Considerations of accelerator systems for FLASH radiation therapy

Disclosure:
While preparing this lecture, and discussing with François Germond (CHUV), a more intriguing and more academic approach emerged compared the mainly project status report the abstract describes. Consequently the contents of this lecture diverges from you may be expecting, but I hope that you will still find this lecture interesting and informative.

Basic considerations

We’ve heard over the past three days that FLASH therapy, irradiation in 100 ms or less, spares healthy tissue while maintaining tumor control, with potentially significant clinical benefits.

The question we will address today is:
What kind of beam, and corresponding accelerator, can we come up with that can irradiate in FLASH timescales that is also reasonable for clinical use?

But before we work out of specifics, there is the question of strategy. Radiation treatment is already extremely successfully. How can a new technique enter such a mature field? Effectiveness, and then any comparative advantage, will take a substantial time to clarify.

General parameters

To address the entry challange, this facility will target tumors that are currently difficult to treat or are even untreatable, specifically **large and deep-seated tumors**.

This gives the basic performances requirements for our accelerator. It needs to treat:

- in very short times – 100 ms (and even lower) rather than minutes. This means the dose rate must be high
- large volumes – Capable of covering tumor cross sections over 10 cm diameter, so no compromise on total dose (no increasing the dose rate by focusing down!).
- deeply – Full depth of body, so distances up to 25 cm.

Basic means

The path CERN and CHUV have chosen to achieve this is to use Very High Energy Electrons, in the range of 100 to 200 MeV, produced and accelerated using linac technology developed for CLIC.

- Large doses in short times – To do this we must accelerate a lot of charge. This is also necessary for CLIC to produce a high luminosity (the other aspect is a very well-controlled and small beam).
- Deeply – 25 cm depth requires something like > 100 MeV electron beams. Another design requirement for CLIC is high-gradient acceleration. We'll use this aspect as well to design a compact facility.

We will also look at other technologies too to better understand the fundamental issues.

Further considerations

Many techniques have been developed over the years to improve the tumor treatment to healthy tissue toxicity ratio; conformality, intensity modulation, Bragg peak etc.

FLASH may give an advantage in treatment, but if we can’t incorporate some of the well-developed techniques that also give advantages, we might not do more than arrive in the same place.

Fortunately, the choice of electrons gives us possibilities of replicating some of these techniques:

- Electrons are charged particles so can be deflected, steered and generally manipulated (compared to X-rays).
- 100 – 200 MeV electrons are not so rigid, so magnets are relatively modest (compared to protons).
- The normal conducting electron linac we will use is pulsed, allowing very fast change of beam parameters, trajectories etc. (compared to rings).

Determining beam parameters

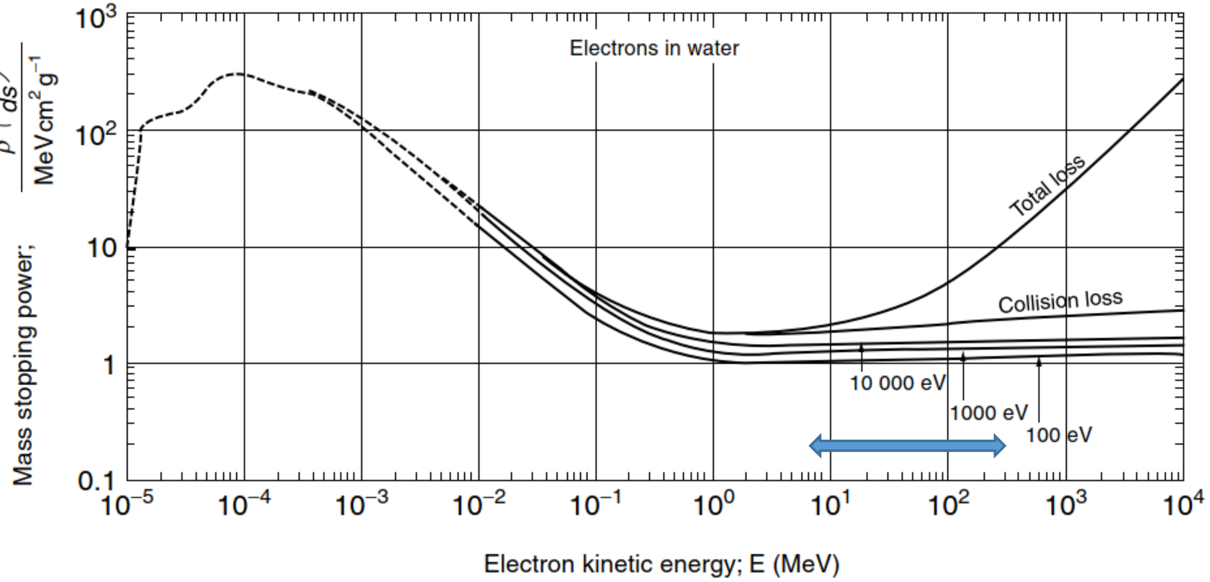
Beam energy

How do our working specifications translate more specifically into beam parameters?

We start with beam energy. The main issue here is getting deep enough into the patient:

- An electron beam losses about 300 MV/m in water, a zero order estimate of beam energy is that to treat to a depth of 25 cm we will need a beam energy of at least 100 MeV.

Water density 1 g/cm^3 so units are in 100 MV/m



(b)

Deceleration in the range of 200-300 MV/m

Coincidence – the peak surface electric field in a CLIC structure is 200 MV/m!

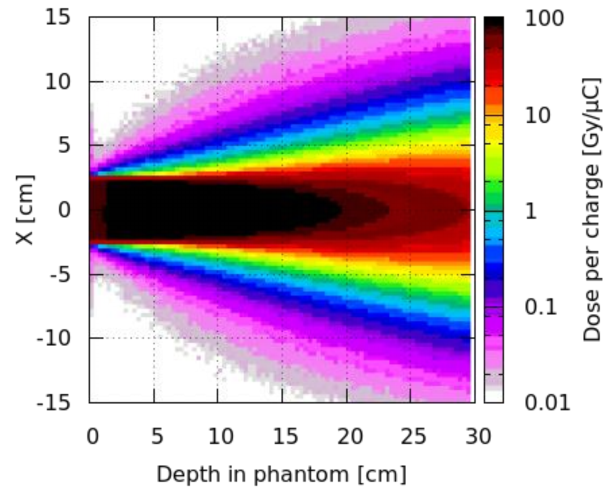
From Alan Nahum. 12 Jun 2007, Interactions of Charged Particles with Matter from: Handbook of Radiotherapy Physics, Theory and Practice CRC Press

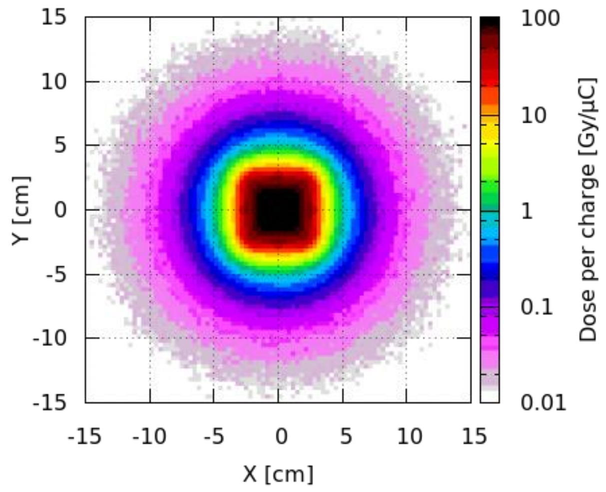
Beam charge

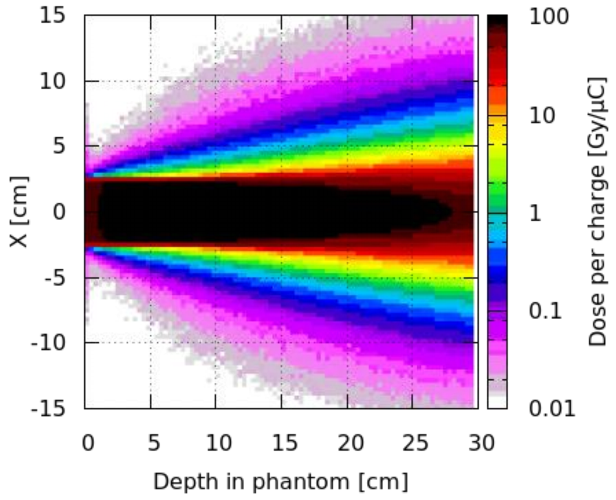
Clinical input – we need to deliver at least 20 Gy/treatment over the volume of the tumor. We will assume a reference case of a 10 cm x 10 cm cross section.

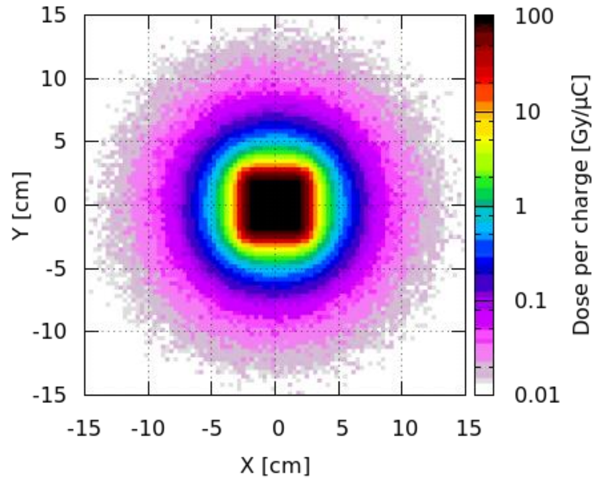
- Reminder: 1 Gy = 1 J/kg
- To first order, a high energy electron beam produces a cylinder of deposited energy that runs straight through the patient (ignoring scattering) with roughly constant dose. This means we have a specification in **charge per unit cross section**.
- For 1 electron, 200 MV/m corresponds to 3.2×10^{-13} J/cm
- To obtain 1 Gy in a 1x1x1 cm^3 volume of water we need 10^{-3} J/cm, so 3.2×10^{9} electrons, equivalently 0.5 nC – similar to a CLIC bunch!
- So to irradiate a 10x10 cm^2 field with 20 Gy, we need 1 µC charge.

