Cryogenic Accelerator Design for Compact Very High Energy Electron Therapy

LINAC’22

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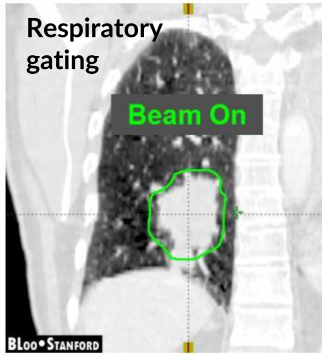
SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University | U.S. DEPARTMENT OF ENERGY

Getting to FLASH VHEE capability

High Dose Rate Radiotherapy



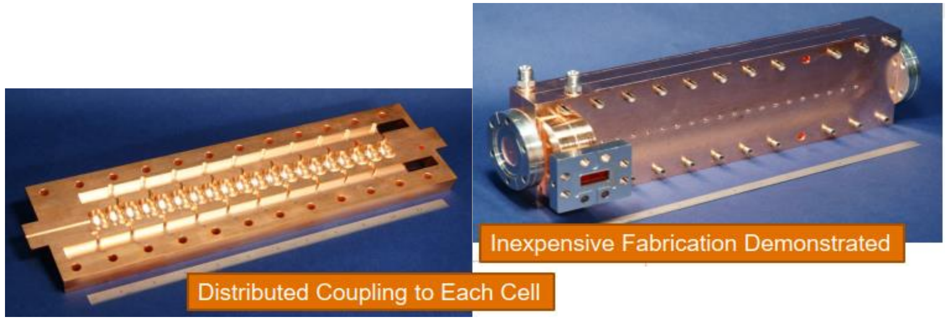
Motion Management

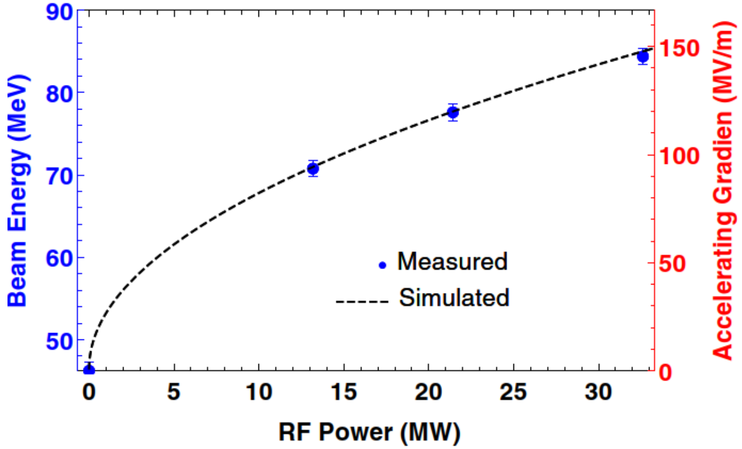
FLASH Therapy

Bourhis, Jean, et al. "Treatment of a first patient with FLASH-radiotherapy." *Radiotherapy and oncology* 139 (2019).

- Sub-second treatment time appears to improve healthy tissue sparing with comparable tumor control
- Demonstrated in preclinical setting with photons, electrons, and protons
- Requires high dose rate >40 Gy/L/s

