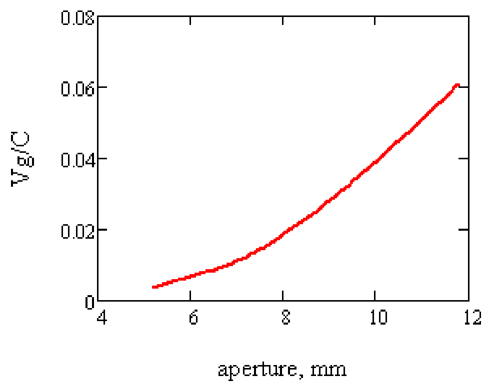
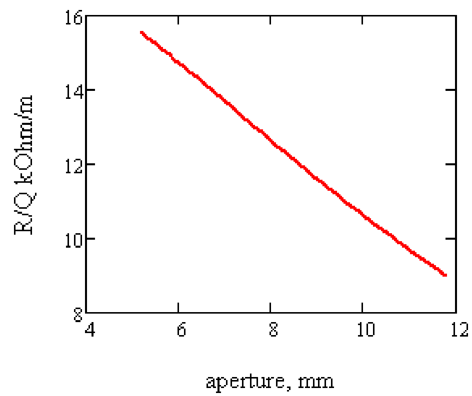
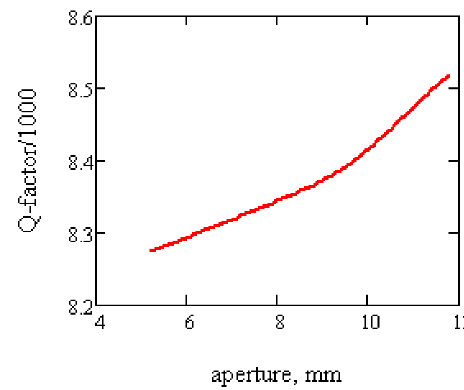
Optimization of the X-band 1 GeV single bunch electron linac, capable to operate at >0.5 KHz repetition rate

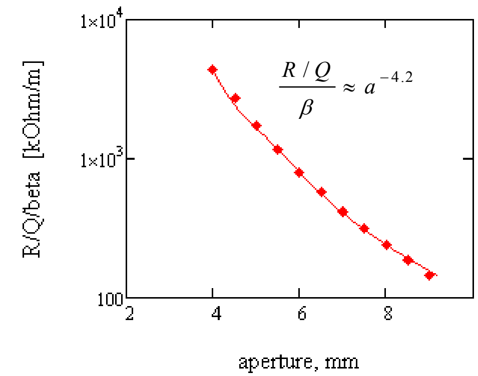
I. Syratchev, CERN 24.03.2010

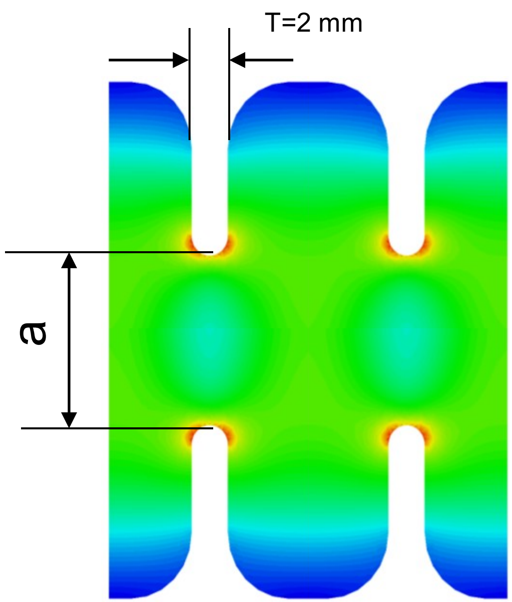
X- band (9.3 GHz) generic (2π/3) constant impedance structure











Accelerating gradient:

$$E_{[MV/m]} = \left[P_{[MW]} \frac{R/Q_{[Ohm/m]}}{\beta \times C} \omega_{[Hz]} \times \int_0^{Ls} \exp(\omega z/(Q\beta \times C))\, dz \right]^{1/2}$$

Scaling:

