Linacs for 100 MeV/u of Ar, Au, B Ions

Sami Tantawi, Valery Dolgashev, SLAC

Larry Phair, Damon Todd, LBL

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U.S. DEPARTMENT OF ENERGY
Office of Science

BERKELEY LAB
Lawrence Berkeley National Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

Background: The state-of-the-art low-beta ion linacs: why they have low gradient

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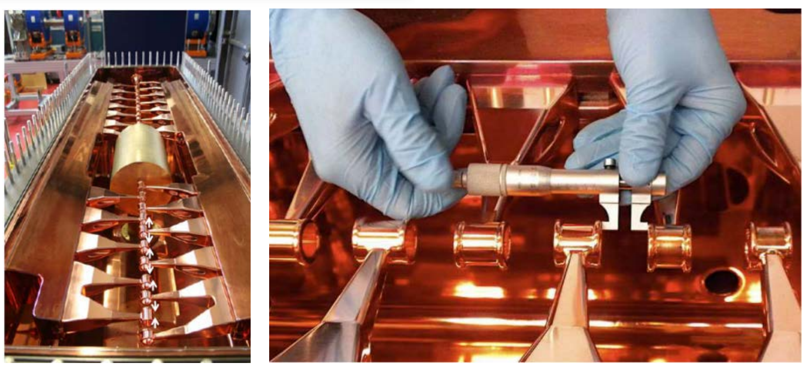
Alvarez Drift Tube Linacs

Alvarez Drift Tube Linac –108 MHz, GSI

High gradient DTLs are impossible for several reasons:

- low rf efficiency at betas up to 0.3;
- focusing elements inside-the-drift-tubes;
- high peak to acceleration field ratio;
- large stored energy in the cavity.



IH structure build by U. Ratzinger (GSI) Group for the BNL EBIS injector, 100 MHz

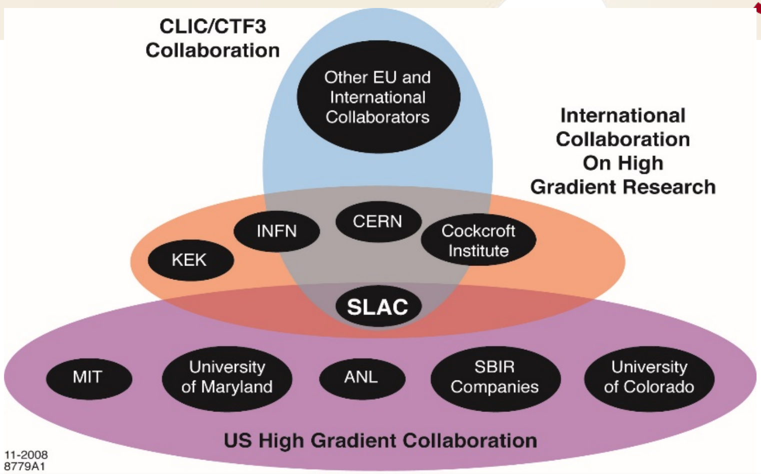
Existing IH structures were never optimized for high accelerating gradients:

- focusing elements reduce accelerating gradient: inside-the-drift-tubes or quadrupole triplets inside cavities
- high peak to acceleration field rati

In 2007 a new collaboration have been formed: The US Collaboration on High Gradient Research

Governance Structure

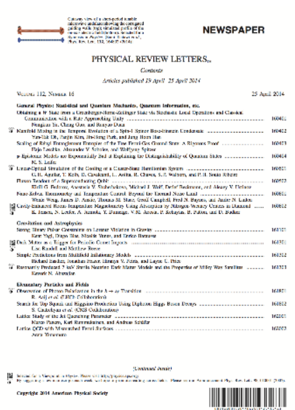
- Spokesperson
  - Sami Tantawi, SLAC
- Advisory Council from across 6 institutions
  - *Ron Ruth, SLAC (initiated)*
  - Richard Temkin, MIT
  - Gregory Nusinovich, UMD
  - Wei Gai, ANL
  - Erk Jensen, CERN
  - Toshi Higo, KEK



Program has fundamentally changed our understanding and the way we design, build, and test high gradient accelerators.

This technology is having a major impact on many applications:

- discovery science machines
- Light sources
- Medical Radiation therapy
- Security applications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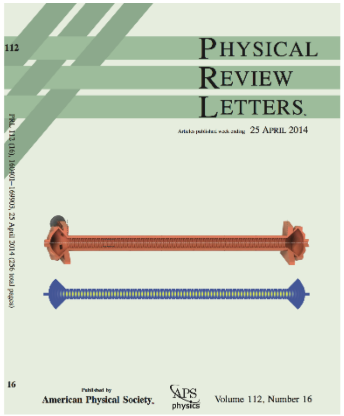
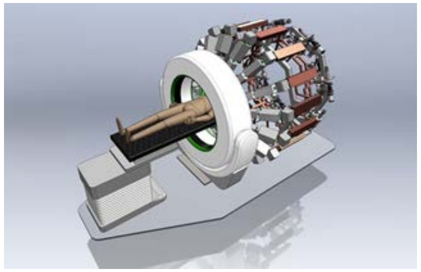
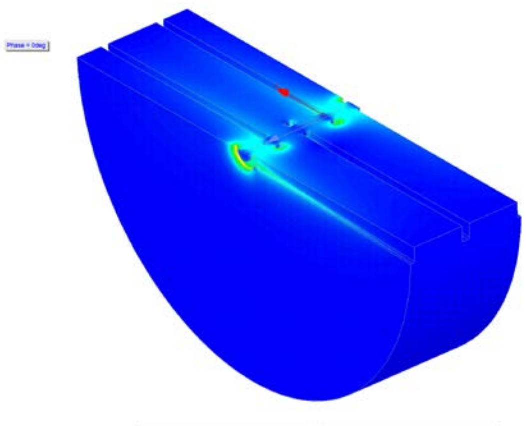




