New applications of high-gradient RF linacs

LINAC 2014, 3 September 2014

Alexej Grudiev, CERN

High gradient is not only cool but also compact and potentially cheaper

State-of-the art acceleration:
Normal conducting:
28 MV/m SwissFEL
35 MV/m SACLA
Superconducting:
24 MV/m European XFEL
31.5 MV/m ILC

I will talk about the future:
100 MV/m CLIC
60-80 MV/m compact XFELs
50 MV/m low-β proton therapy linacs

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- Introduction
  - Initial motivation for high-gradient acceleration
  - The CLIC R&D towards 100 MV/m acceleration
- New applications
  - Energy upgrade of existing FELs (e.g. FERMI@Elettra, Trieste)
  - Compact hard X-ray FELs (e.g. SINAP, Shanghai)
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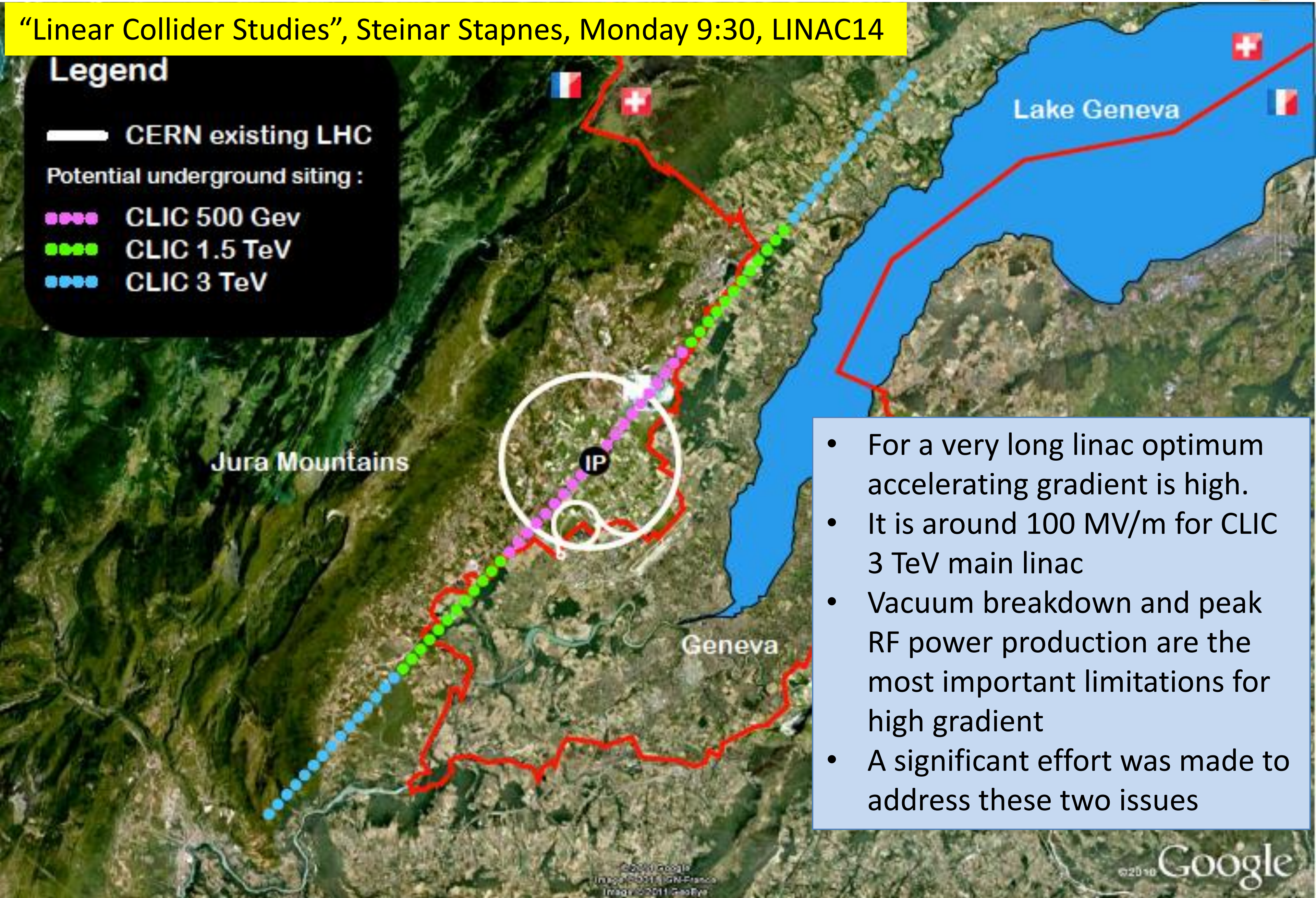
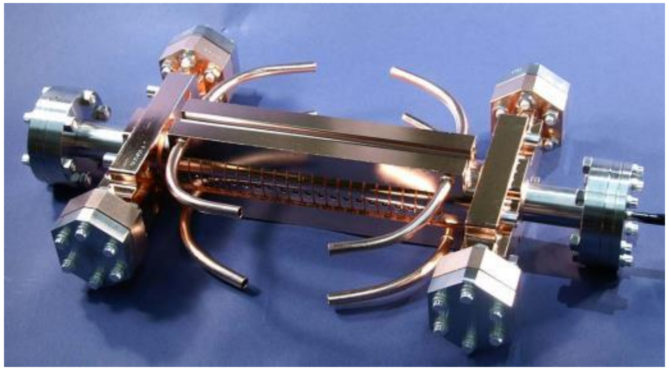
CLIC near CERN

"Linear Collider Studies", Steinar Stapnes, Monday 9:30, LINAC14



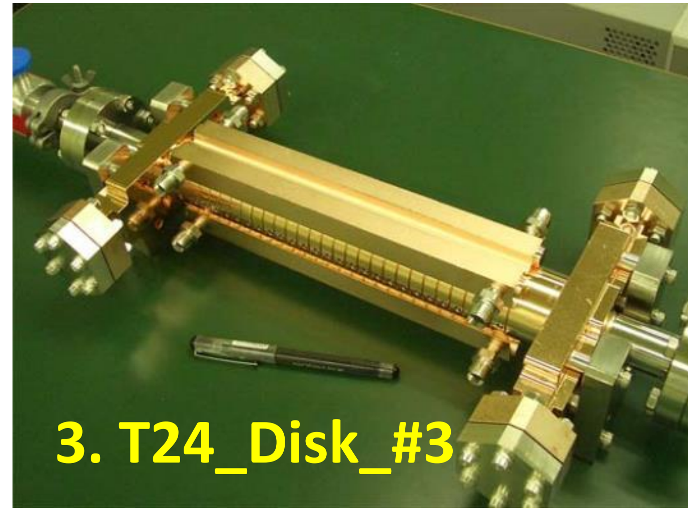
- For a very long linac optimum accelerating gradient is high.
- It is around 100 MV/m for CLIC 3 TeV main linac
- Vacuum breakdown and peak RF power production are the most important limitations for high gradient
- A significant effort was made to address these two issues

CLIC test structures towards high gradient
(2007) T18 →TD18→T24→TD24→TD26CC (2014)