Advances in High Gradient Accelerator Design





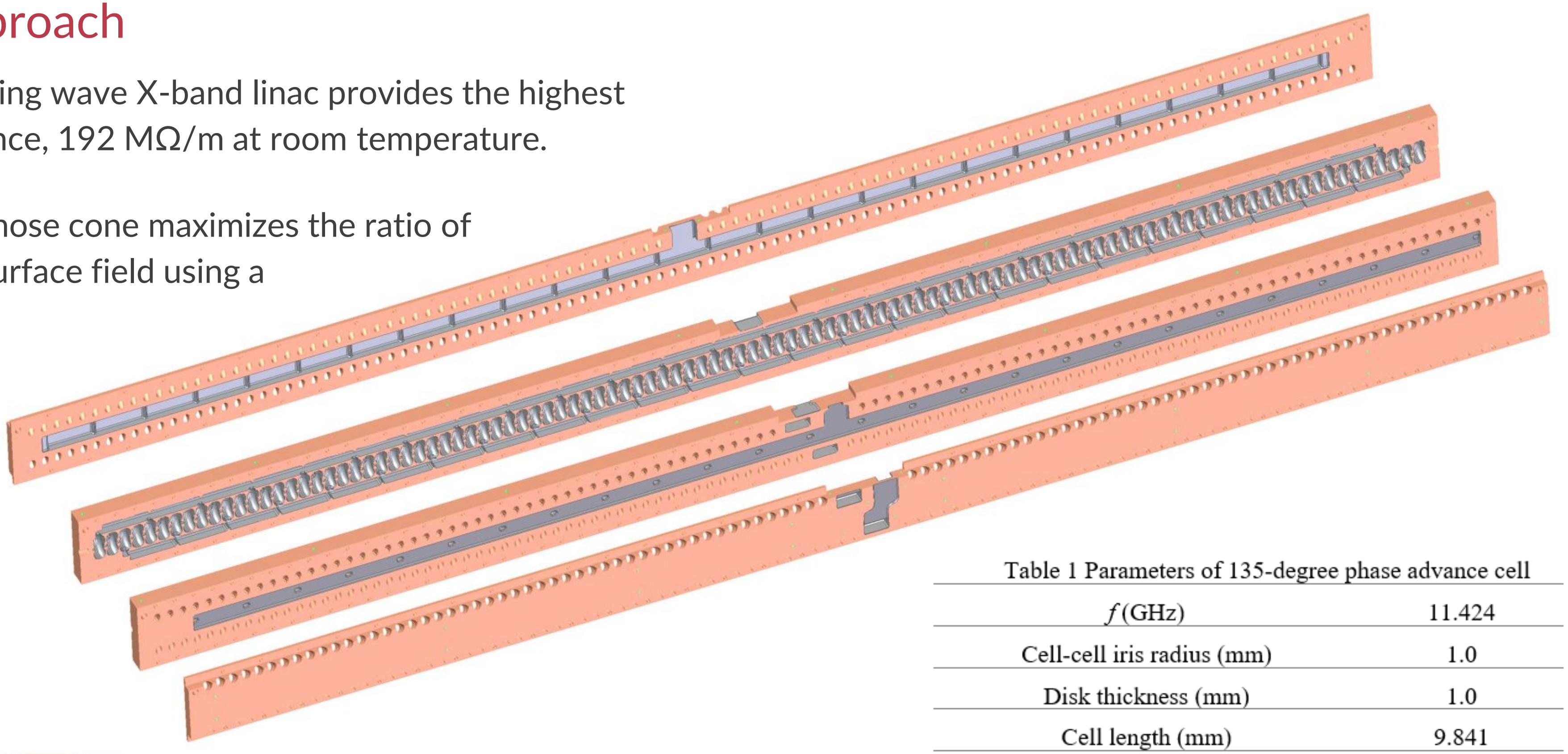
Nasr, M., et. al, 2021. Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature. *PRAB*, *24*(9), p.093201.

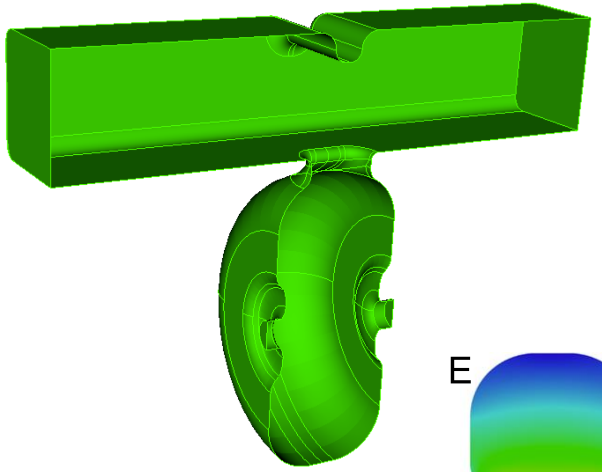
Program Objective: Deliver 100 MeV electron beam from 1 m accelerator at dose rate of ≥40 Gy/s using an accelerator design and power supply that is compatible with existing clinical infrastructure

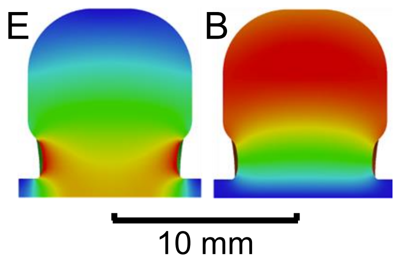
135° Phase Advance Linac

Distributed Coupling Approach

- 135° phase advance of this standing wave X-band linac provides the highest possible geometric shunt impedance, 192 MΩ/m at room temperature.
- Cavity geometry with re-entrant nose cone maximizes the ratio of on-axis accelerating gradient to surface field using a geometric optimization approach.







- Coupling iris and waveguide features optimized using SLAC's parallel ACE3P solvers for the correct transfer S-matrix and coupling for a beam-loaded cavity.