Monte Carlo results


140 MeV Electrons on water phantom, 5cm x 5cm field [Y=-2..2]


140 MeV Electrons on water phantom, 5cm x 5cm field [Z=14..16]

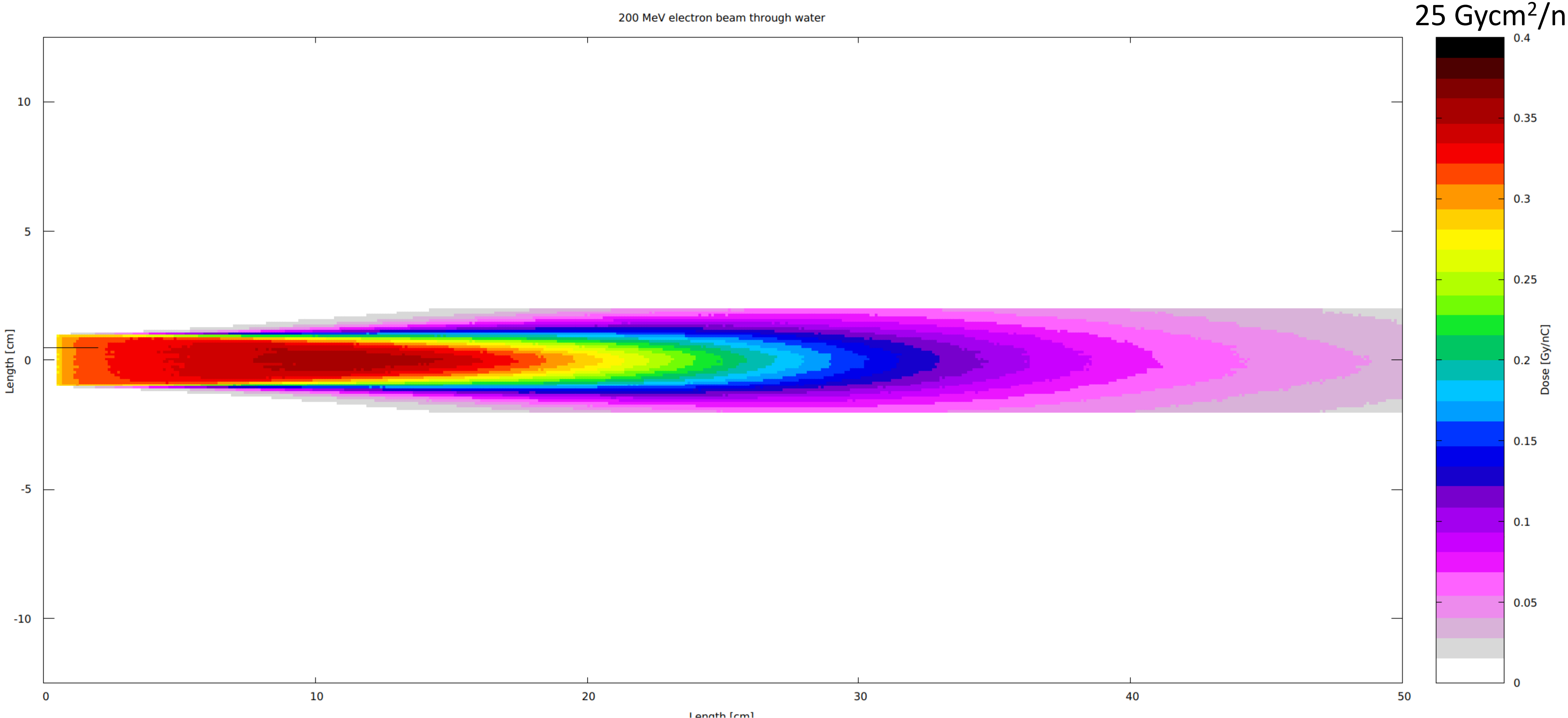

210 MeV Electrons on water phantom, 5cm x 5cm field [Y=-2..2]


210 MeV Electrons on water phantom, 5cm x 5cm field [Z=14..16]

Markus Widorski

Monte Carlo results 2

25 Gycm^2/nC



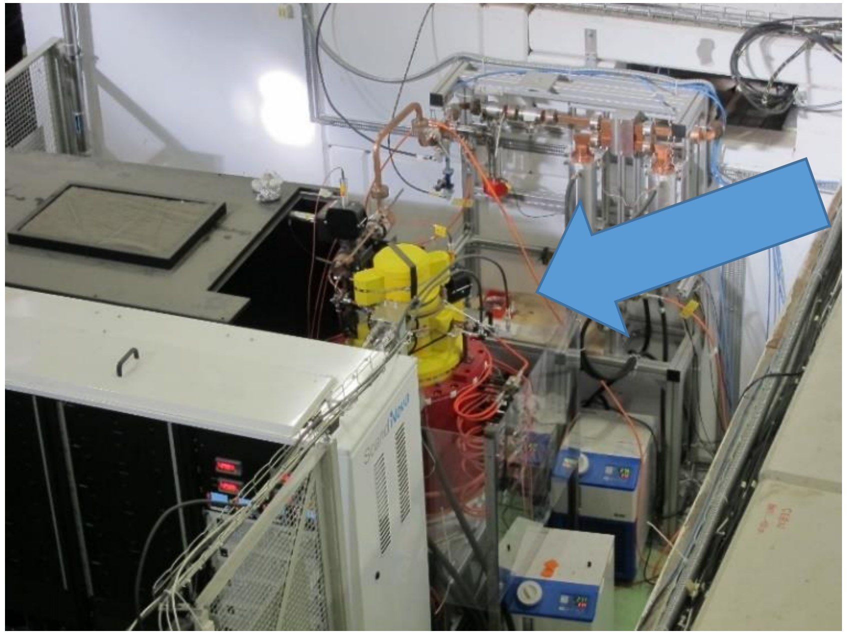
Estelle Brierre

Energy balance

Total energy considerations

We will use as a reference treatment a 10x10 cm^2 field with 20 Gy, and resulting 1 µC charge.

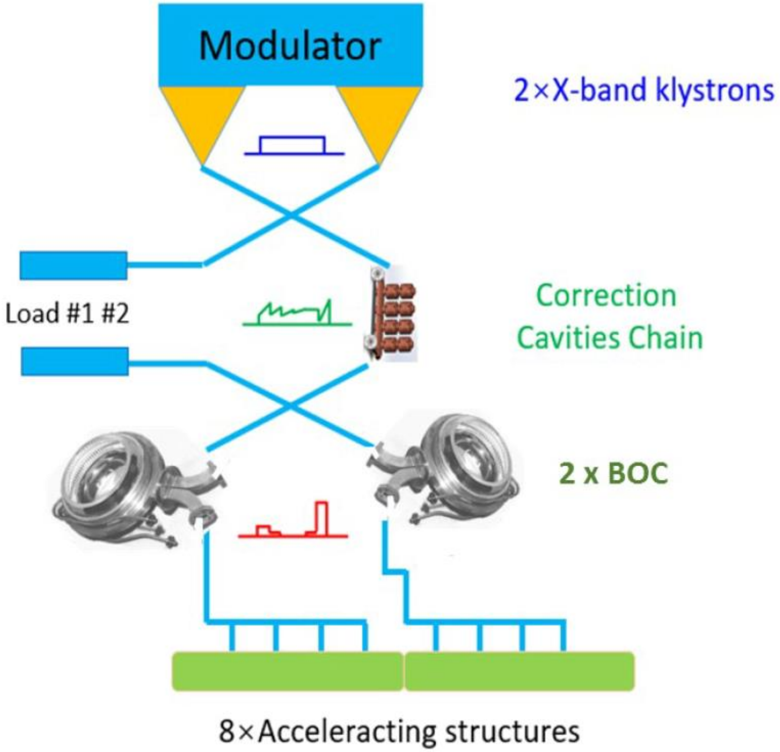
1 µC with an energy of 100 MV (per electron), U=Q*V, has a total energy of 100 J. Let's compare this to a klystron, like that used in the CLIC XBox test stands and numerous applications.



CPI X-band klystron

- Peak power 50 MW
- Pulse length 1.5 µs
- Pulse energy 75 J
- Continuous repetition rate of 100 Hz.
- 750 J/100 ms
- Costs about 1.5 MCHF with modulator

The CLIC klystron-based rf unit



rf power production
- mains to 12 GHz power

Pulse compression
- 100 MW, 1.5 µs pulse to 320 MW, 334 ns.

rf power to beam
- 40 MW to 75 MV/m accelerating gradient

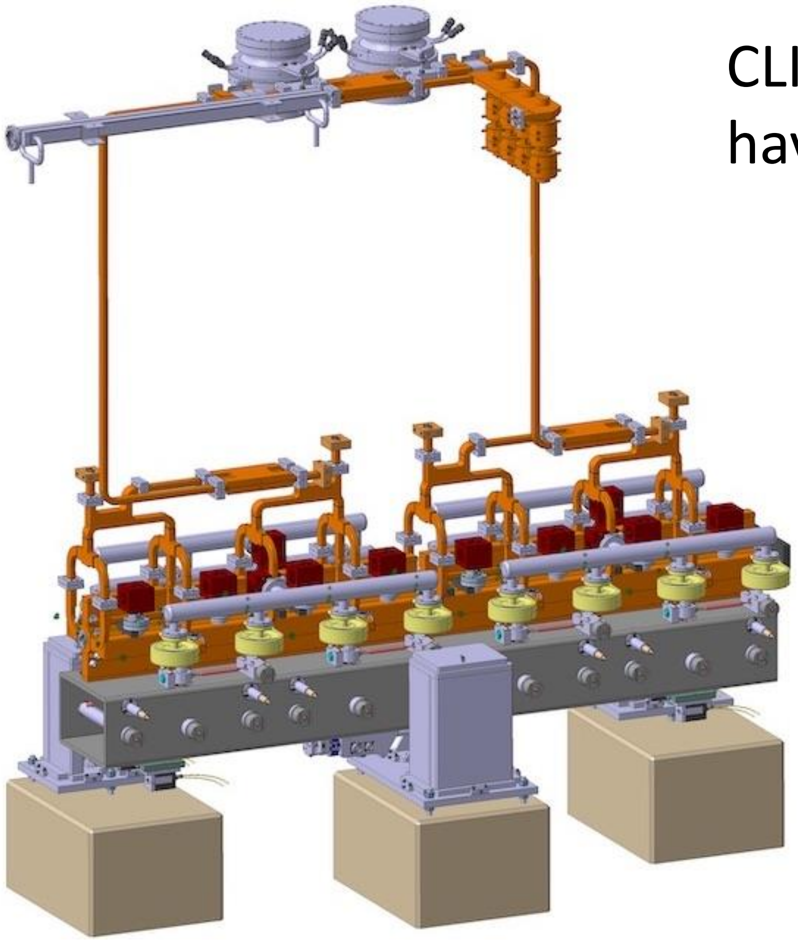

CERN-2018-010-M
20 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
PROJECT IMPLEMENTATION PLAN

GENEVA
2018

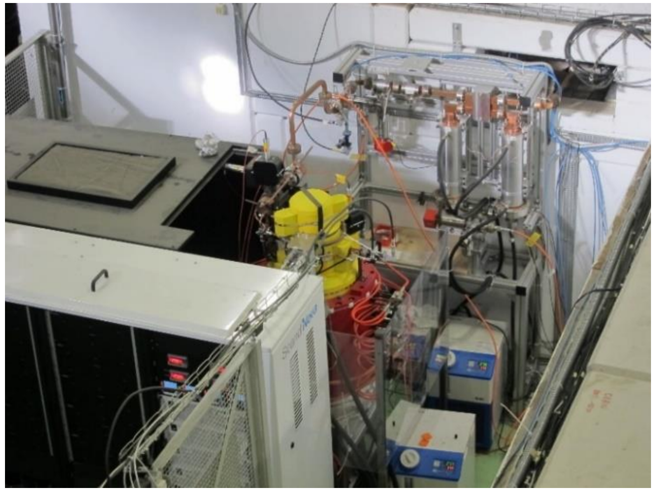
CLIC klystron-based rf unit

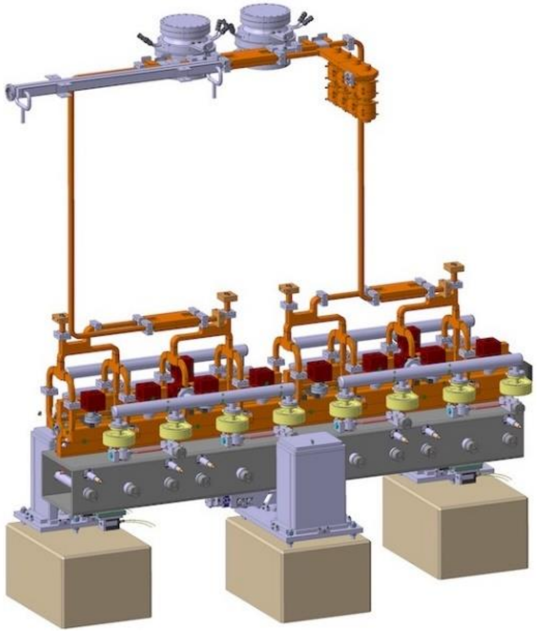


CLIC has as a baseline two-beam RF power generation, but we have also studied a klystron-based version.