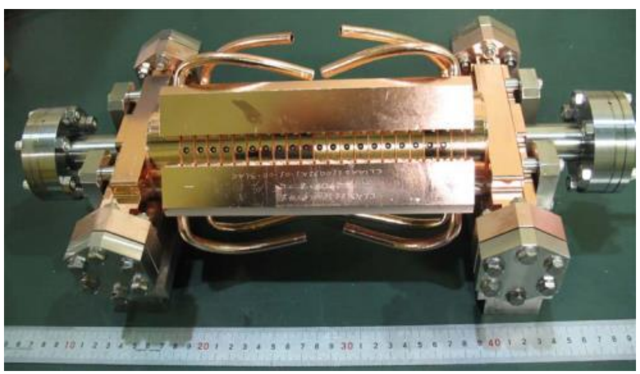


1. T18_Disk_#2

undamped



3. T24_Disk_#3



2. TD18_Disk_#2

damped

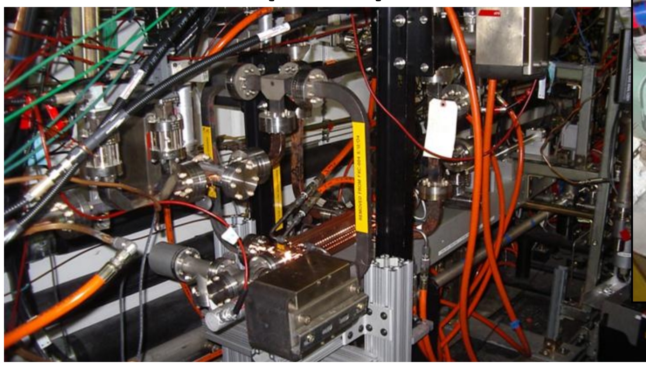
4. TD24_Disk_#4

5. TD26CC under test now

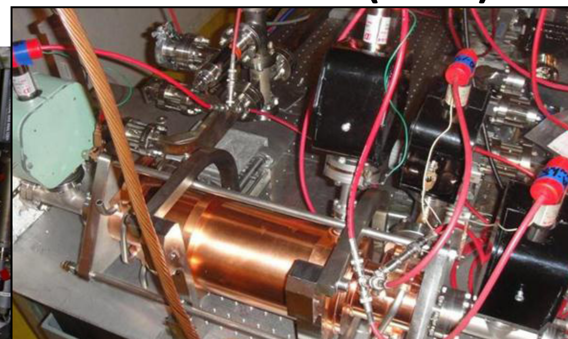
High gradient testing infrastructure

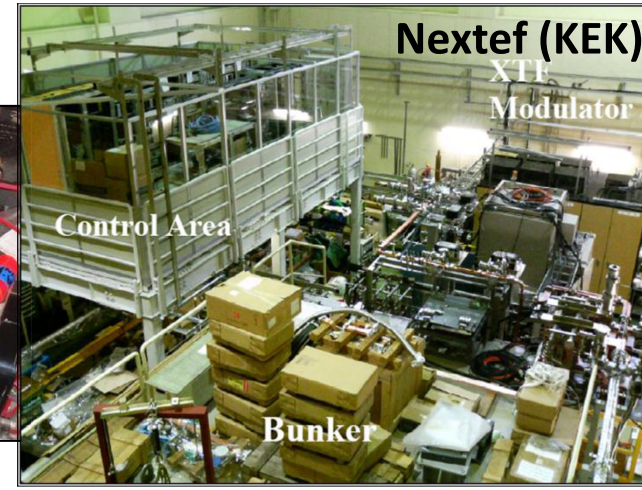
- 11.424 GHz at SLAC and KEK

NLCTA (SLAC)



ASTA (SLAC)

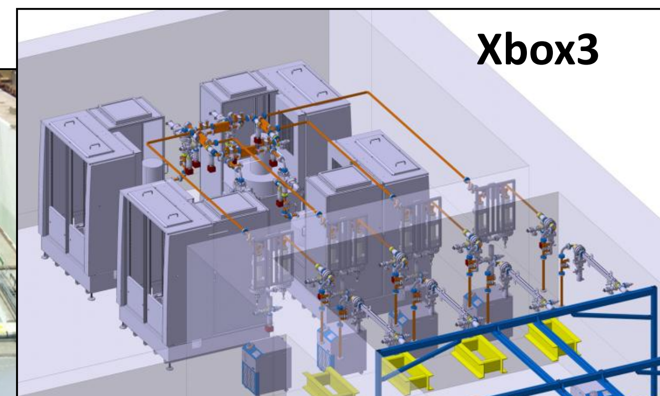




- 11.994 GHz at CERN

Xbox1

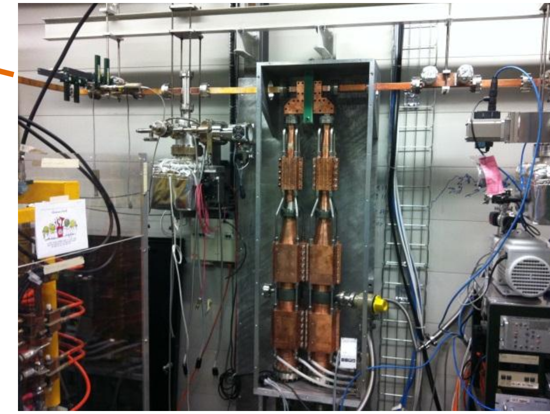
Xbox2



Xbox1 layout

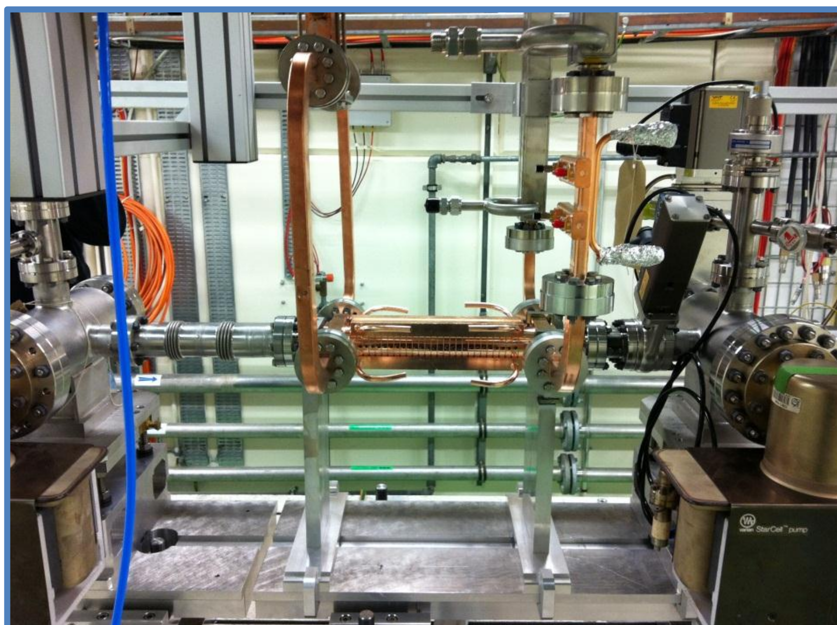
Clockwise from top-left:

- Modulator/klystron (50MW, 1.5us pulse)
- Pulse compressor (250ns, ratio 2.8)
- DUT + connections
- Acc. structure (TD26CC)



Gallery

Bunker



X-band klystrons: High gradient driving force
From “fait maison” to production in industry