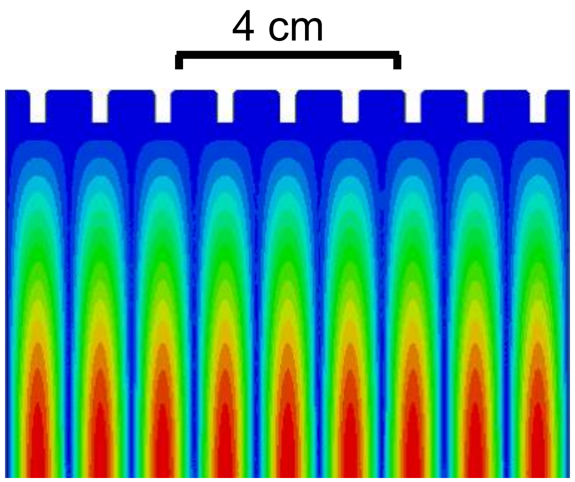
Table 1 Parameters of 135-degree phase advance cell

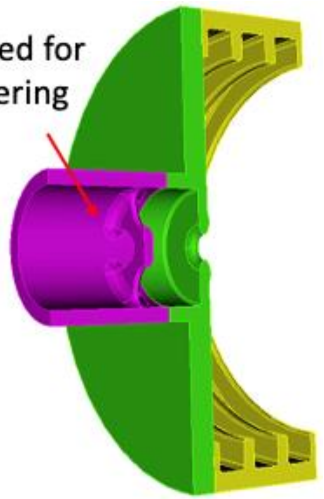
f (GHz)	11.424
Cell-cell iris radius (mm)	1.0
Disk thickness (mm)	1.0
Cell length (mm)	9.841
Operating temperature (K)	77
Q0	22146
Shunt impedance R (MΩ/m)	526
Es/Ea	2.0
Hs/Ea (kA/m/(MV/m))	2.06
Coupling beta	1.8

Compact RF pulse compression

Powering the FLASH-VHEE linac

- Same principle as original SLED, now with two polarized modes in a single high-Q cavity
- HE_{11}-mode in the corrugated cylindrical cavity (right) achieves a Q_0 of 405,000 with a cavity length of 0.87 m.

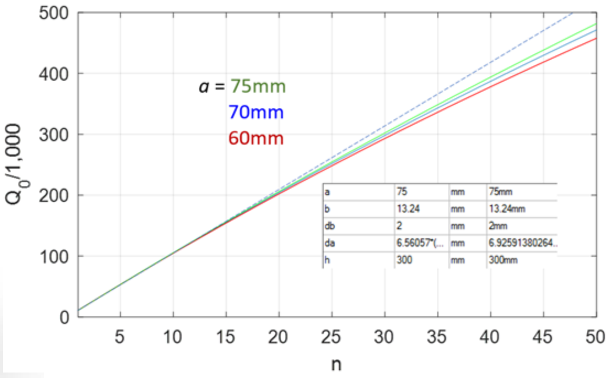




K200 Solid State Modulator System from ScandiNova

- 11.424 GHz
- Peak power 6 MW
- Pulse length 4 µs

	Unit	Klystron	
RF Peak Power	MW	6	
RF Average Power	KW	10	
Modulator Peak power	MW	20.1	
Modulator Average power	kW	49.5	
Operational Voltage range	kV	193	
Operational Current range (incl 10% marg	A	115	
PRF range (min/max)	Hz	1	400
Pulse length (top)	µs	0.1	4.0
Top flatness (dV)	< +/- %	1.00	
Rate of rise (min/max)	kV/µs	100	150
Amplitude stability	< +/- %	0.01	
Trig delay	µs	~1.2	
Pulse to Pulse time jitter	ns	<±5	
Pulse width time jitter	ns	<±8	



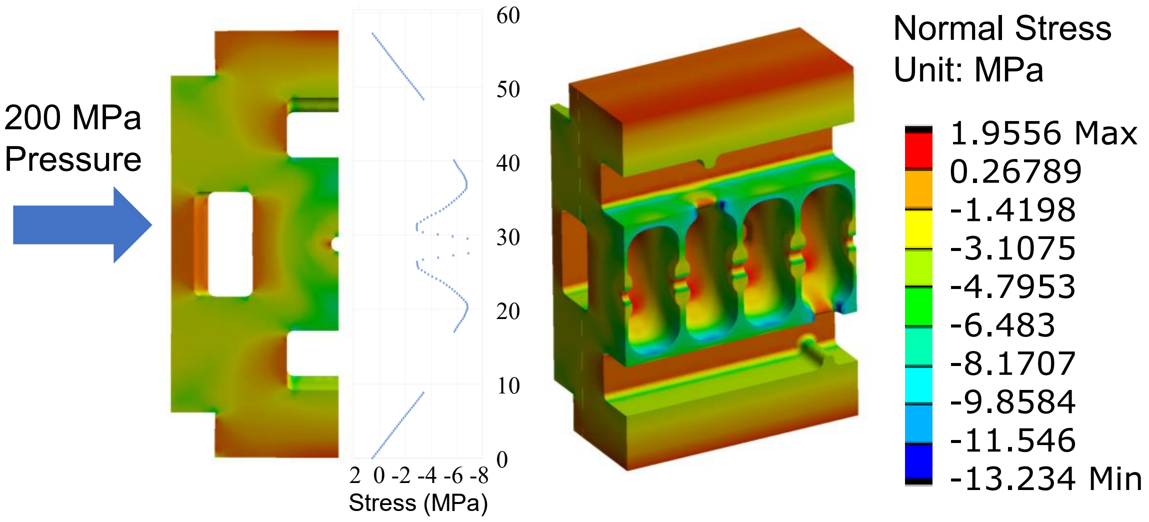
$$Q_0 = \frac{2391.448 a^3 f^{5/2} L}{a^3 f^2 + 121.126 L}$$