$$R/Q \approx \omega$$

$$Q \approx \omega^{-1/2}$$

$$E \approx \sqrt{P}\omega \times a^{-2}$$

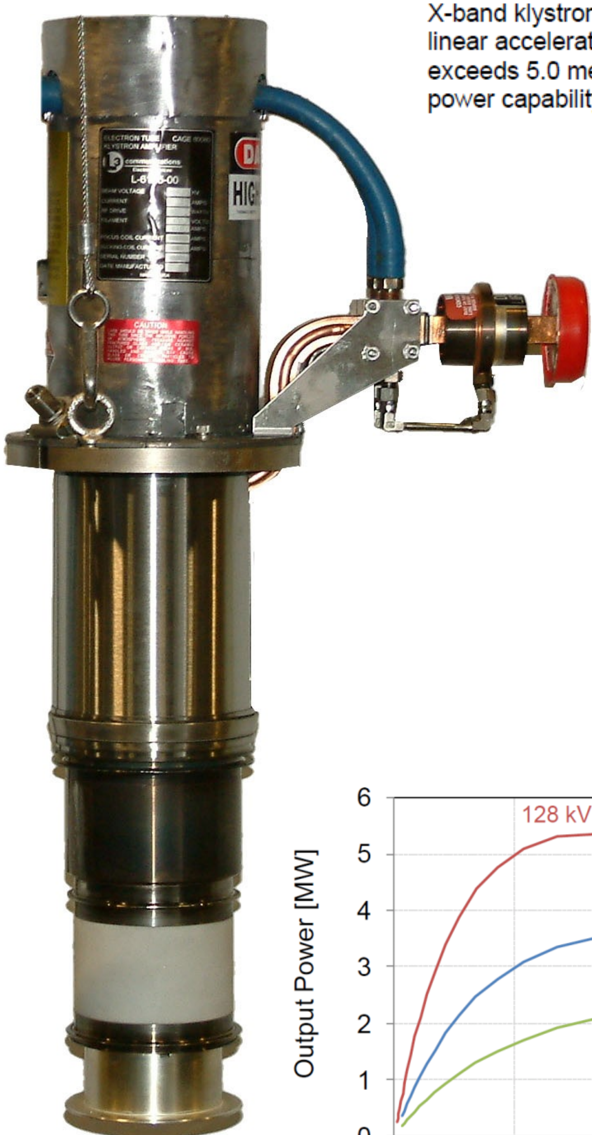
To accelerate rapidly, one should go:

- Higher peak power
- Higher frequency
- Smaller aperture

High power klystrons short list

Type:	Freq.	P_{peak}	T_{pulse}	Rep. rate	$P_{aver.}$
ILC(MBK)	1.3 GHz	10 MW	1.5 msec	5 Hz	75 kW
CLIC (MBK)	1.0	15 MW	0.14 msec	50 Hz	100 kW
S-band	3.0	45 MW	6 μsec	50 Hz	13.5 kW
C-band	6.0	50 MW	2.5 μsec	50 Hz	6.2 kW
X-band$_1$	12	50 MW	1.6 μsec	50 Hz	4.kW
X-band$_2$	9.3	5.5 MW	3.2 μsec	1000 Hz	20 kW (6 KW demonstrated)

The klystron average power is limited by the collector performance. Going higher frequency it is naturally reduced. If, at X-band, the high repetition rate is required, one should agree to operate at a moderate (5-10 MW) RF peak power levels.



The L6145 is a fixed-tuned, cathode-pulsed X-band klystron amplifier for use in high energy linear accelerator systems. Peak output power exceeds 5.0 megawatts at 0.4% duty: average power capability is 20 kilowatts.

DS61450410

Electron Devices

L6145 X-Band Klystron Amplifier

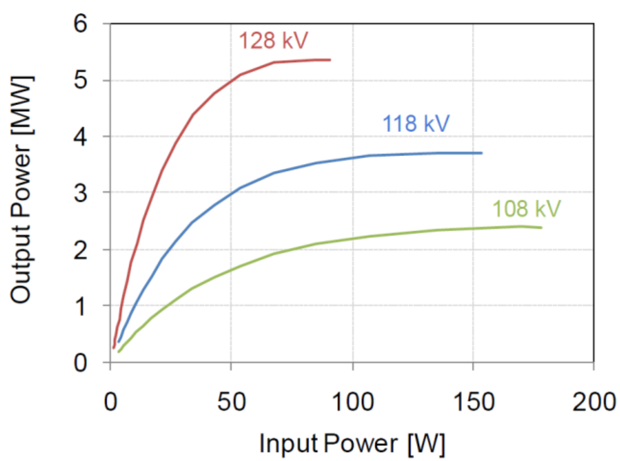
Performance (As specified)

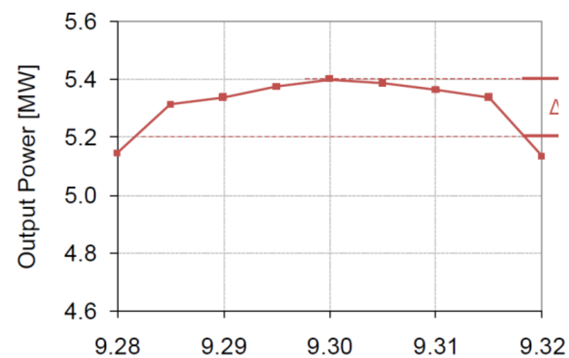
Performance	(As specified)
Frequency (MHz)	9300
Peak Output Power (min, MW)	5.0
Beam Voltage (max, kV)	135
Beam Current (max, A)	86
Drive Power (max, W)	50
Duty (RF, %)	0.4
RF Pulse Width (typical, μs)	3.2
Beam Pulse Width (typical, μs)	4.0
Heater Voltage (V_{rms} or Vdc)	7.0
Heater Current (A_{rms} or Adc)	21
Ion Pump Voltage (min, kV)	3.0
Solenoid Voltage (max, Vdc)	130
Solenoid Current (Adc)	35±1
Bucking Coil Current (max, Adc)	1.5

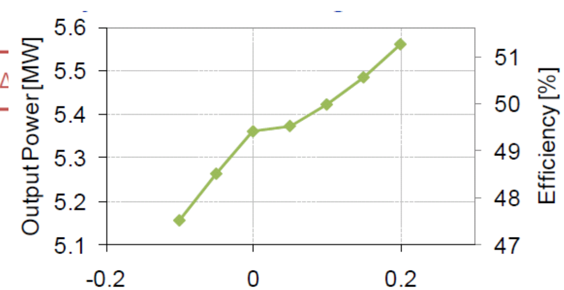
Demonstrated:

- Excellent performance demonstrated
  - 5.4 MW peak at 9.3 GHz
  - Operated at 128 kV and 84 A
  - Efficiency of 50 percent
  - Tested to 6 kW average power
    - Higher average power testing on hold until we find a suitable water-load

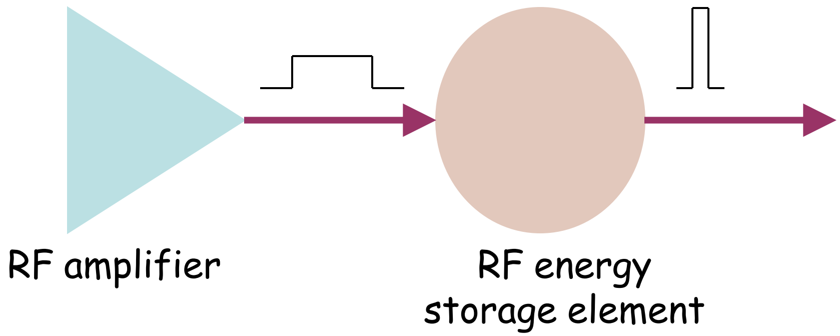
With 3.2μs, 5.4 MW pulses and 6 kW average,
The repetition rate was **350 Hz**!
If 20 kW is within reach, then **1.1 kHz** will come

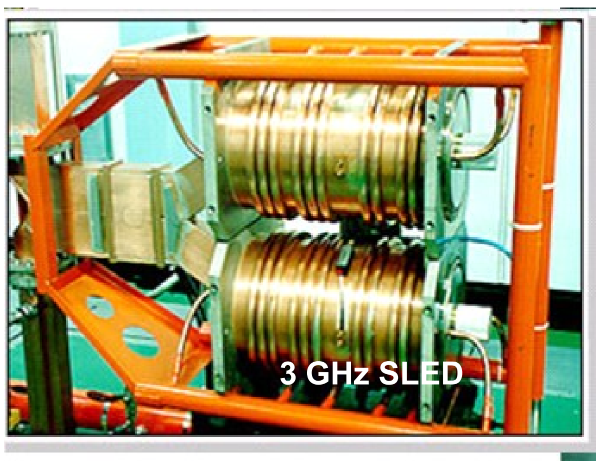






The pulse compression is a technology which allows to increase the peak RF power in exchange for the RF pulse length reduction.