50 MW
1.5 μs
50 Hz

6 MW, 5 μs, 400 Hz

Tested at Toshiba last week

CPI
Communications & Power Industries

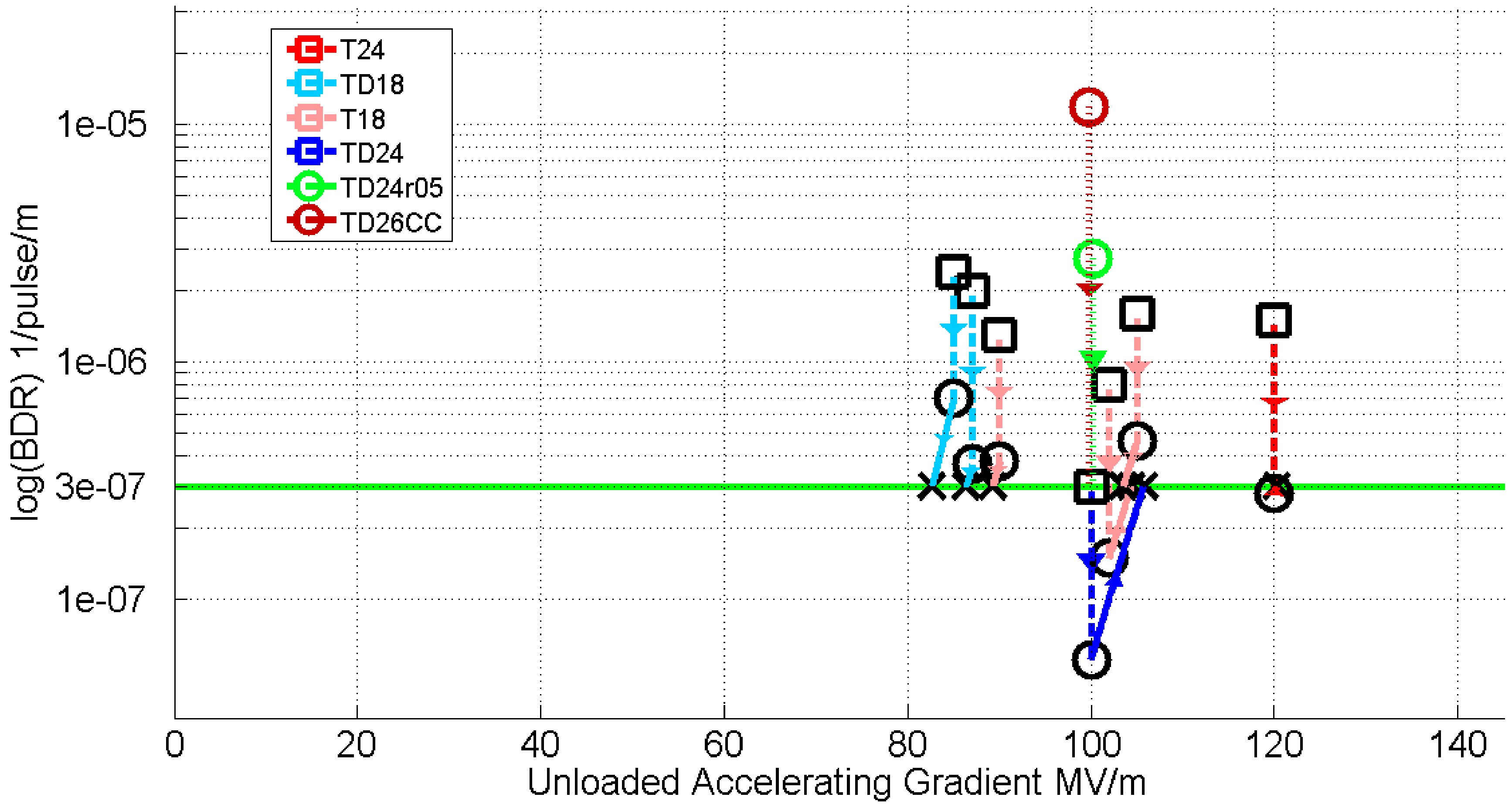
VKX-8311A

Pulsed klystron operating at 11.994 GHz, 50 MW peak, 5 kW average power. Electromagnet focused, liquid cooled. Waveguide output WR-90, vacuum flange.

CPI VKX-8311A

Now a catalogue item

Accelerating structure performance summary based on testing at SLAC, KEK and CERN



Geometrical dependency – our understanding of what is important for RF design of the high gradient structures

The functions which determine the high-gradient operation of the structures are:

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

Global power flow

$$S_c = \left\|\mathrm{Re}(\boldsymbol{S})\right\| + \frac{1}{6}\left\|\mathrm{Im}(\boldsymbol{S})\right\|$$

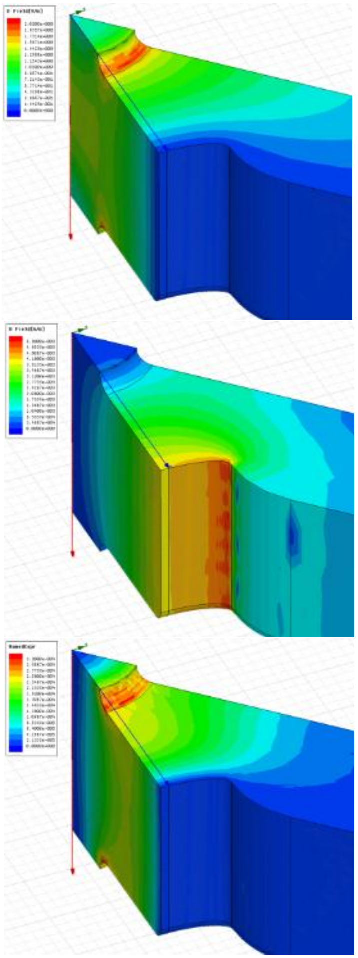
Local modified Poynting vector

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

E_s/E_a

H_s/E_a

S_c/E_a^2



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FERMI@Elettra: present layout and energy upgrade

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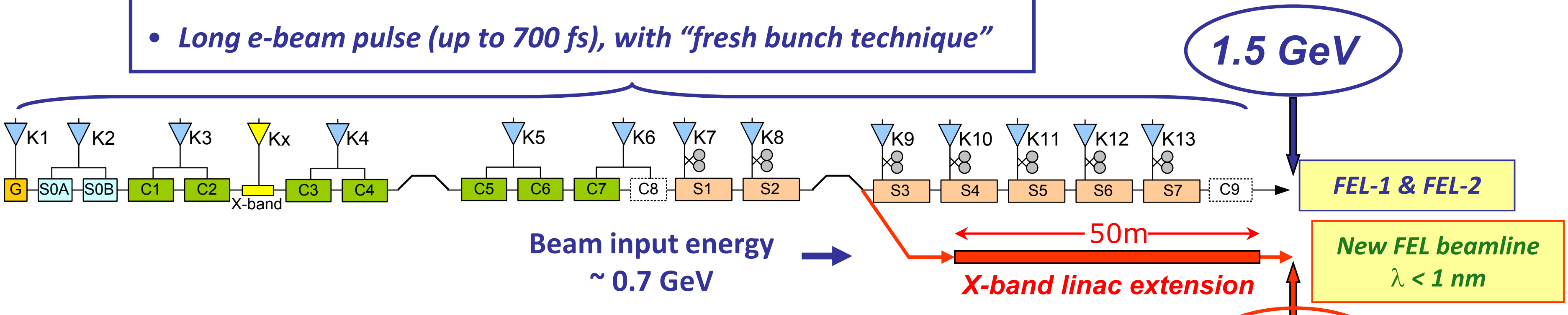
FERMI current layout and performance

- *E_{beam} up to 1.5 GeV*
- *FEL-1 at 80-10 nm and FEL-2 at 10-4 nm*
- *Long e-beam pulse (up to 700 fs), with "fresh bunch technique"*

More details in MOPP023



High gradient X-band linac extension

- *Active accelerating length* — *40 m*
- *Accelerating gradient* — *70 MV/m*
- *Beam energy gain* — *2.8 GeV*
- *Injection energy* — *0.7 GeV*

New FEL beamline expected performance	
Undulator period	30 mm
Undulator parameter	1
Fundamental wavelength	**0.5 nm**
Peak power at saturation	5.6 GW

N.B. The new layout could also provide two electron beams at the same time (@25 Hz) with different energies