- 75 MV/m accelerating gradient
- 2 m long
- 135 MeV energy gain per module
- 0.62 nC/bunch
- 485 bunches per train
- 300 nC/train
- 0.5 ns bunch spacing
- 1.2 A peak beam current
- 38 % rf-to-beam efficiency
- 100 Hz repetition rate
- 30 µA average current

Round numbers

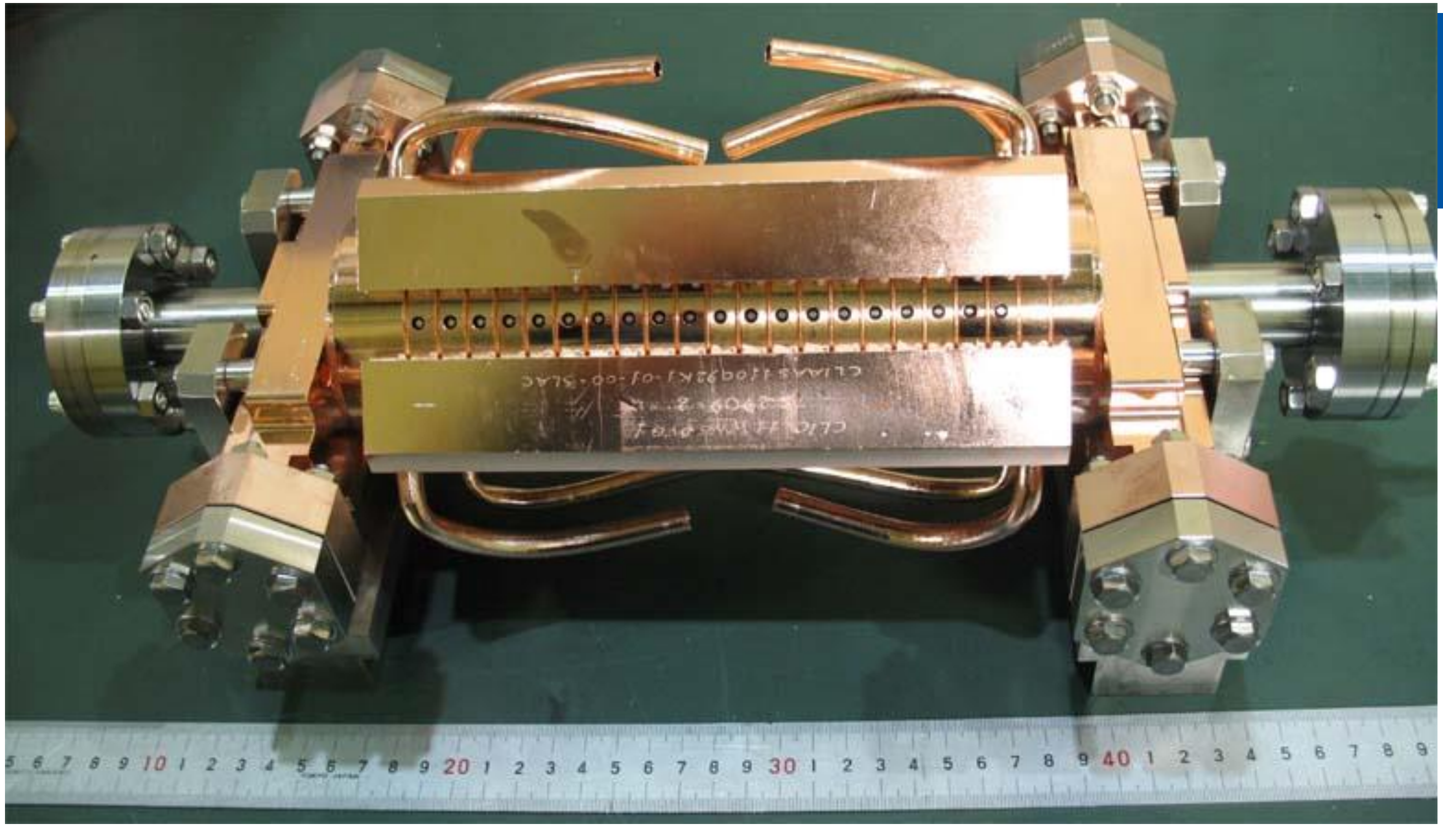




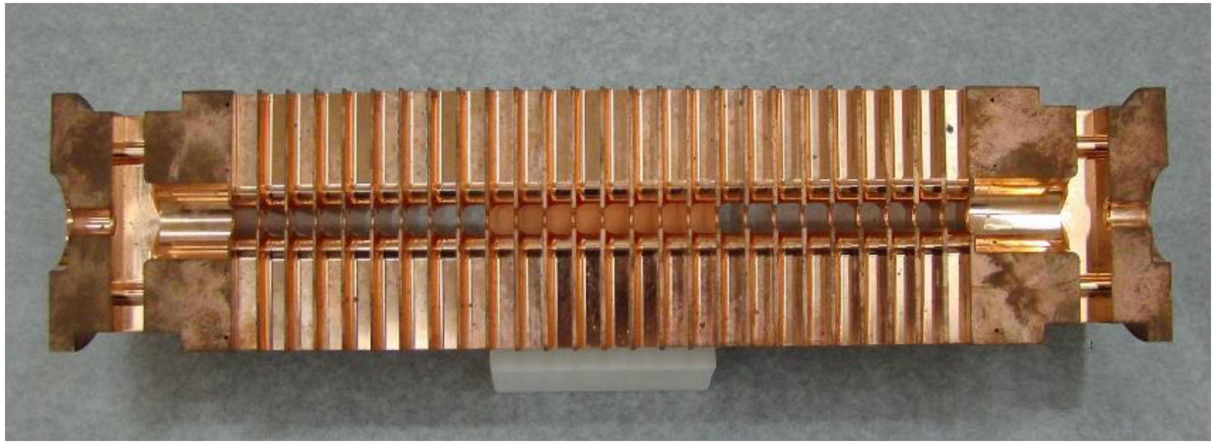
- 38 % rf-to-beam efficiency comes from from maintaining a high gradient in travelling wave structures, pulse compression, ohmic losses. We will return to this point.
- For now taking 38 % rf-to-beam efficiency and 75 J/pulse from the klystron, we get 28 J/pulse of accelerated charge, or correspondingly 280 nC at 100 MV, so treatment in 4 pulses.
- 100 Hz is 10 pulses per 100 ms, our FLASH timescale, so in from an energy perspective our reference treatment can be made with a single 50 MW klystron.
- But we must also establish an accelerating gradient, so we will look at acceleration in a bit more detail.

Travelling wave acceleration basics

A CLIC prototype accelerating structure.