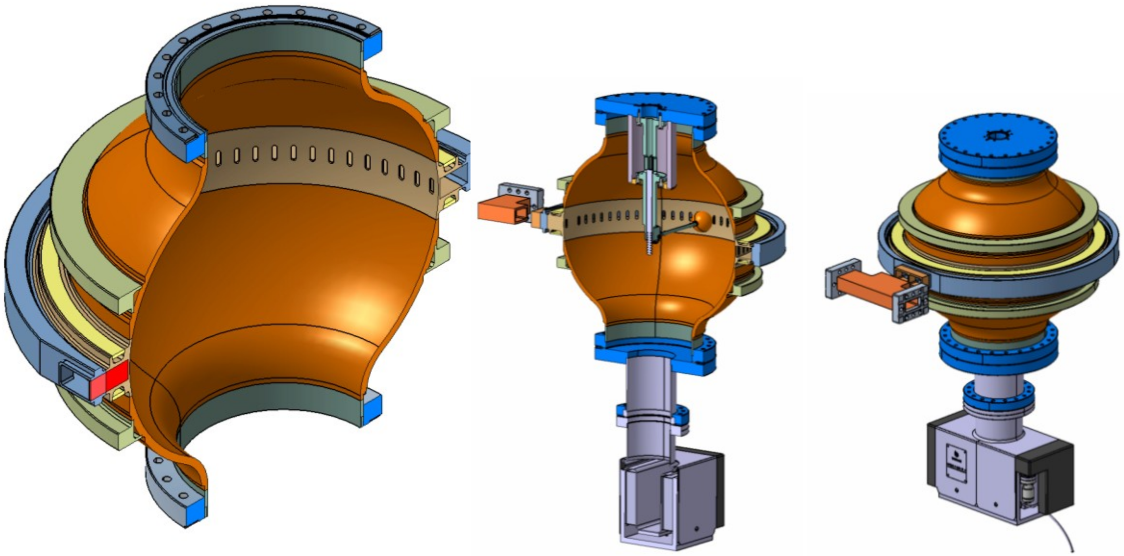


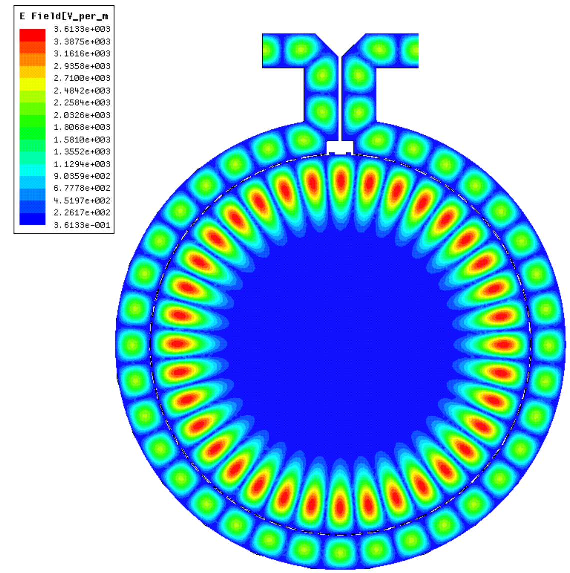


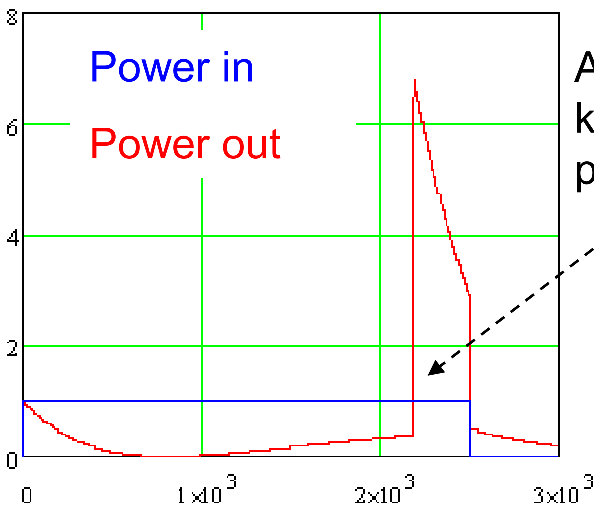
Comparing the two, BOC uses single cavity. No extra 3dB hybrid and no reflection back to klystron like in SLED, when the two cavities are slightly detuned.

6 GHz BOC design (PSI, R. Zennaro)

The pulse compressor is a storage device (Q~220000);it accumulates the energy of the incoming “long” pulse and releases a short pulse.







A 180° phase jump kicks off the output power

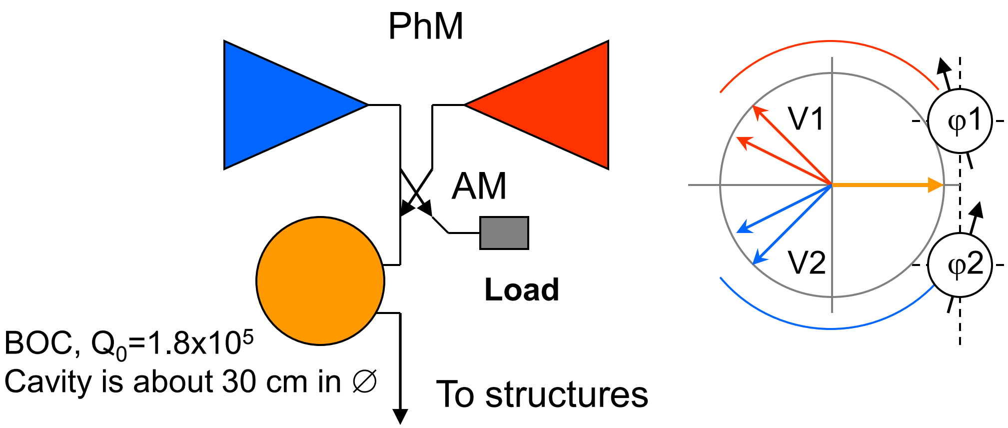
The working mode is the TE18,1,1. The coupling (β~10) is provided by 70 slots. The travelling wave in the WG must be in phase with the rotating resonance.

PROTOTYPE

STATUS: RF design ready; mechanical design well advanced

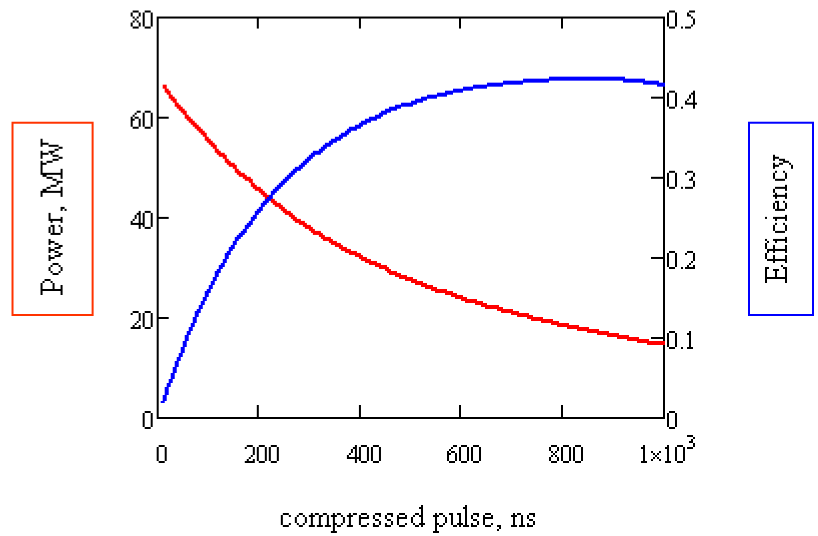
GOAL: prototype ready for summer 2011, measured and tuned September/October 2011