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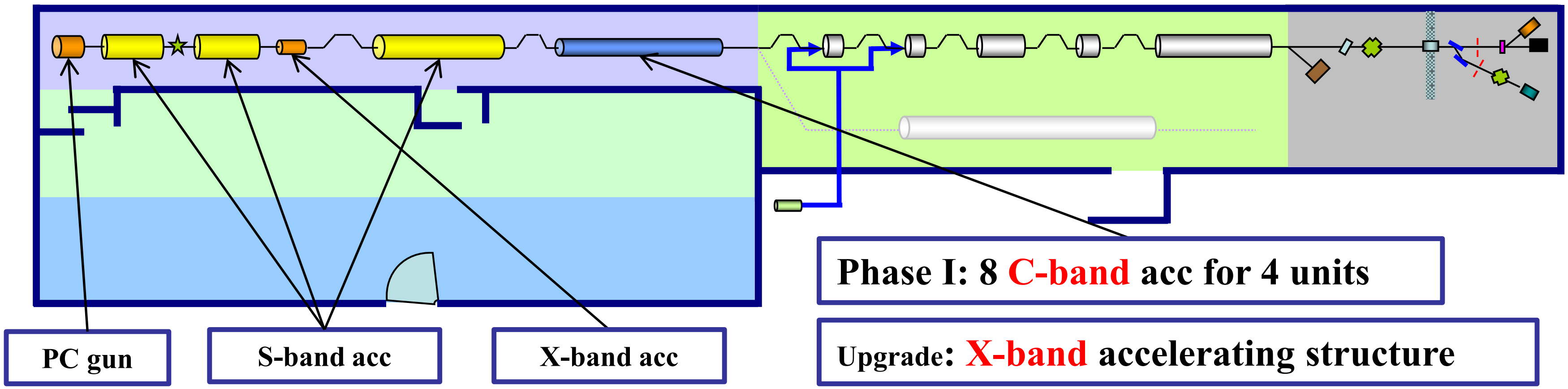
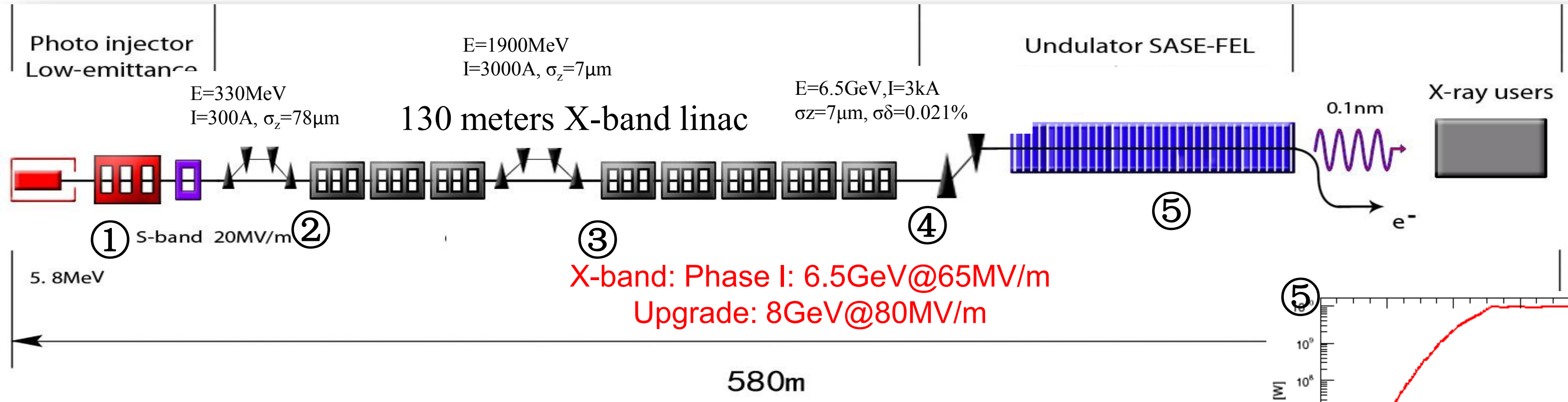
Shanghai Photon Science Center at SINAP

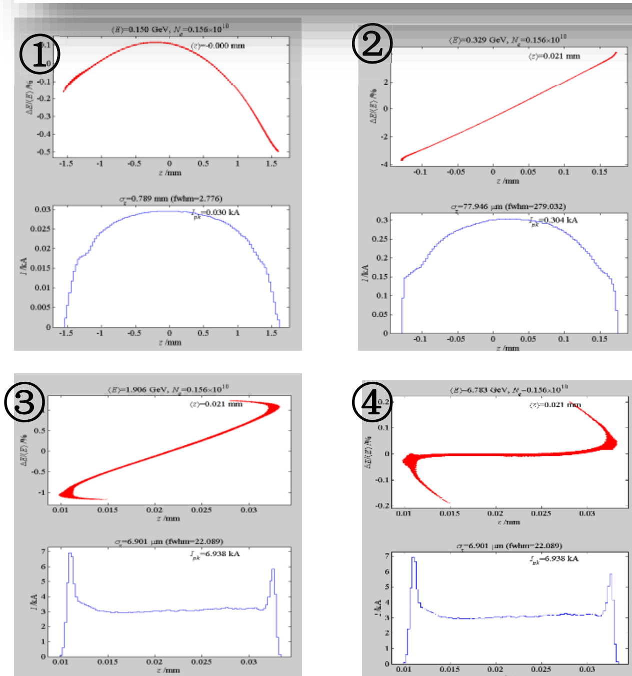
C-band and X-band plans for soft X-ray FEL (SXFEL started in 2014)



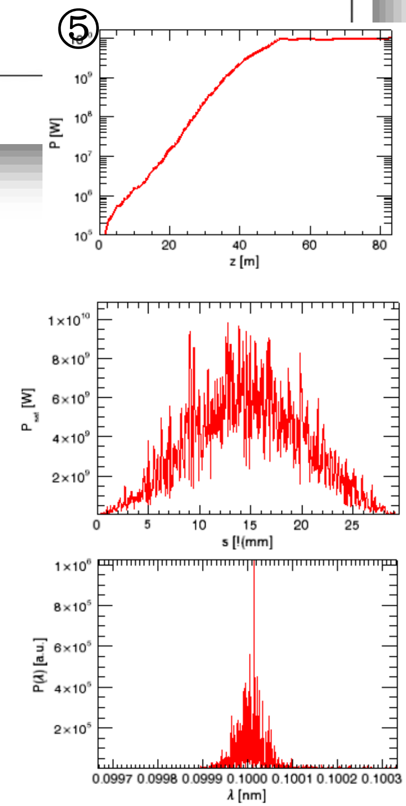
Parameters	Phase I	Upgrade	Unit
Output Wavelength	9	3	nm
Bunch charge	0.5~1	0.5~1	nC
Energy	0.84	1.2~1.3	GeV
Gradient	**40**	**70-80**	**MV/m**
Energy spread (sliced)	0.1-0.15 (0.02)	0.15 (0.03)	%
Normalized emittance	2.0~2.5	2.0~2.5	mm.mrad
Pulse length (FWHM)	1.	1	ps
Peak current	~0.5	0.5	kA
Rep. rate	1~10	1~10	Hz

X-band plan for compact hard X-ray FEL (On proposal)





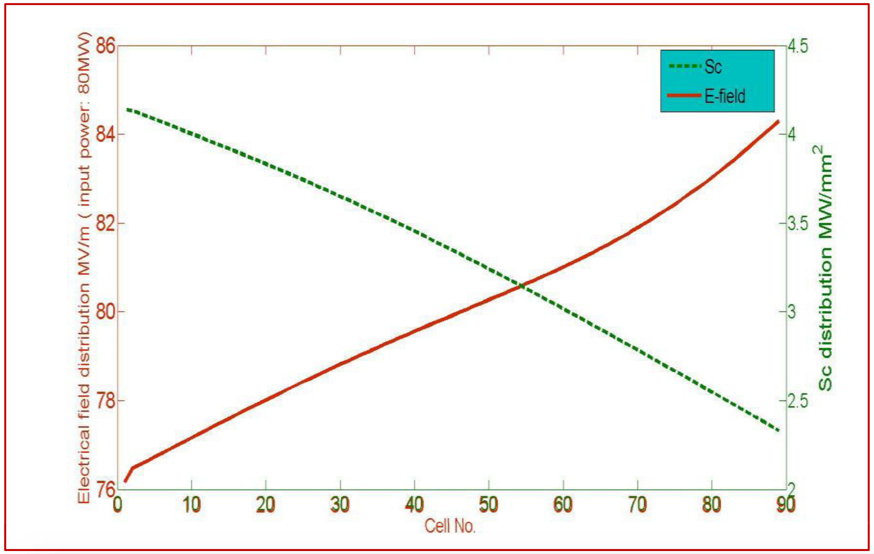
Parameters	Value
Output Wavelength	0.07nm
Bunch charge	250pC
Energy	6.5GeV
Normalized emittance	0.4μm
Energy spread (projected)	0.02%
Pulse length (Full)	40fs
Peak current	3kA
Rep. rate	60Hz
Peak power	10GW
Peak brightness	2*10^{33}