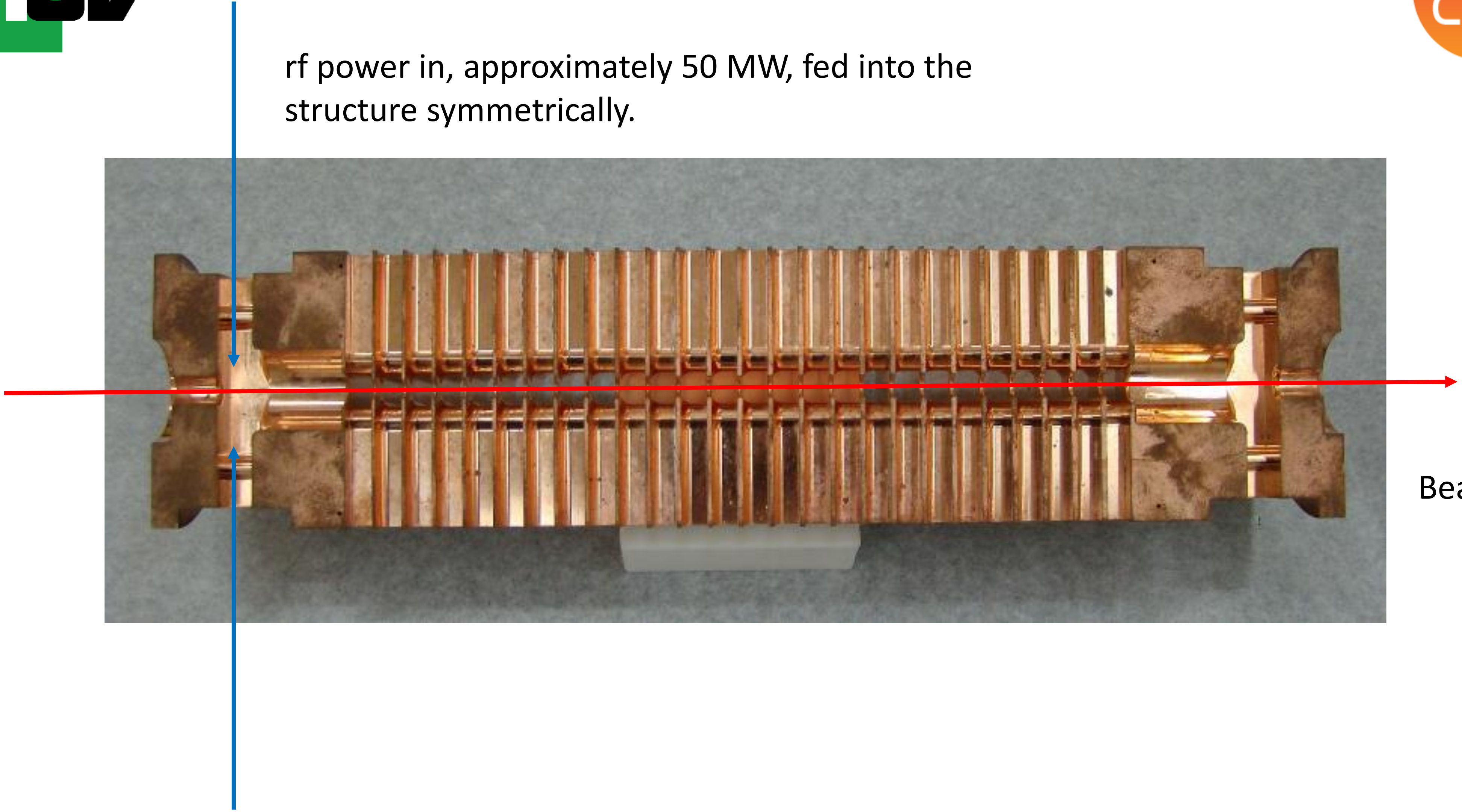


outside



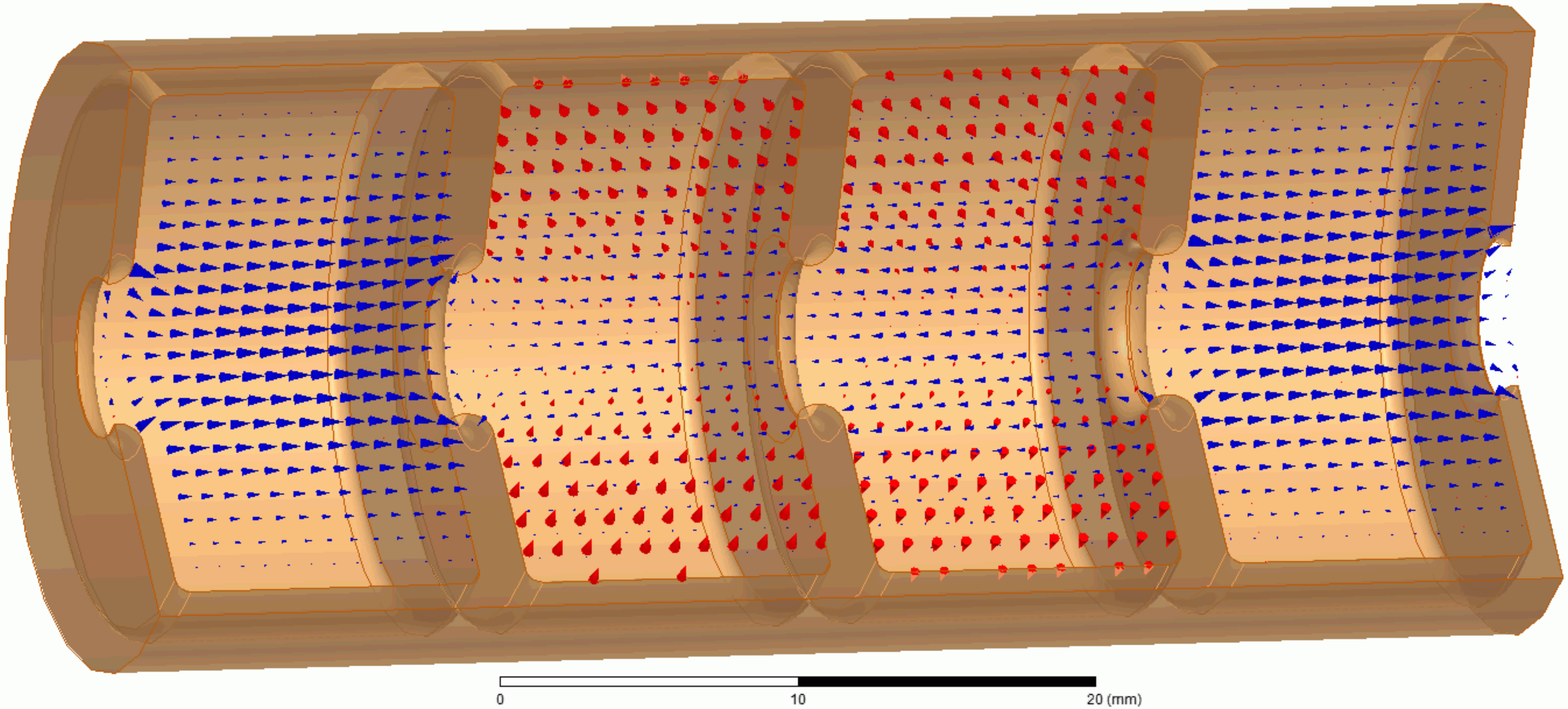
inside

rf power in, approximately 50 MW, fed into the structure symmetrically.



Beam accelerated

Electric field
Magnetic field



Some rf

$$Q = \frac{\omega W}{P_{loss}}$$

Quality factor

$$R = \frac{\left|V_{acc}\right|^2}{P_{loss}}$$

Shunt impedance [MΩ]. Often the quantity used to optimize cavity design.

$$\frac{R}{Q} = \frac{\left|V_{acc}\right|^2}{\omega W}$$

Ratio of acceleration to stored energy.

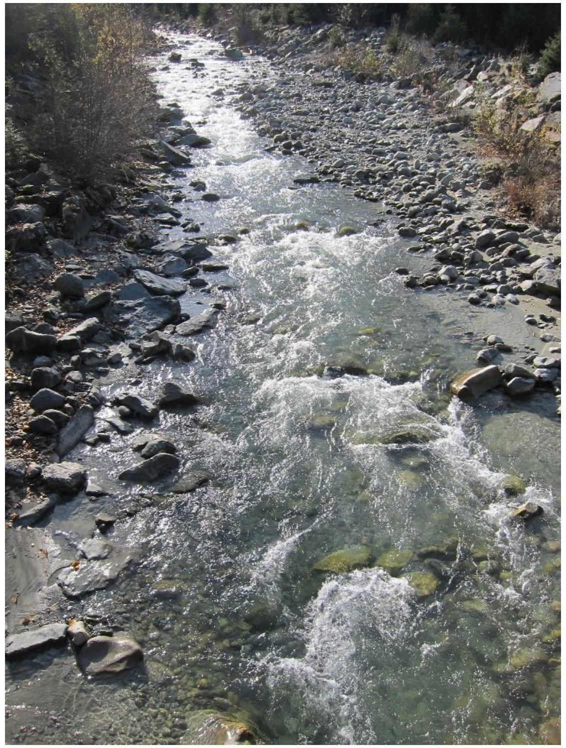
We can go from stored energy to power via group velocity:

$$P = v_g W'$$

Accelerating gradient:

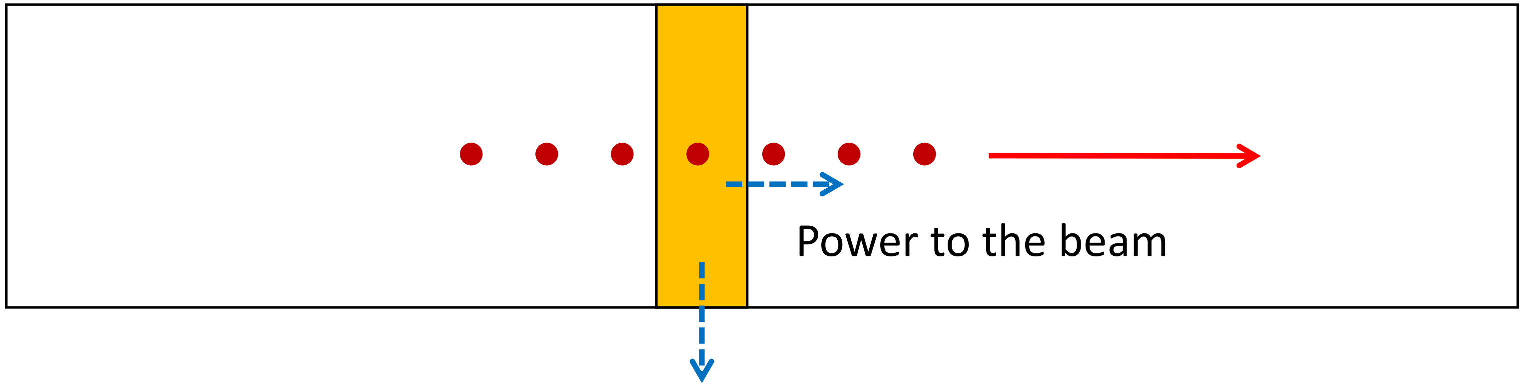
$$G = \frac{|V_{acc}|}{l}$$

$$G = \sqrt{\omega \frac{1}{v_g} \frac{R'}{Q} P}$$



group velocity

Differential equation of power flow

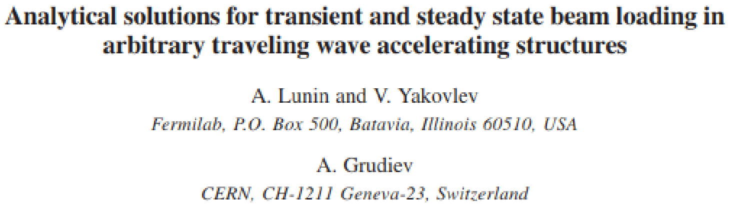


Power to the beam

Power to the wall

$$\frac{dP}{dz} = -P_{wall} - P_{beam}$$

$$\frac{dP}{dz} = \frac{\omega}{Q v_g} P - \sqrt{\frac{\omega}{v_g} \frac{R'}{Q} P I}$$



Analytical solutions for transient and steady state beam loading in arbitrary traveling wave accelerating structures