40 MW x few hundred ns, 9.3 GHz power station

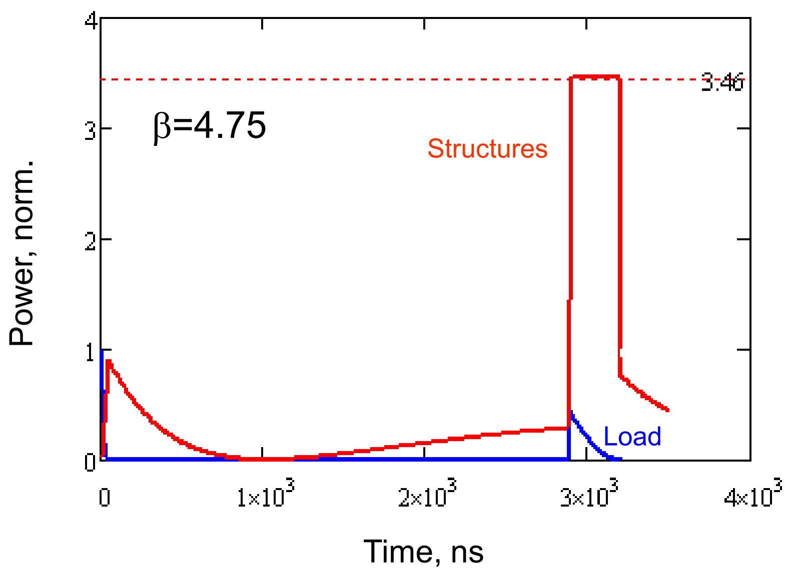


Peak power vs. pulse length

T_{in}=3.2μs, β=4.75

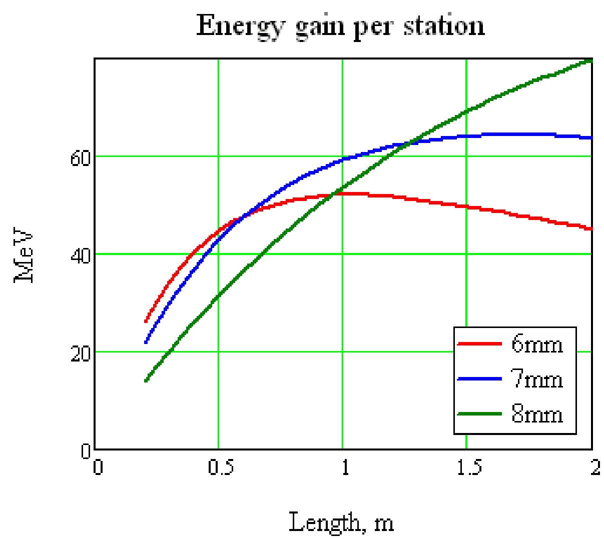


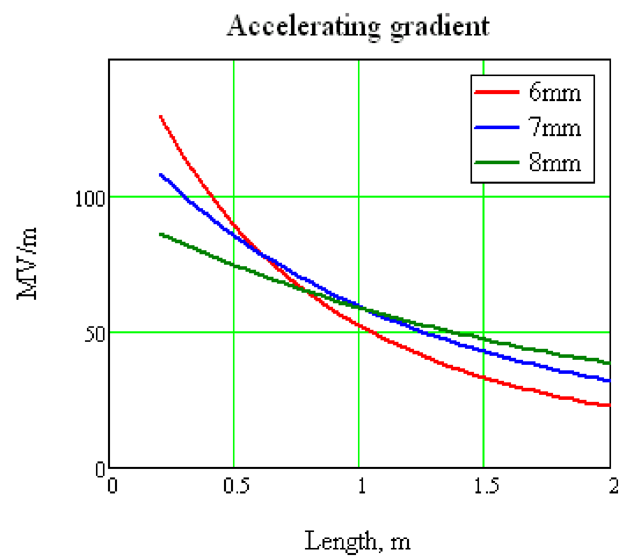
Example: T_{in}=3.2μs, T_{out}=300 ns
P_{in}=2 x 5.5 MW, P_{out}=38 MW