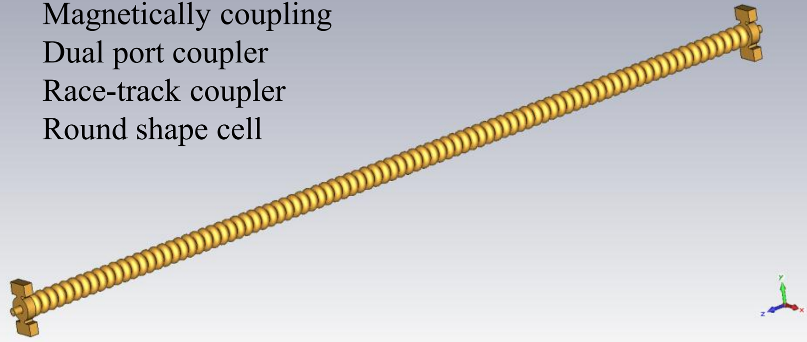
SINAP 中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

X-band accelerating structure for XFEL for 65MV/m, 80MV/m

Frequency	11424MHz
Phase advance	4π/5
Cell No.	89+2
Effective length	**944.73 mm**
Cell length, d	10.497mm
Iris thickness, 2a	1.5 mm
Ratio of elliptic radius, b_a	1.8
Aperture, a_r	**4.3~3.05 mm**
Group velocity, Vg/c	3.45%~1.12%
Shunt impedance, R	86.7~108.7MΩ/m
Attenuation factor, τ	0.61
Filling time, t_f	150 ns
Sc	4.14~2.33 MW/mm^2
Emax/E0	2.68~2.02
Hmax/E0	2.68~2.39 mA/V
Input power, P_{in}	52MW @65MV/m 80MW @80MV/m
Two-Klystrons units 30 MW/klystron	34 @65MV/m 51 @80MV/m



1. Magnetically coupling
2. Dual port coupler
3. Race-track coupler
4. Round shape cell



More details in TUPP127

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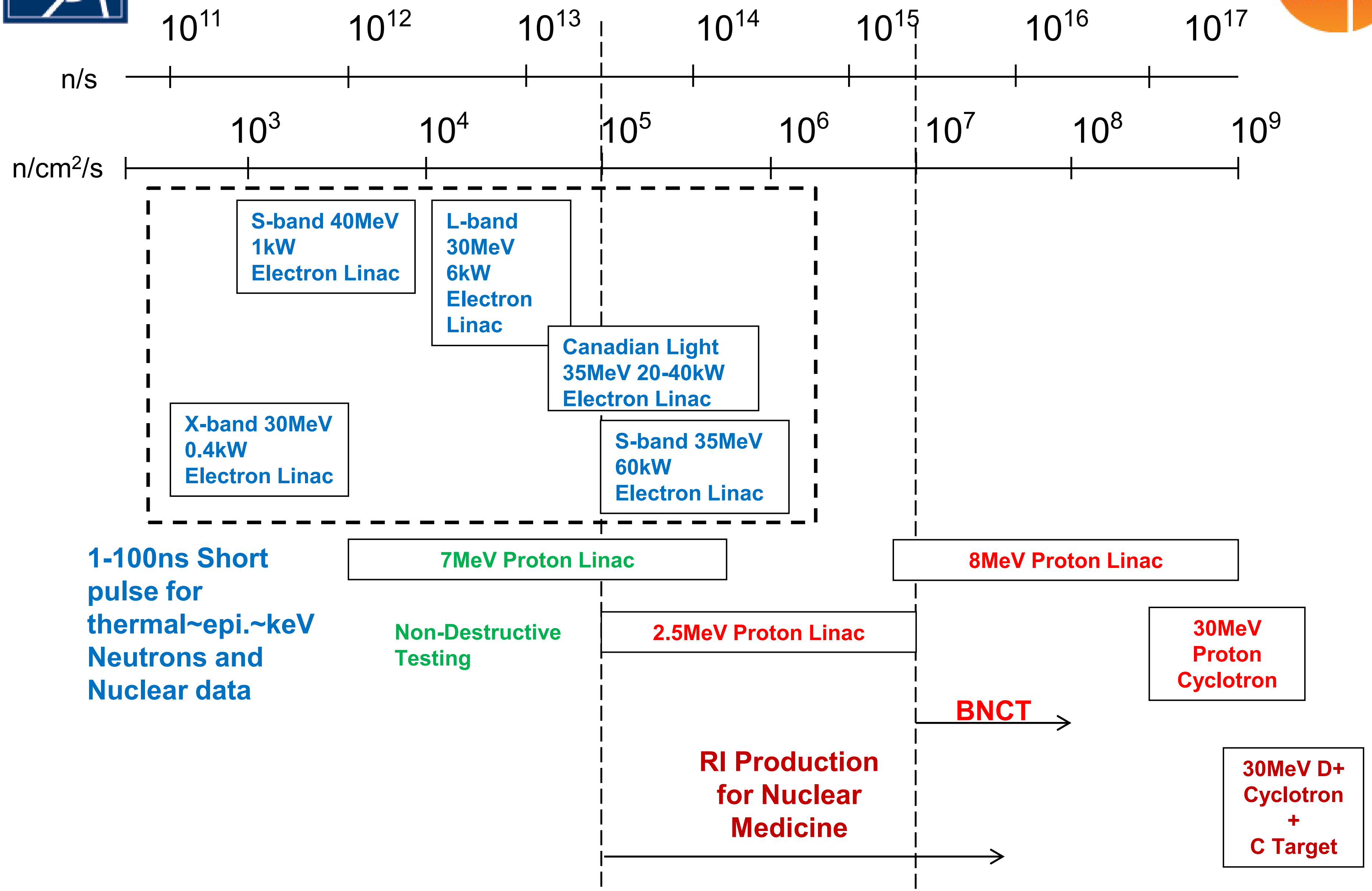
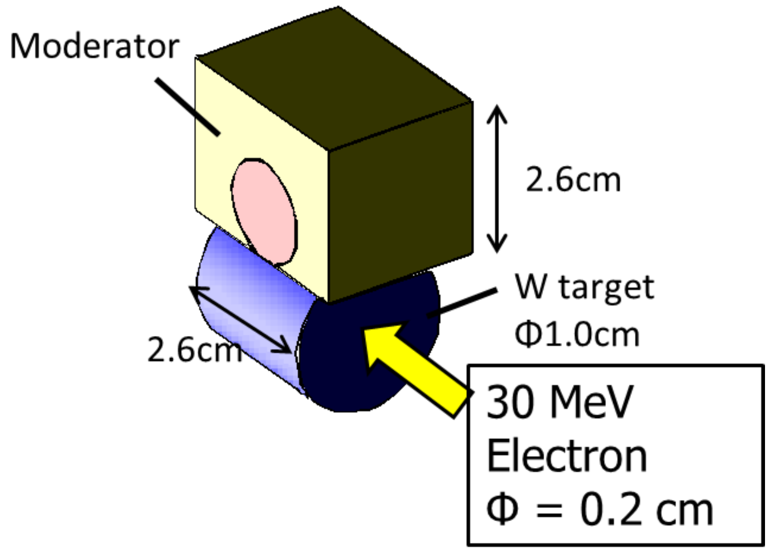
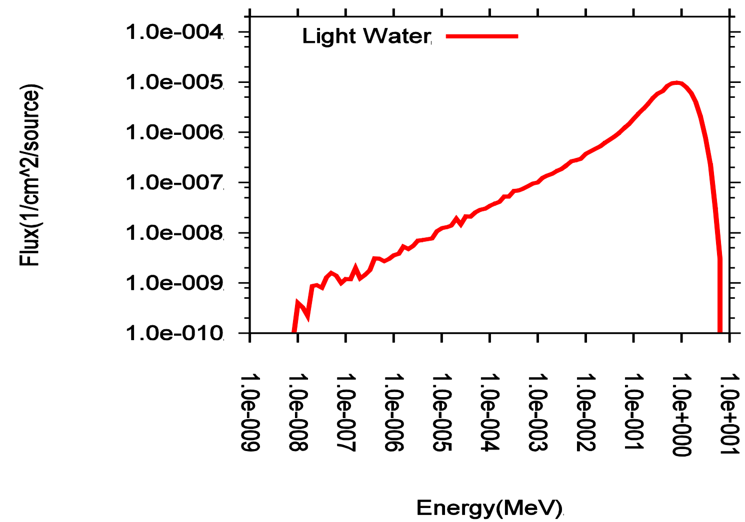
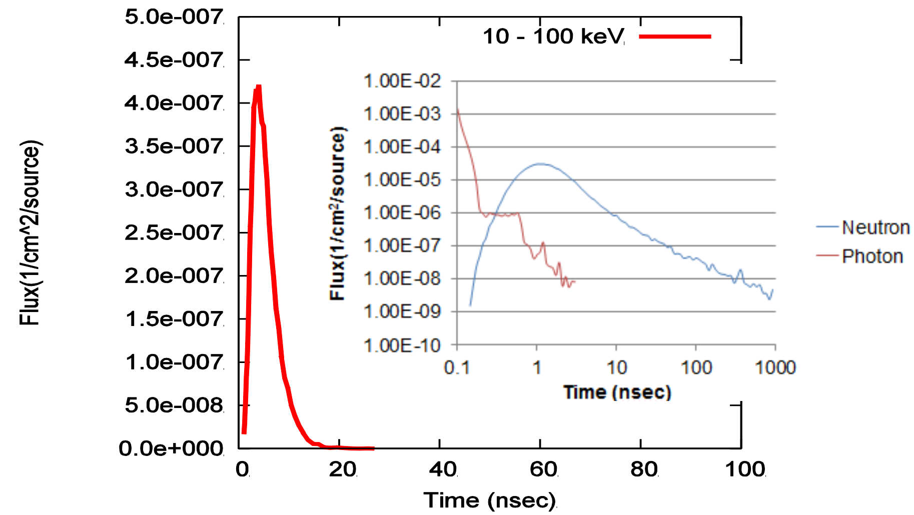
Application of Compact Accelerator Neutron Sources