A. Lunin and V. Yakovlev

Fermilab, P.O. Box 500, Batavia, Illinois 60510, USA

A. Grudiev

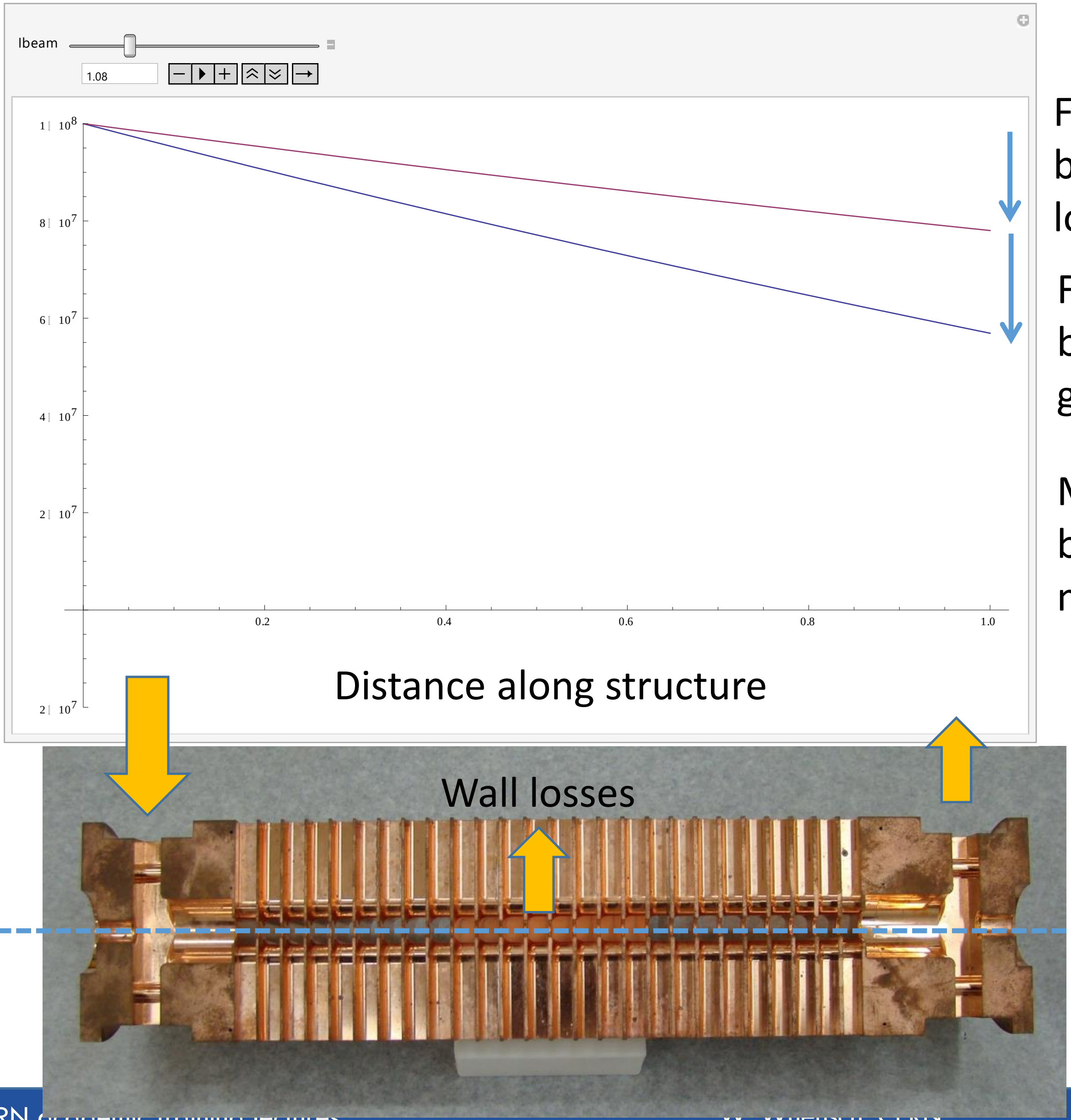
CERN, CH-1211 Geneva-23, Switzerland

http://dx.doi.org/10.1103/PhysRevSTAB.14.052001

Beam loading

100 MV/m

rf power in



Distance along structure

Wall losses

Field goes down because of wall losses.

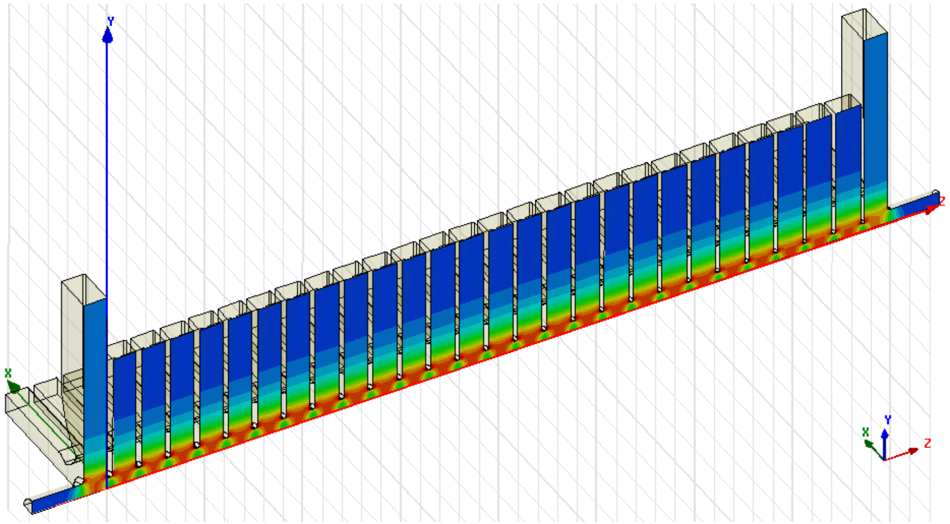
Field goes down because power goes into beam.

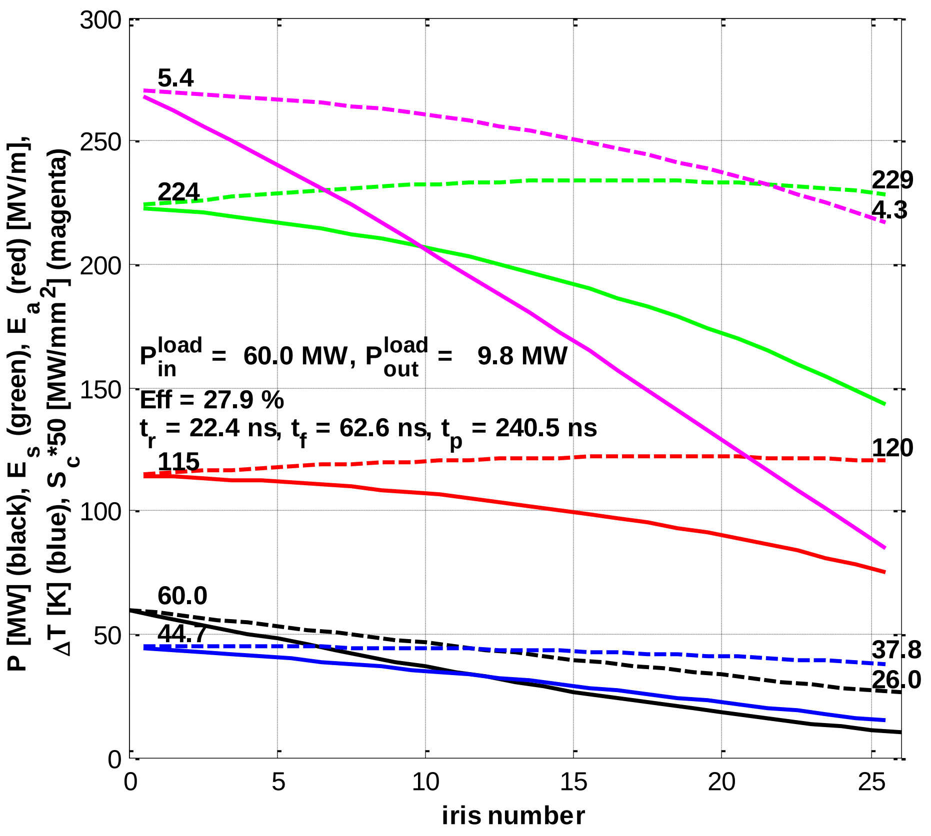
More beam, more beam loading, more efficient.

Less power out

Beam accelerated

CLIC 3 TeV structure



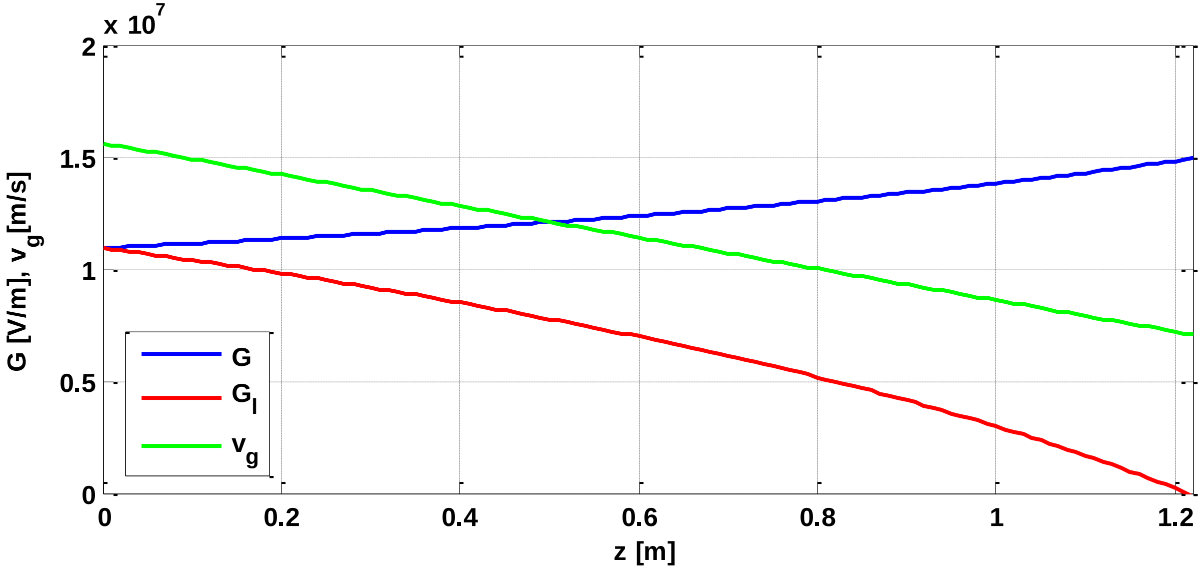


CTF3 drive beam accelerating structure

Parameters: input – output	
f [GHz]	3
L_s [m]	1.22
v_g/c [%]	5.2 – 2.3
Q_0	14000 – 11000
R' [MΩ/m]	42 – 33
I_b [A]	4
Pin [MW]	33

Parameters calculated	
η^{CW} [%]	95

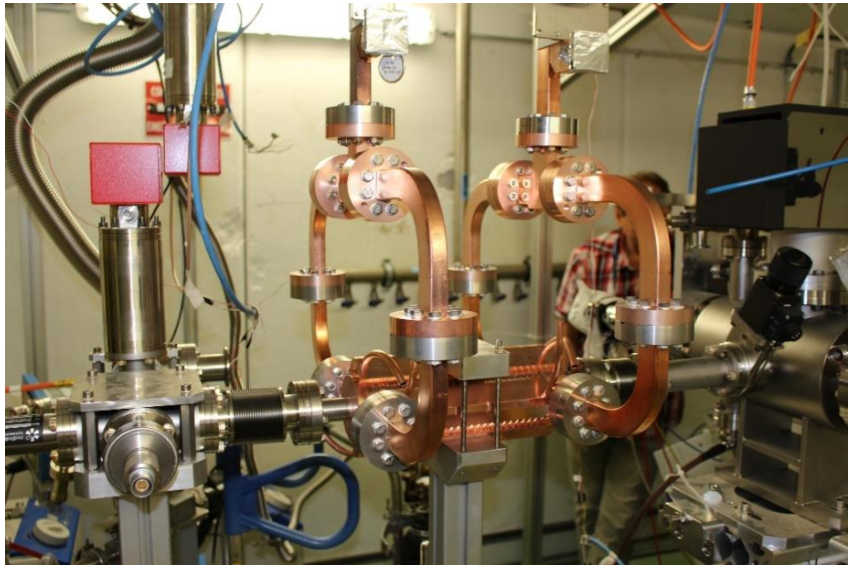
This structure is designed to operate in full beam loading regime



