources, low breakdown rate high-gradient accelerators, low cost accelerator fabrication technologies, novel accelerator designs, accelerator applications to light source, medical, and industrial technologies etc. While it will be virtual, the format of HG2021 follows the format of preceding workshops, i.e. oral presentations and discussions.

We look forward to seeing you.

Local Organizing Committee:

Emilio Nanni (SLAC)

Evgenya Simakov (LANL)

Sami Tantawi (SLAC)

John Lewellen (LANL)

Registration open!
Organized by SLAC and LANL

<https://indico.fnal.gov/event/22025/>



Conclusions



High-gradient technology innovations that have emerging from normal conducting linear collider development make significant impacts in many areas.

The cumulative effort in X-band and high-gradient technology in applications significantly exceeds that of CLIC.

Based on a very rough estimate of the distribution and procurement of X-band klystrons, this is a factor above 5 and counting.

Spread over a wide variety of projects and applications.

This adoption is crucial for CLIC to maintain continuity in a core technology during the long years ahead while science politics runs its course.