Spectrum and pulse shape of neutrons



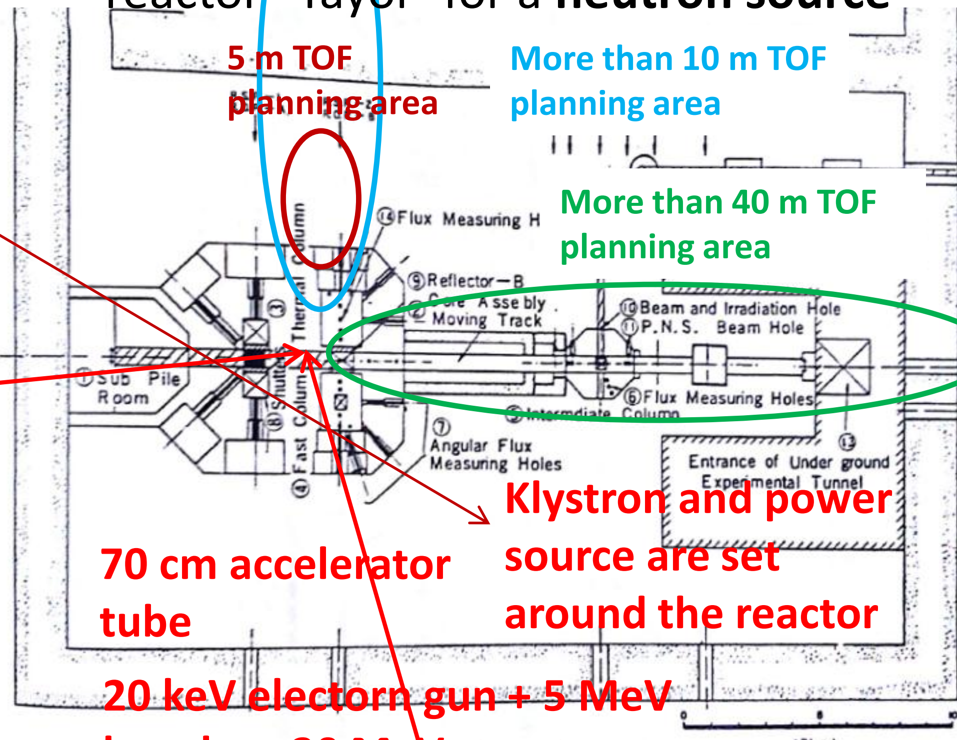




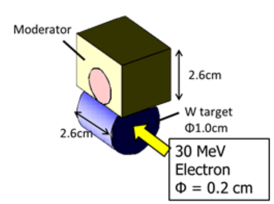
Beam Power	375 W
Target intensity	1.3×10^{11} n/s
Pulse width behind moderator (10 – 100 keV neutron)	6.66 ns
Neutron flux at measurement point (5m TOF)	1.1×10^{3} n/cm²/s

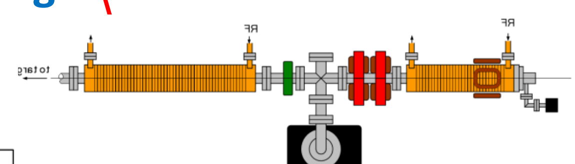
Compact X-band 30 MeV electron linac at Univ. of Tokyo

Linac will be moved from **Compton source** to the area of decommissioned research reactor "Yayoi" for a **neutron source**



20 keV electorn gun + 5 MeV buncher+30 MeV structure
+ Neutron target





Application of the system is to measure more accurately the nuclear data for analysis of the fuel debris at Fukushima (F-1), nuclear transformation at ADS and design of new reactors in future.