10 MV/m

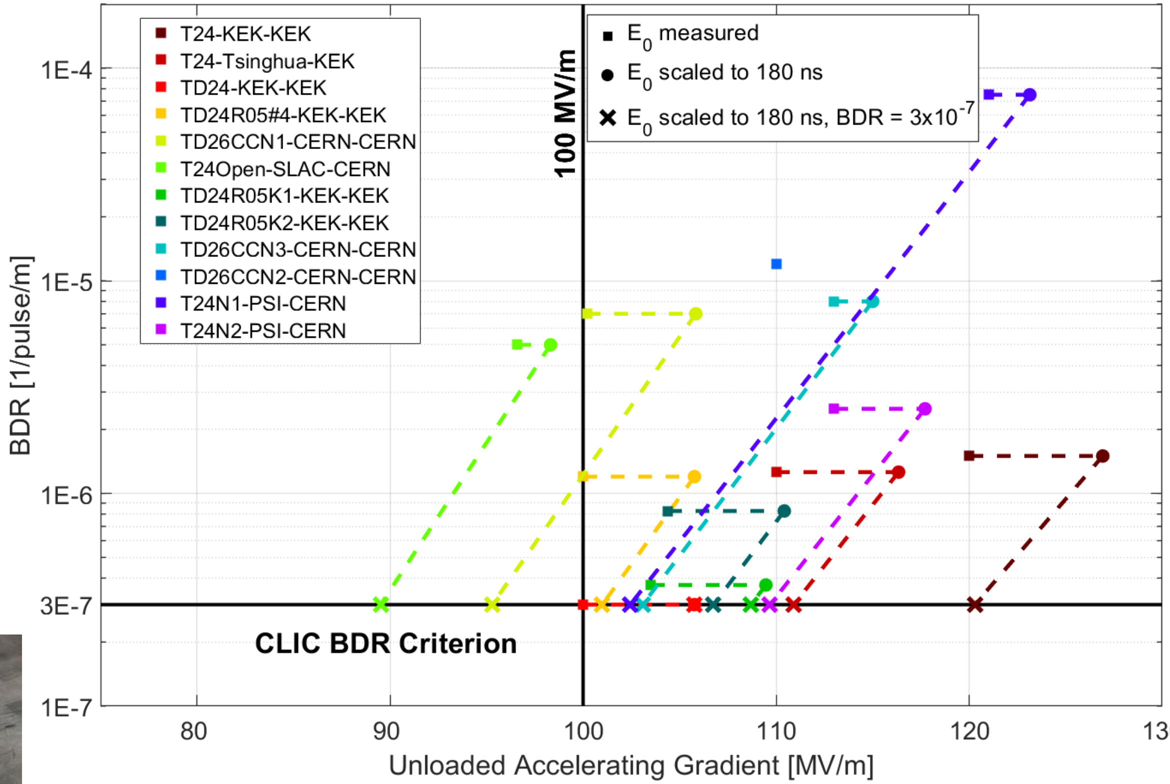
More efficient than a superconducting cavity!

X-band accelerating structures



Test structure

Assembly methods



Achieved accelerating gradients in tests

High current beam stability

High-current beam requires Higher-Order-Mode suppression for beam stability, just like CLIC

Transverse long-range Wakefield in CLIC-G structure

Structure name	CLIG-G TD26cc
Work frequency	11.994GHz
Cell	26 regular cells+ 2 couplers
Length (active)	230mm
Iris aperture	2.35mm - 3.15mm

transverse long-range wakefield calculation using Gdfidl code:

Peak value :

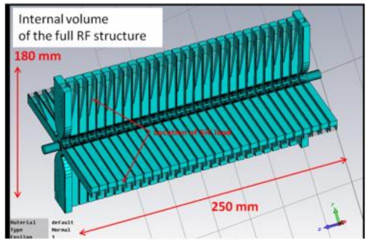
250 V/pC/m/mm

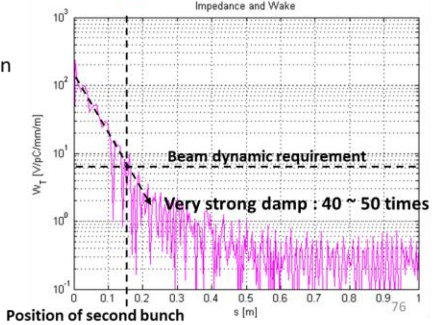
At position of second bunch (0.15m):

5~6 V/pC/m/mm

Beam dynamic requirement:

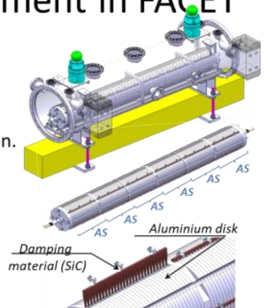
< 6.6 V/pC/m/mm

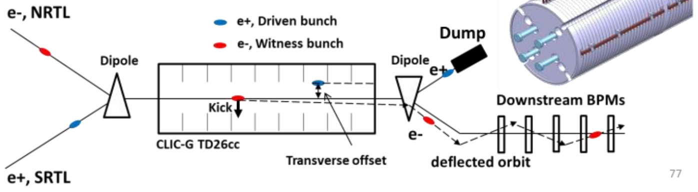




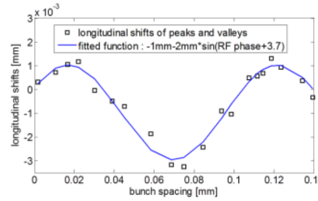
Direct wakefield measurement in FACET

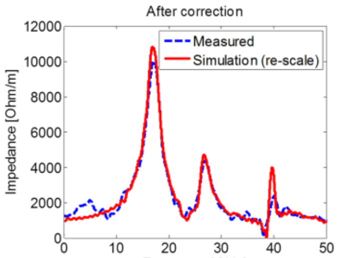
- Prototype structure are made of aluminium disks and SiC loads (clamped together by bolts).
- 6 full structures, active length = 1.38m
- FACET provides 3nC, 1.19GeV electron and positron.
- RMS bunch length is near 0.7mm.
- Maximum orbit deflection of e- due to peak transverse wake kick (1mm e+ offset):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

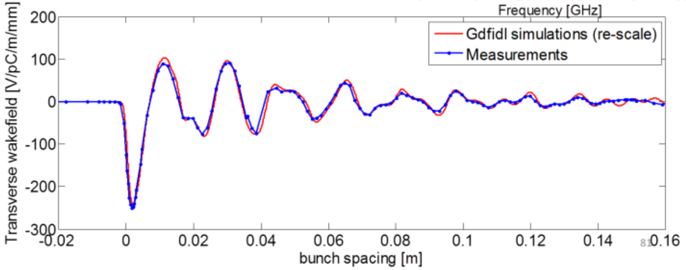


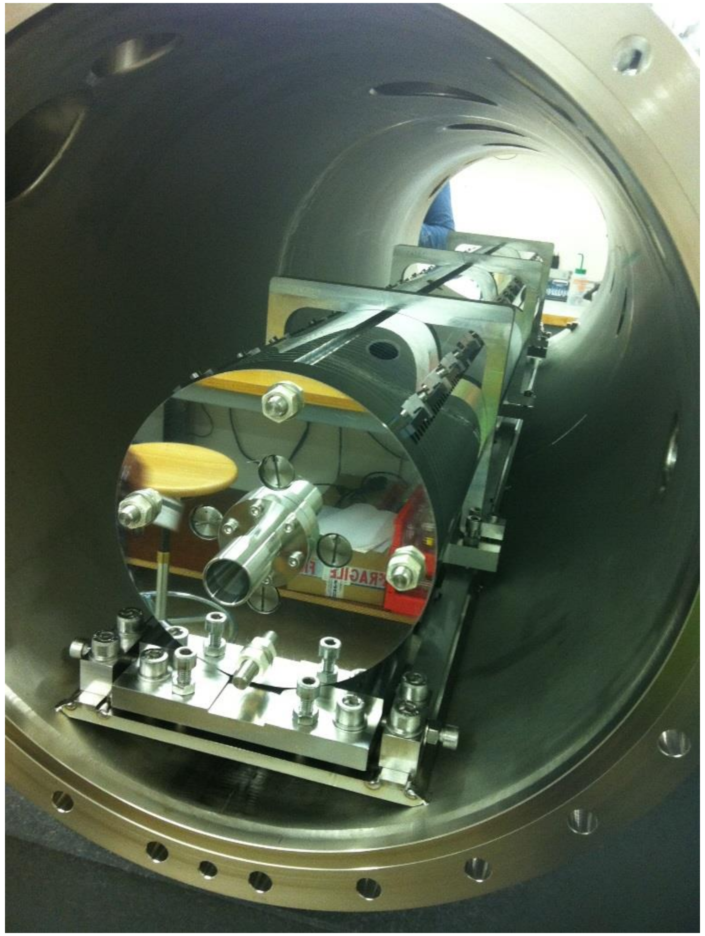


Timing correction









https://doi.org/10.1103/PhysRevAccelBeams.19.011001

Alternative techniques

Low energy electron RT

- Existing X-ray machines produce few-MeV photons, from few-MeV electrons, which penetrate deeply but flux is low, irradiation takes minutes.
- Major limitation is X-ray conversion target which has a few per-mill energy efficiency
- One solution is to remove target, just use electrons. Plenty of charge but low energy limits treatment to surface. Clinical trials are underway.

Approximate values:

- Peak current about 200 mA
- Magnetron pulse length 10 µs
- Charge per pulse 2 µC
- Repetition rate 100 Hz


FLASHKNiFE PMB

PRESS RELEASE

FLASHKNiFE

FLASH RADIOTHERAPY

Arrival @ CHUV
March 17th 2021

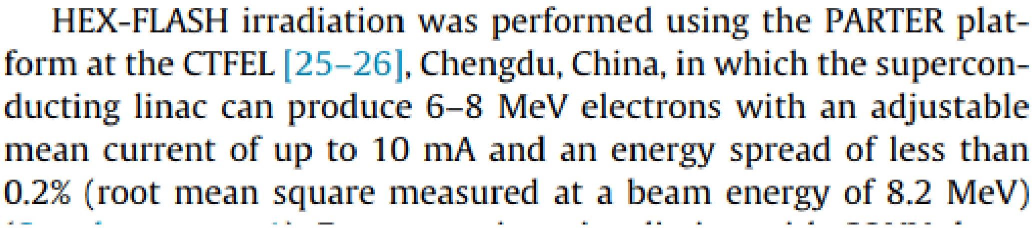
www.pmb-alcen.com

FLASH Radiotherapy Device (Clinical Trials Only)

Clinical trials for skin cancer underway at CHUV.

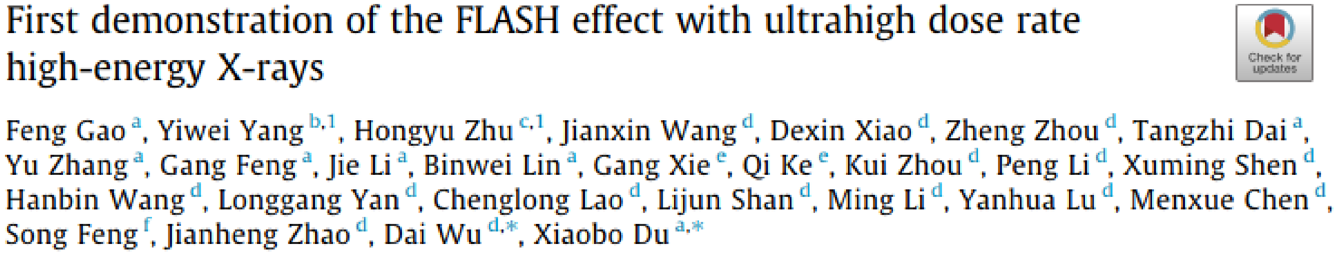
Photon FLASH

Photon FLASH is a possibility if average current can be raised by x 1000, the conversion target efficiency. The standard RT pulsed normal conducting RF has a duty cycle of 10^{-4} so one way to gain average current is to use CW superconducting RF.



HEX-FLASH irradiation was performed using the PARTER platform at the CTFEL [25–26], Chengdu, China, in which the superconducting linac can produce 6–8 MeV electrons with an adjustable mean current of up to 10 mA and an energy spread of less than 0.2% (root mean square measured at a beam energy of 8.2 MeV)

60 kW on target!