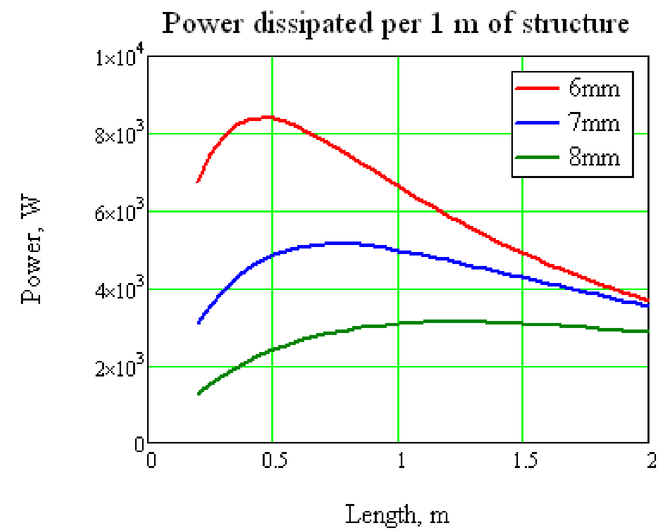


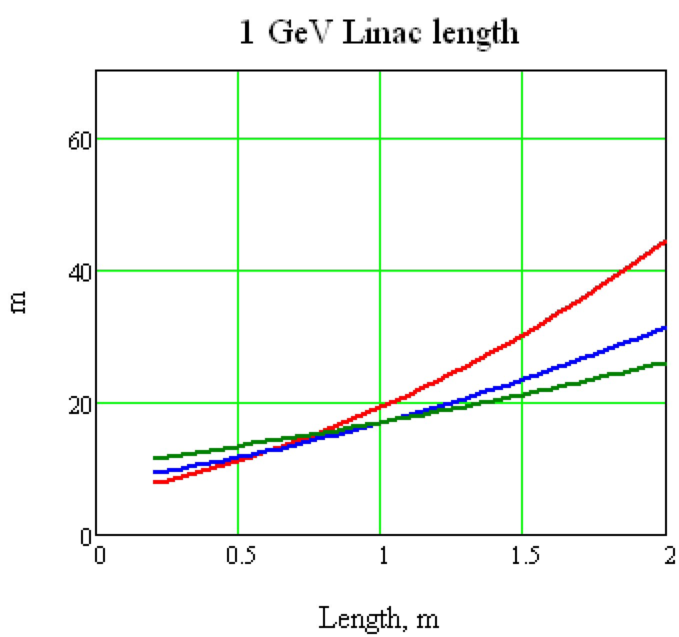
Increasing input pulse length, the extra 2 MW /+1μs can be approximately gained.

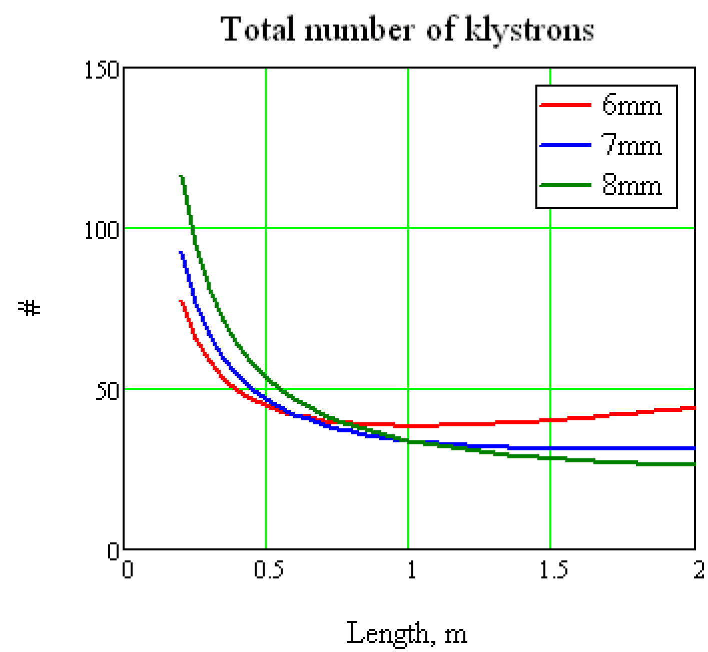
X-band 1.0 GeV Accelerator performance vs. accelerating structure length and aperture



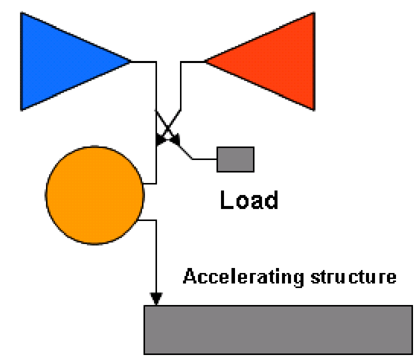






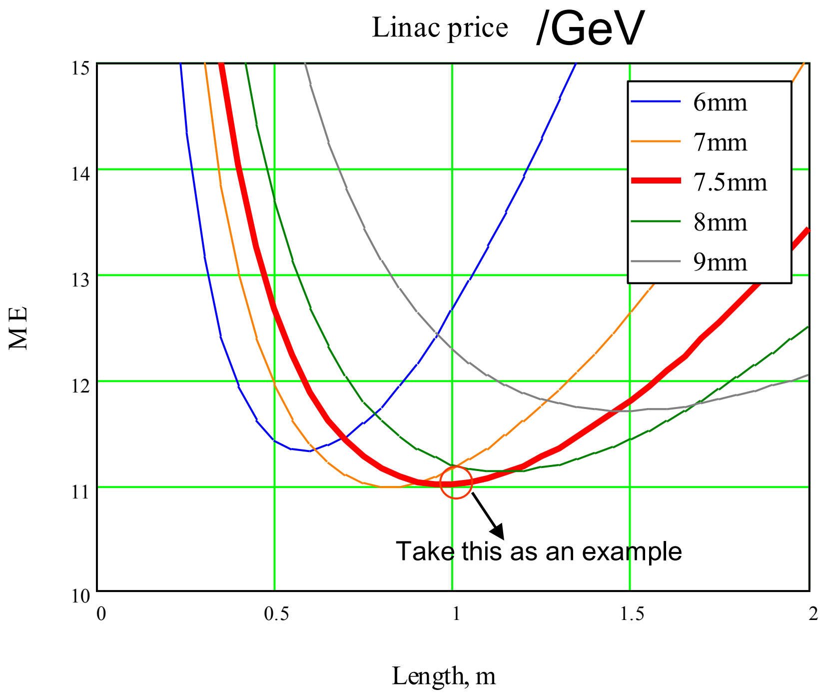


Module Layout:



Cost model:

$P = N_{kl+mod} \times 160kE + N_{PC} \times 40kE + L_{Linac} \times 300kE/m$



The cost optimal structure stays in the range:
Aperture: 7 to 8 mm
Structure Length: 0.8 to 1.2 m

Structure:
Aperture: 7.5 mm
Length: 1.0 m (93 cells)
V_{group}/C: 0.014
Q: 8300
R/Q: 13.1 kOhm
Filling time: 230 ns
Gradient: 60 MV/m
Power input: 43 MW
Dissipated power: 4 kW/m
Power to the load: 1 kW

0.5 kHz

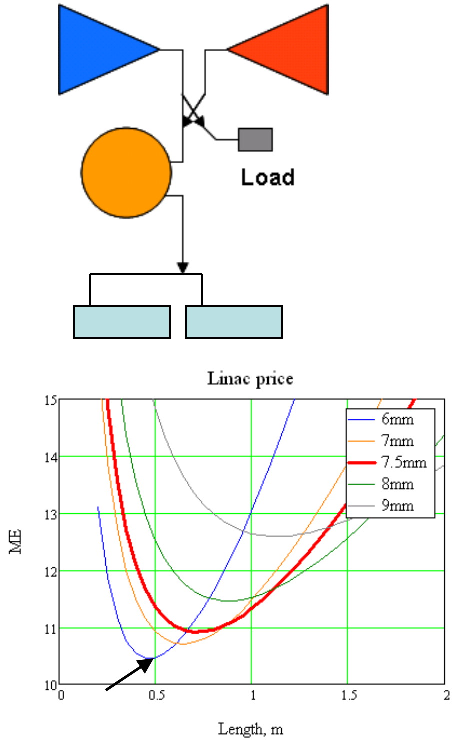
Klystrons:
Peak power: 5.5 MW
Pulse length: 3.2 microsecond
Rep rate: 0.5 kHz
Efficiency: 0.5

Pulse compressor:
Q0: 1.8×10^5
Beta=4.75
Power gain: 3.92
Efficiency: 0.282

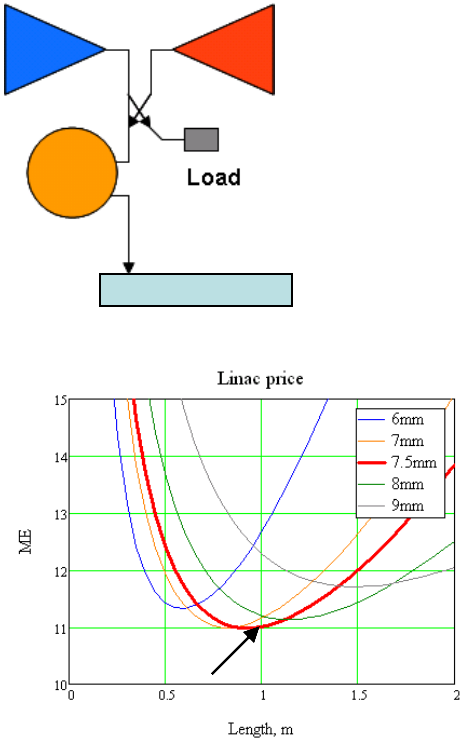
Linac:
Energy gain: 1.02 GeV
Active length: 17 m
structures: 17
#Klystrons: 34
RF Compressors: 17
Pug to RF Efficiency: 0.141

*Note: beam dynamic issues were not accounted

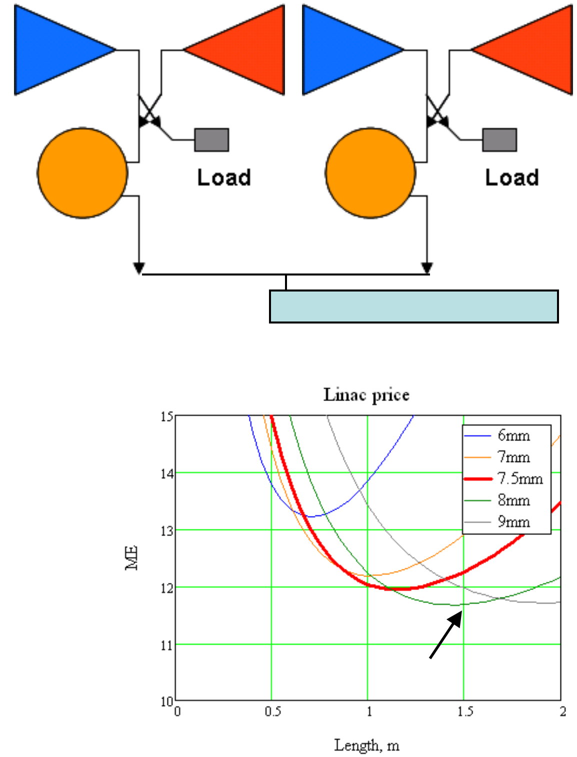
The different layouts comparison



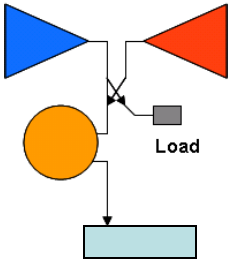
Structure:
Aperture: 6.0 mm
Length: 0.5 m
V_{group}/C: 0.0069
Filling time: 243 ns
Gradient: 63.1 MV/m
Power input: 21 MW
Dissipated power: 4.2 kW/m
Power to the load: 0.46 kW
Linac:
Energy gain: 1.01 GeV
Active length: 16 m
structures: 32
#Klystrons: 32
RF Compressors: 16