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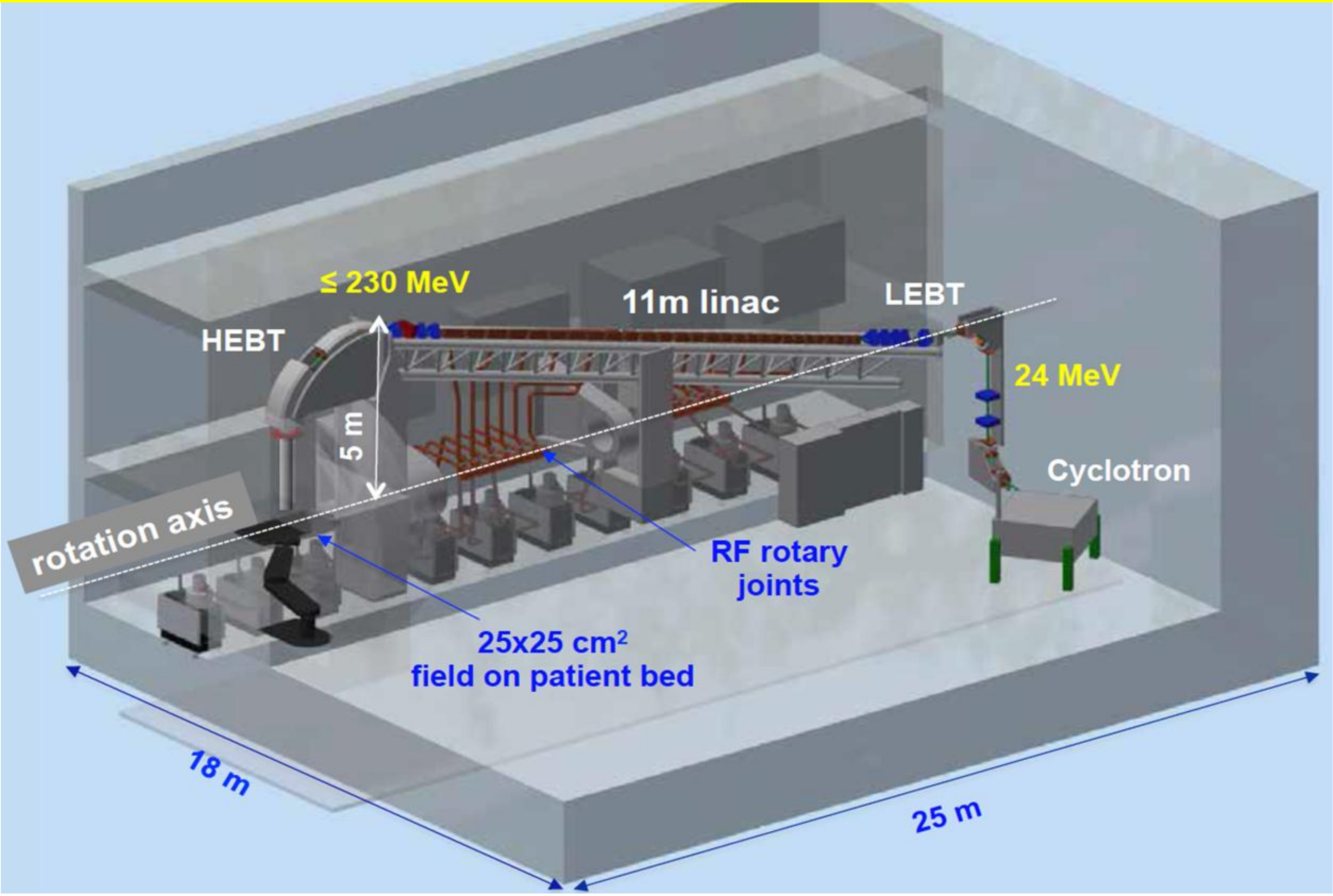
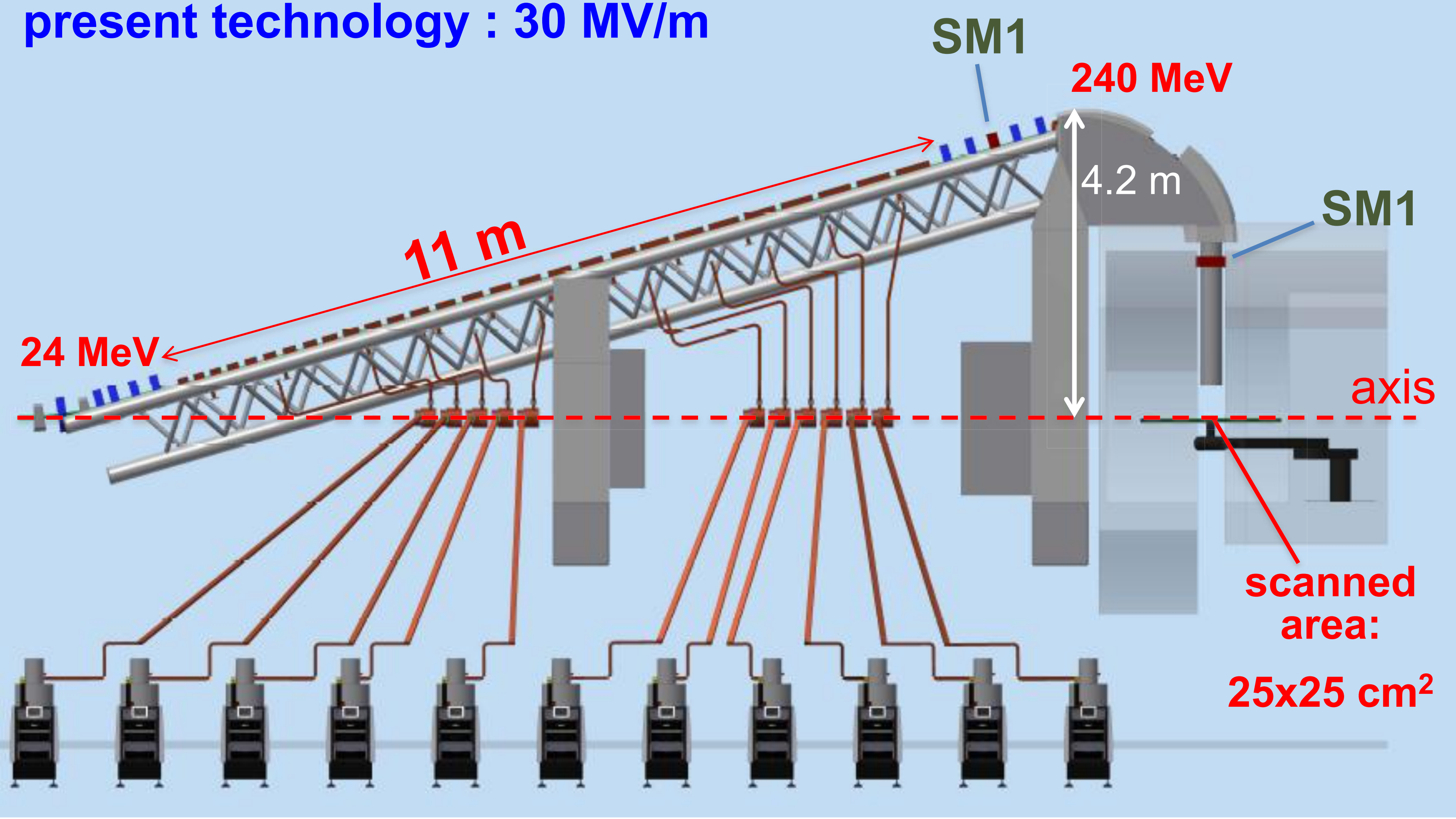
TULIP (TUrning LInac for Protontherapy)