First demonstration of the FLASH effect with ultrahigh dose rate high-energy X-rays

Feng Gao[a], Yiwei Yang[b,1], Hongyu Zhu[c,1], Jianxin Wang[d], Dexin Xiao[d], Zheng Zhou[d], Tangzhi Dai[a], Yu Zhang[a], Gang Feng[a], Jie Li[a], Binwei Lin[a], Gang Xie[e], Qi Ke[e], Kui Zhou[d], Peng Li[d], Xuming Shen[d], Hanbin Wang[d], Longgang Yan[d], Chenglong Lao[d], Lijun Shan[d], Ming Li[d], Yanhua Lu[d], Menxue Chen[d], Song Feng[f], Jianheng Zhao[d], Dai Wu[d,*], Xiaobo Du[a,*]

https://doi.org/10.1016/j.radonc.2021.11.004

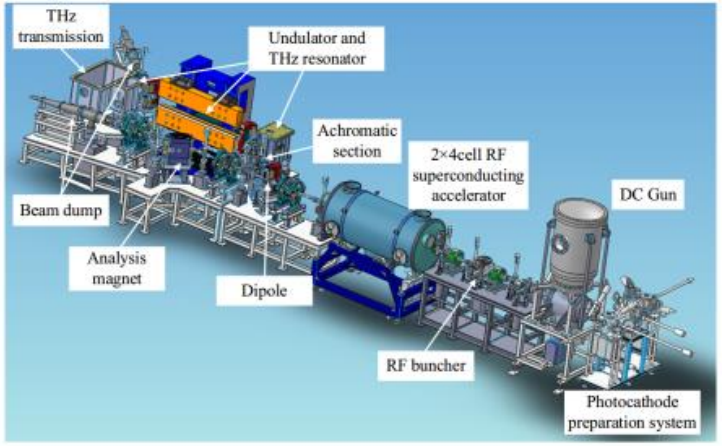


Figure 1. The layout of the CTFEL facility

Superconducting and electrons - LCLS-II

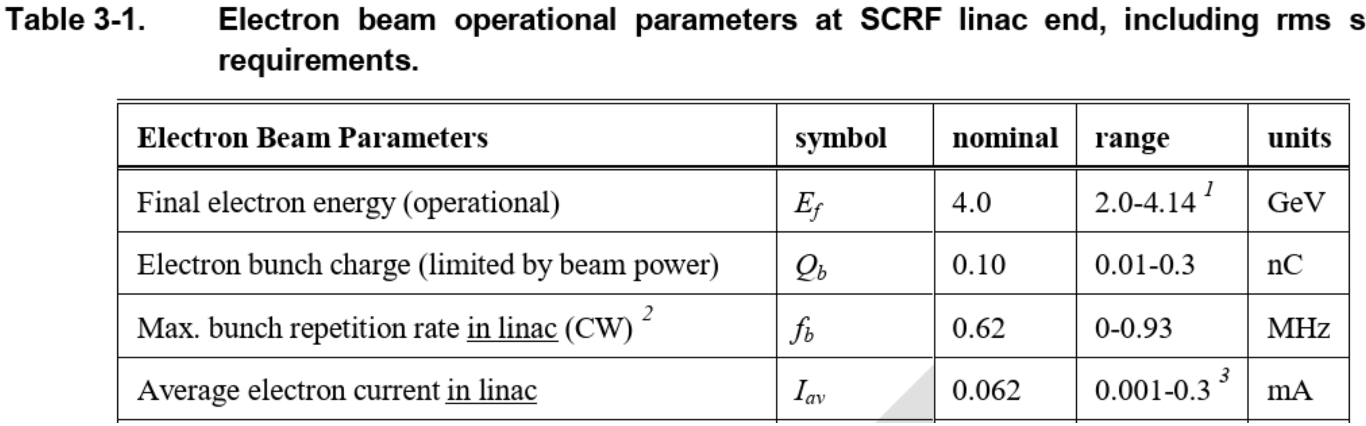


Table 3-1. Electron beam operational parameters at SCRF linac end, including rms stability requirements.

Electron Beam Parameters	symbol	nominal	range	units
Final electron energy (operational)	E_f	4.0	2.0-4.14[1]	GeV
Electron bunch charge (limited by beam power)	Q_b	0.10	0.01-0.3	nC
Max. bunch repetition rate in linac (CW)[2]	f_b	0.62	0-0.93	MHz
Average electron current in linac	I_{av}	0.062	0.001-0.3[3]	mA

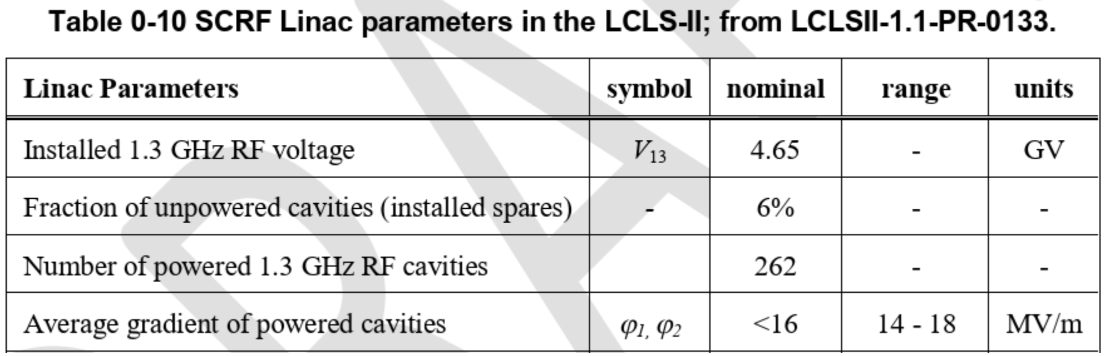


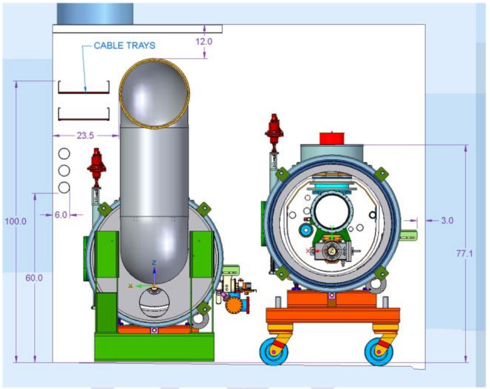
Table 0-10 SCRF Linac parameters in the LCLS-II; from LCLSII-1.1-PR-0133.

Linac Parameters	symbol	nominal	range	units
Installed 1.3 GHz RF voltage	V_{13}	4.65	-	GV
Fraction of unpowered cavities (installed spares)	-	6%	-	-
Number of powered 1.3 GHz RF cavities		262	-	-
Average gradient of powered cavities	φ_1, φ_2	<16	14 - 18	MV/m

CLIC - 30 µA average current

12 m long cryomodule gives about 180 MeV/module

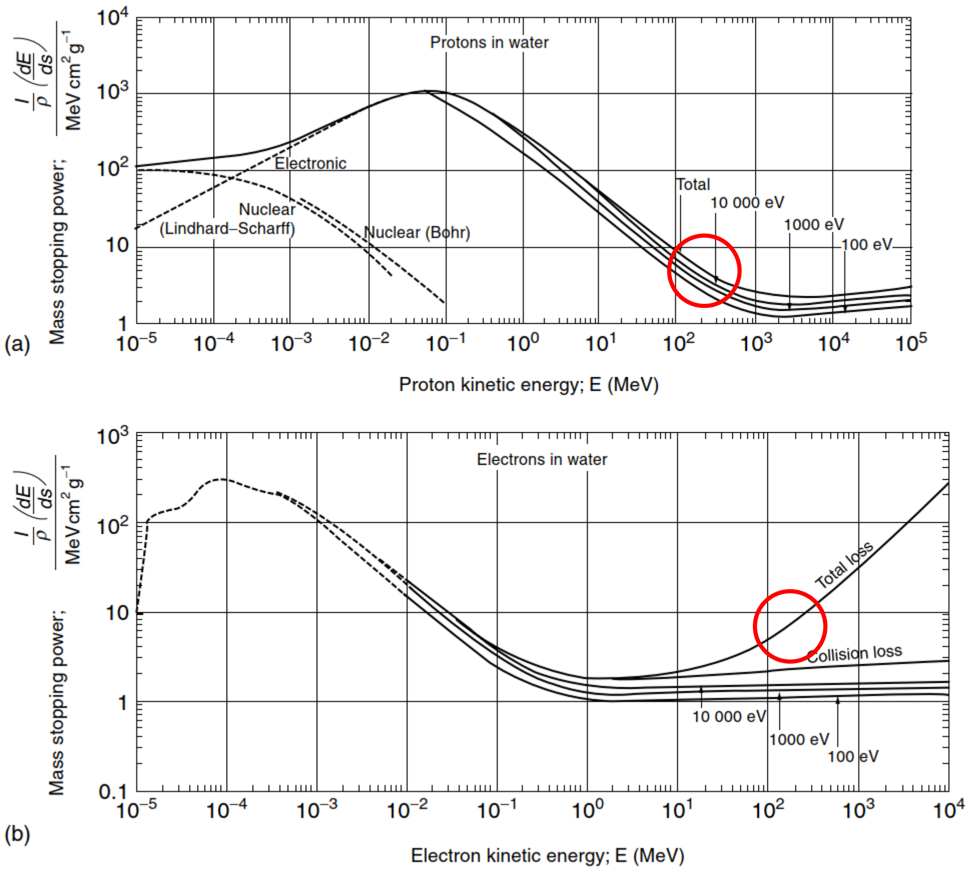
LCLC-II the new XFEL at SLAC, based on a CW superconducting RF linac.



From LCLS-II Final Design Report

By comparison – FLASH with protons

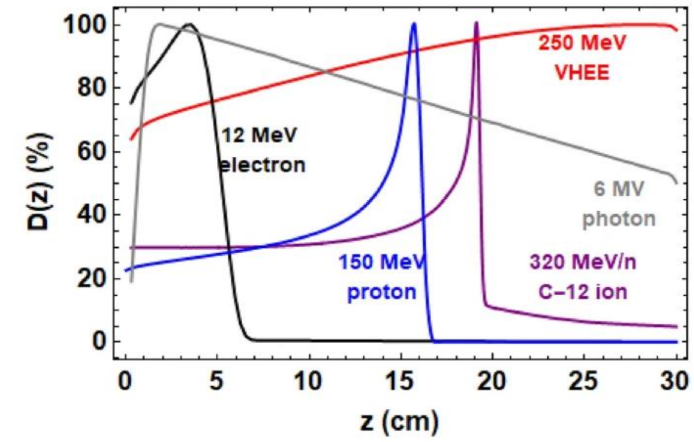
n.b. – very general discussion to understand issues by comparing!