Structure:
Aperture: 7.5 mm
Length: 1.0 m
V_{group}/C: 0.014
Filling time: 230 ns
Gradient: 60 MV/m
Power input: 43 MW
Dissipated power: 4 kW/m
Power to the load: 1 kW
Linac:
Energy gain: 1.02 GeV
Active length: 17 m
structures: 17
#Klystrons: 34
RF Compressors: 17

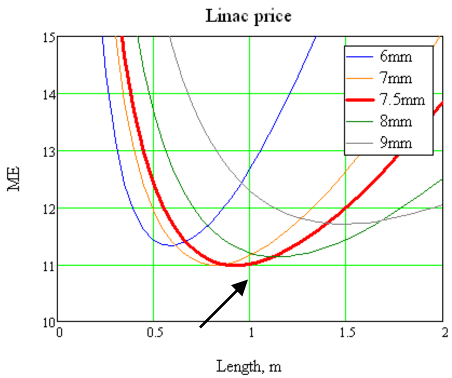


Structure:
Aperture: 8 mm
Length: 1.5 m
V_{group}/C: 0.018
Filling time: 270 ns
Gradient: 66.8 MV/m
Power input: 80 MW
Dissipated power: 6.14 kW/m
Power to the load: 1.63 kW
Linac:
Energy gain: 1.0 GeV
Active length: 15 m
structures: 10
#Klystrons: 40
RF Compressors: 20



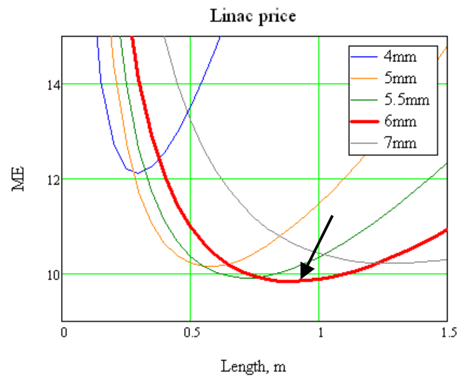
Going higher (12 GHz) frequency

9.3 GHz



Structure:
Aperture: 7.5 mm
Length: 1.0 m
V_{group}/C: 0.014
Filling time: 230 ns
Gradient: 60 MV/m
Power input: 43 MW
Dissipated power: 4 kW/m
Power to the load: 1 kW
Linac:
Energy gain: 1.02 GeV
Active length: 17 m
structures: 17
#Klystrons: 34
RF Compressors: 17

12 GHz



Structure:
Aperture: 6 mm
Length: 0.9 m
V_{group}/C: 0.016
Filling time: 184 ns
Gradient: 71 MV/m
Power input: 47. MW
Dissipated power: 3.7 kW/m
Power to the load: 1 kW
Linac:
Energy gain: 1.024 GeV
Active length: 14.4 m
structures: 16
#Klystrons: 32
RF Compressors: 16

Klystron:

Scaling the 9.3 GHz to 12 GHz is a straightforward and low risk operation because of the low peak power level. In CERN we are also seriously discussing similar approach with 4 klystrons to organize 80MWx250ns and 0.5kHz test stand. Joining the efforts, it will make the order for companies more attractive.

Pulse compressor:

The system (BOC, SLED or other) developed for CERN X-band RF power station can be used straightaway. The same true for the other WG components, loads and etc.

Accelerating structure:

The 70 MV/m accelerating gradient at such a high rep. rate looks as a good approach. Any of the CLIC structures run at $3x10^{-7}$ breakdown trip rate and gradients above 85 MV/m with 240 ns long pulses, but certainly at lower rep. rate (50 Hz). Going to 100 MV/m in the similar aperture will double power dissipation in the structure (10 kW/m), but if requested is still feasible. Also the linac price will be increased by 15% (more klystrons will be needed, but less structures).

The CLIC fabrication/assembly and brazing technologies again are well applicable.

The special studies should be done for:

- Structure operation at a high (~4kW/m) power dissipation. Should structure operate at say 60^{0}C? or the cooling circuit needs to be well advanced/understood.

-The beam dynamics study is needed to define the smallest acceptable aperture of the structure.

The 6 mm aperture ($a/\lambda=0.12$) looks rather small?

A few words, in the case if one will decide to use high (50 MWx1.6μsecx60Hz) power klystrons, similar to that what was developed by SLAC for CLIC.
Together with PC, the 175 MW in 230 ns are the feasible numbers. It will allow to feed 4 structures in parallel. For 17 structures the ~4 klystrons (+1 spare) + 4 PC will be needed.
The klystron/modulator cost is about 1ME (optimistically), with pulse compressors the total investment will be 5.16 ME.
In the case of 5 MW klystron, the total investment will be:
34(+2 spare)x0.16ME + 17x0.04ME = 6.44 ME

The second approach requires 26% higher initial investment, but delivers ~10 times higher repetition rate.