"Proton and Carbon Linacs for Hadron Therapy", Ugo Amaldi, Friday 11:30, LINAC14



TULIP at 3 GHz with E_0 = 30 MV/m

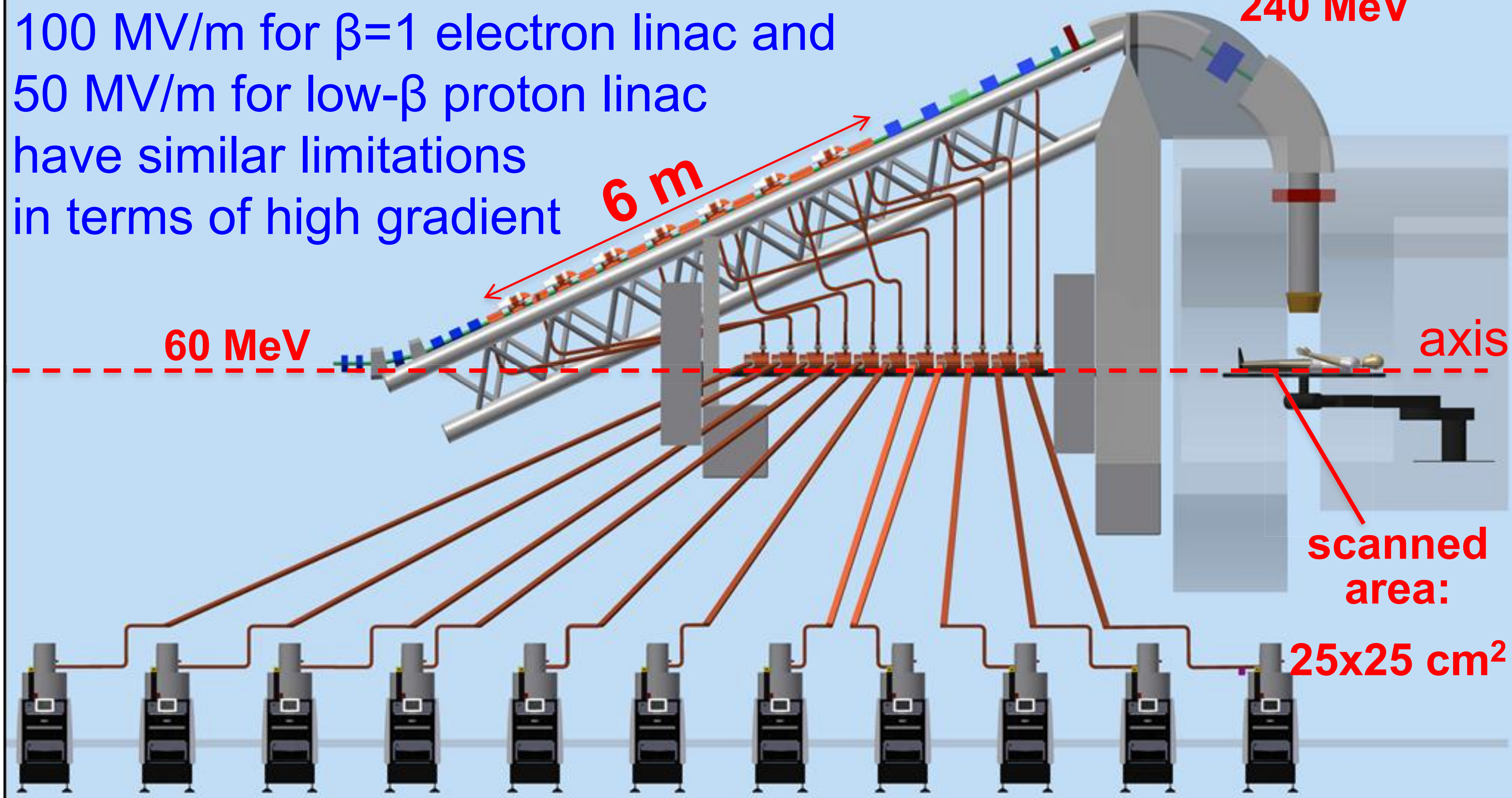
present technology : 30 MV/m



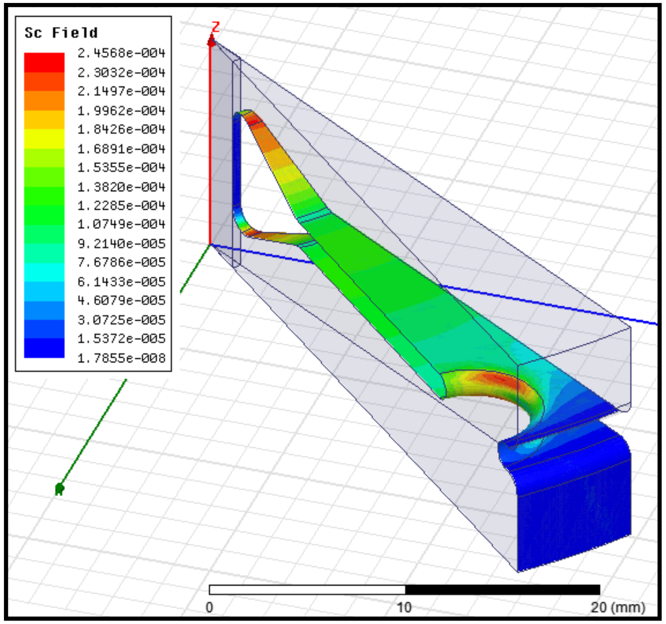
TULIP-2

CLIC high gradient technology applied to S-band:

100 MV/m for β=1 electron linac and
50 MV/m for low-β proton linac
have similar limitations
in terms of high gradient



TULIP-2 HG backward TW structure



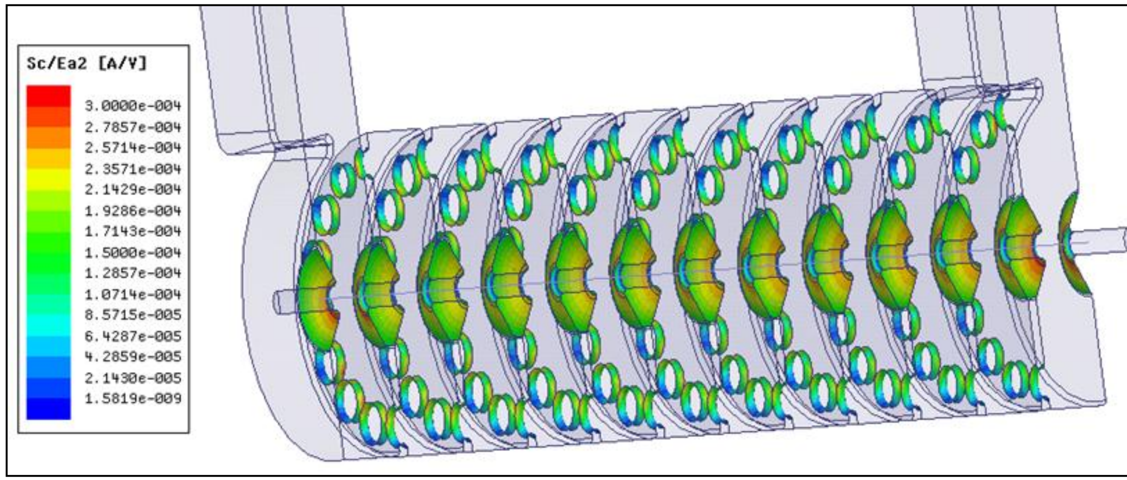
Cells are optimized to have minimum:

$$\boxed{\frac{P}{E_a^2}\cdot\frac{S_c}{E_a^2}} = \frac{v_g}{\omega}\cdot\frac{S_c/E_a^2}{R'/Q}$$

Expected performance

Accelerating gradient: 50 MV/m

Breakdown rate: 10^{-6} bpp/m



First prototype is being built by CERN and TERA in the framework of CERN KT funded project: “High-gradient accelerating structures for proton therapy linacs”

More details in THPOL08 and THPP061

Conclusions

- For large linac-based installations, like a linear collider, the optimum gradient is high. It approaches the highest possible gradient limited by the fundamental physical phenomena
- For medium and small sized linac-based installations, built in a “green field”, the optimum gradient is usually not the highest possible
- BUT there are many cases where **high gradient is required**:
  - Given the final energy of the linac and the space limitations of existing infrastructure (e.g., research labs., universities)
  - The cost of infrastructure is very high (e.g. medical facilities)

Acknowledgements

- Walter Wuensch, Nuria Catalan Lasheras (CERN)
- Toshiyasu Higo (KEK)
- Gerardo D'Auria, Simone Di Mitri (Elettra-Sincrotrone Trieste)
- Zhentang Zhao, Qiang Gu, Wencheng Fang, Meng Zhang, Chao Feng (SINAP)
- Mitsuru Uesaka (University of Tokyo)
- Ugo Amaldi (TERA)

Thank you for your attention.

Last but not least, I would like to apologize for not being able to cover all high gradient linacs related projects and activities.