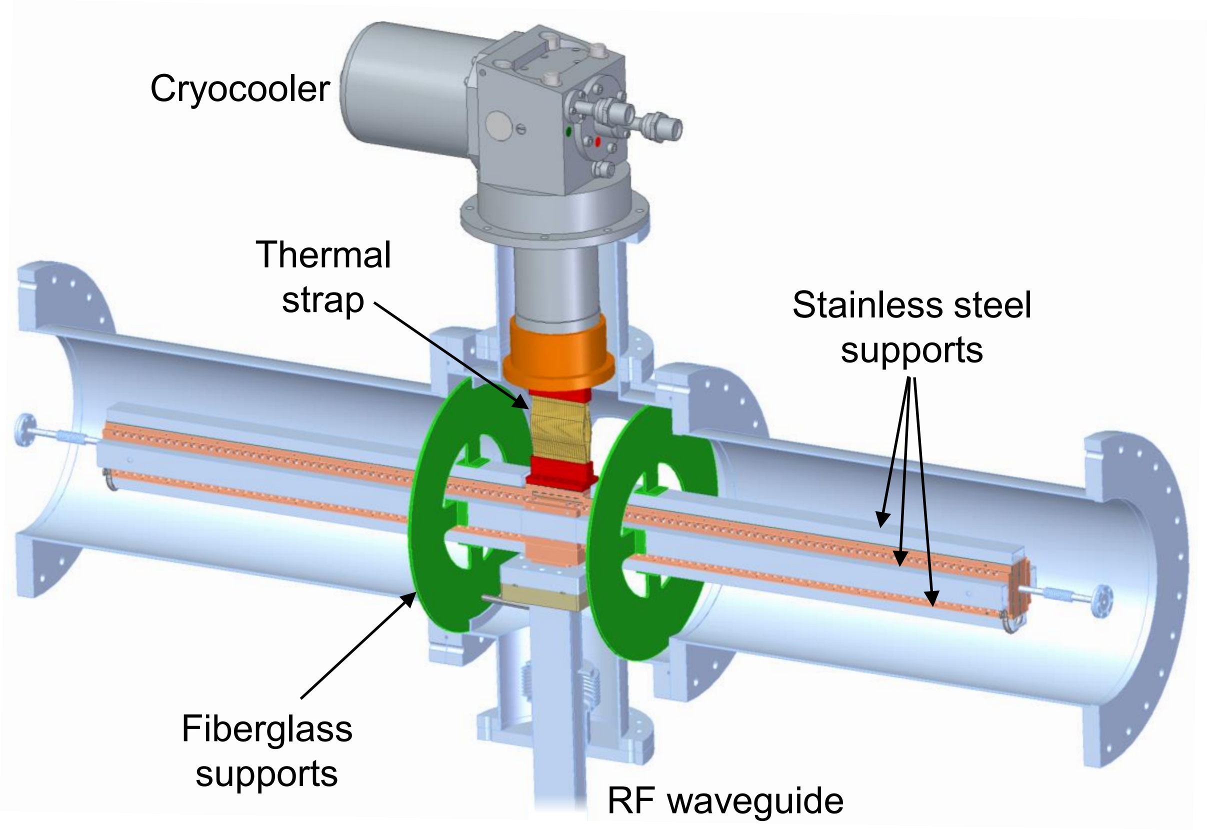
- Coupler designed with an intermediary low-Q TE_{11} cavity (above)
  - small aperture to the compressor minimizes the perturbation to the HE_{11} mode
  - four irises into the low-Q cavity enhance the coupling factor
- Compressed pulse reaches 19 MW peak power in a 200 ns flattop

Mechanical Design

Diffusion bonding

- Linac and power distribution manifolds milled from four 1-meter copper slabs
- Stress distribution analysis (below) in one half of the VHEE linac during diffusion bonding
  - variation in normal stress at the interface running through the center of the cavities covers a range up to 8 MPa
  - within the expected tolerance for diffusion bonding





- Schematic of VHEE linac mounted inside cryostat
- Single stage cold head will provide up to 250 W of cooling power at 80 K