From Alan Nahum. 12 Jun 2007, Interactions of Charged Particles with Matter from:Handbook of Radiotherapy Physics, Theory and Practice CRC Press

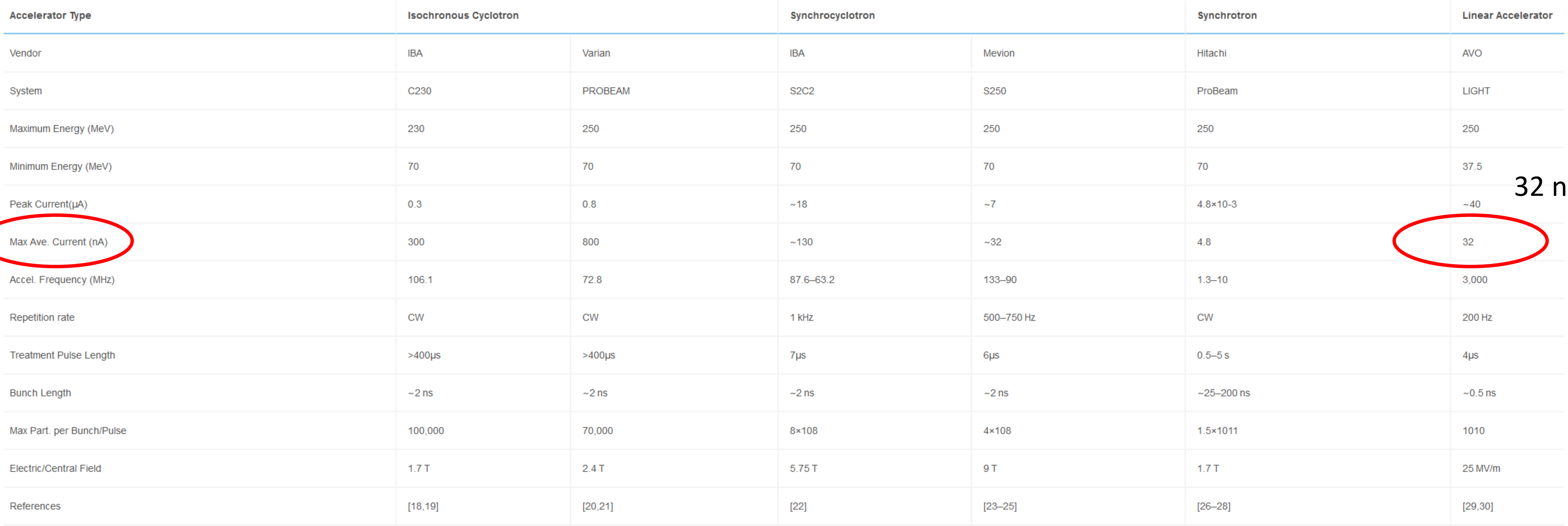
- Beam energy – ADAM’s LIGHT facility has a beam energy up to 230 MeV.
- Broad part of stopping power spectrum not so different from electrons - similar charge would be required.
- Bragg peak has much higher stopping power – but extends only over very small depth. Charge needed is multiplied by longitudinal coverage.
- I very approximately assume the same charge is needed!

Figure 1



Whitmore, L., Mackay, R.I., van Herk, M. *et al.* Focused VHEE (very high energy electron) beams and dose delivery for radiotherapy applications. *Sci Rep* **11,** 14013 (2021). https://doi.org/10.1038/s41598-021-93276-8

AVO LIGHT



Accelerator Type	Isochronous Cyclotron		Synchrocyclotron		Synchrotron	Linear Accelerator
Vendor	IBA	Varian	IBA	Mevion	Hitachi	AVO
System	C230	PROBEAM	S2C2	S250	ProBeam	LIGHT
Maximum Energy (MeV)	230	250	250	250	250	250
Minimum Energy (MeV)	70	70	70	70	70	37.5
Peak Current(μA)	0.3	0.8	~18	~7	4.8×10-3	~40
Max Ave. Current (nA)	300	800	~130	~32	4.8	32
Accel. Frequency (MHz)	106.1	72.8	87.6–63.2	133–90	1.3–10	3,000
Repetition rate	CW	CW	1 kHz	500–750 Hz	CW	200 Hz
Treatment Pulse Length	>400μs	>400μs	7μs	6μs	0.5–5 s	4μs
Bunch Length	~2 ns	~2 ns	~2 ns	~2 ns	~25–200 ns	~0.5 ns
Max Part. per Bunch/Pulse	100,000	70,000	8×108	4×108	1.5×1011	1010
Electric/Central Field	1.7 T	2.4 T	5.75 T	9 T	1.7 T	25 MV/m
References	[18,19]	[20,21]	[22]	[23–25]	[26–28]	[29,30]

32 nA

Technical challenges for FLASH proton therapy

Simon Jolly • Hywel Owen • Marco Schippers • Carsten Welsch

Open Access • Published: September 15, 2020 • DOI: https://doi.org/10.1016/j.ejmp.2020.08.005 •

CLIC average current 30 μA

LINAC4

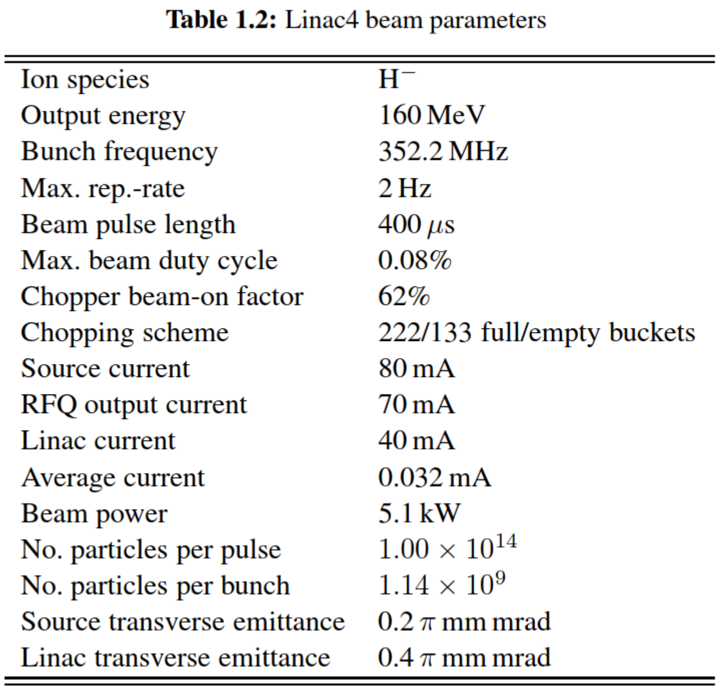


Table 1.2: Linac4 beam parameters

Ion species	H^-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Max. rep.-rate	2 Hz
Beam pulse length	400 μs
Max. beam duty cycle	0.08%
Chopper beam-on factor	62%
Chopping scheme	222/133 full/empty buckets
Source current	80 mA
RFQ output current	70 mA
Linac current	40 mA
Average current	0.032 mA
Beam power	5.1 kW
No. particles per pulse	1.00×10^{14}
No. particles per bunch	1.14×10^{9}
Source transverse emittance	0.2 π mm mrad
Linac transverse emittance	0.4 π mm mrad

86 m long

Linac4 Technical Design Report
CERN–AB–2006–084 ABP/RF

Energy almost OK.

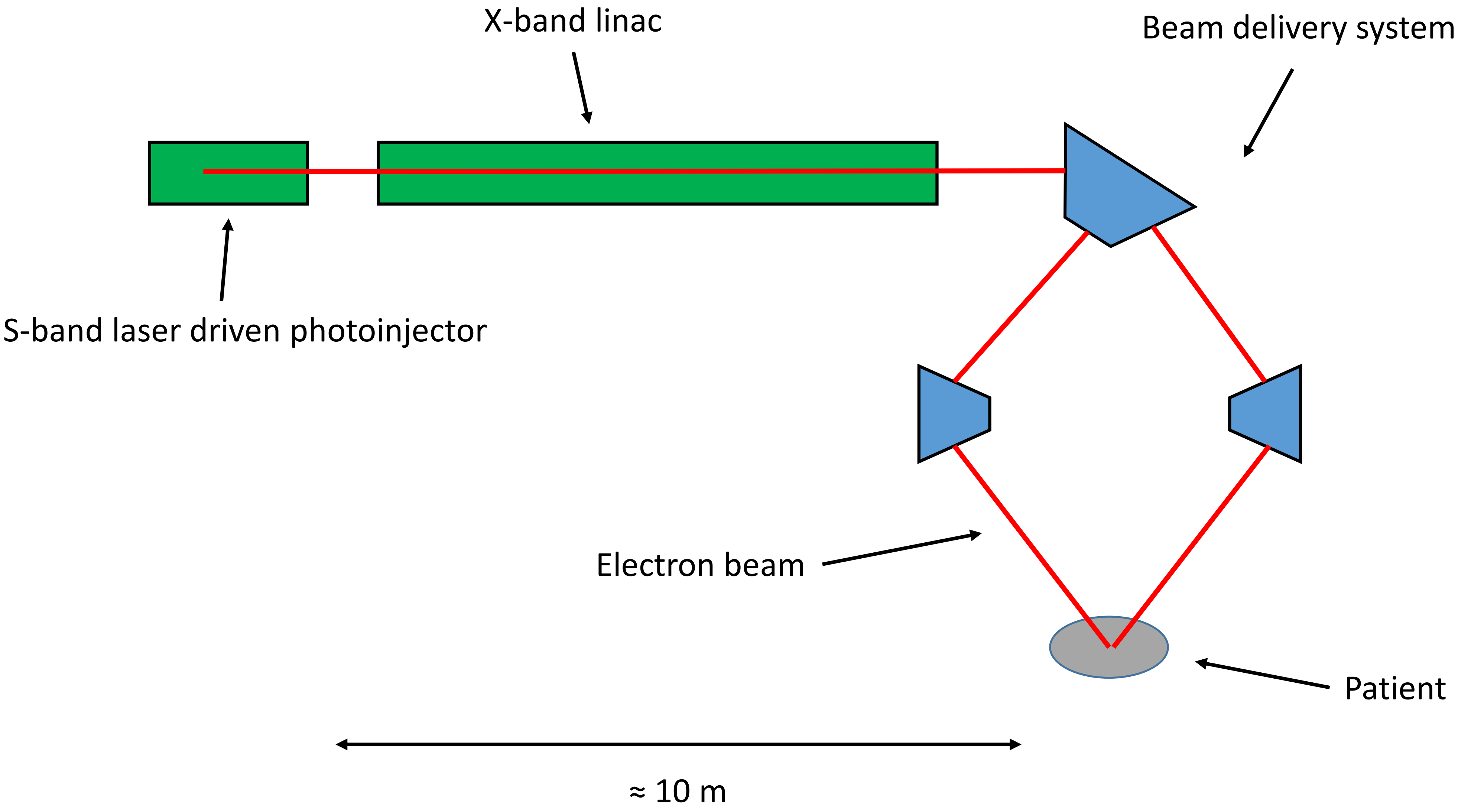
16 µC per pulse!

160 MCHF/160 MeV= 1 CHF/eV

Really need about 230 MeV
I don't know how much LIGHT costs. Would be interesting to know how cost scales with beam power.

CLIC klystron-based:
6 GCHF/ 380 GeV = 0.016 CHF/eV

The CHUV/CERN facility layout



X-band linac

Beam delivery system

S-band laser driven photoinjector

Electron beam

Patient

≈ 10 m

Wrapping up

I hope I have given you some insight in one of the most fundamental aspects of a FLASH facility – understanding how much charge can be accelerated in a short time by considering available energy.
Many crucial subjects remain untouched today, an hour is just too short!

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