Pluridirectional High-energy Agile Scanning Electronic Radiotherapy (PHASER)

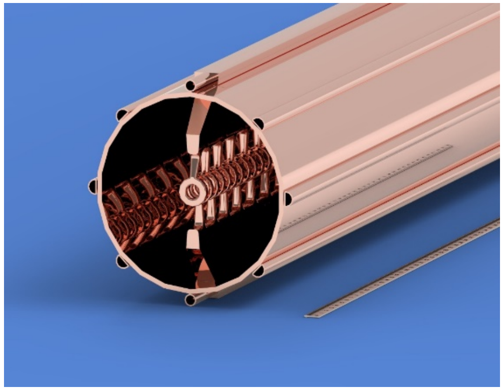
Ion linac with accelerating gradient above 20 MV/m to accelerate ions beyond 100 MeV/u

- High frequency, small outer diameter H-type backward wave traveling wave structure for efficient high gradient acceleration
- Superconducting solenoid for beam focusing of high current beams **or no focusing for a few particle beams**

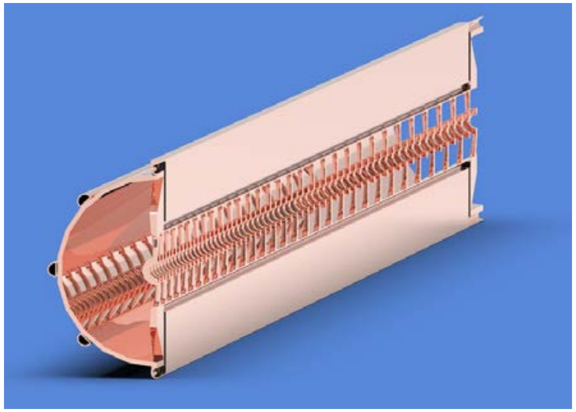


Electric fields in Traveling Wave IH structure

A.S. Bogomolov's talk: Proton Accelerators for Subcritical Nuclear Energy, 2000



IH accelerating structure input



Cooling cirquit

H structures have highest RF power efficiency of any structures at betas below 0.6

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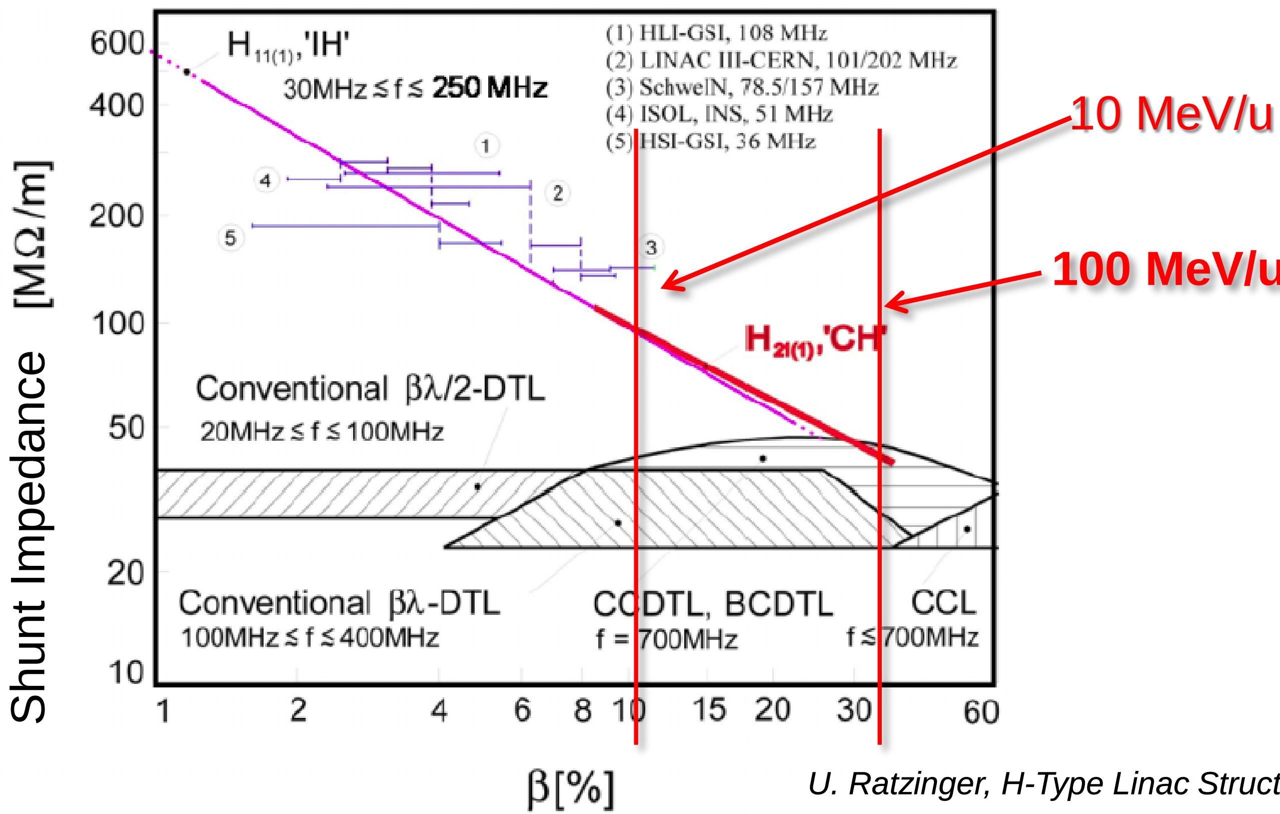
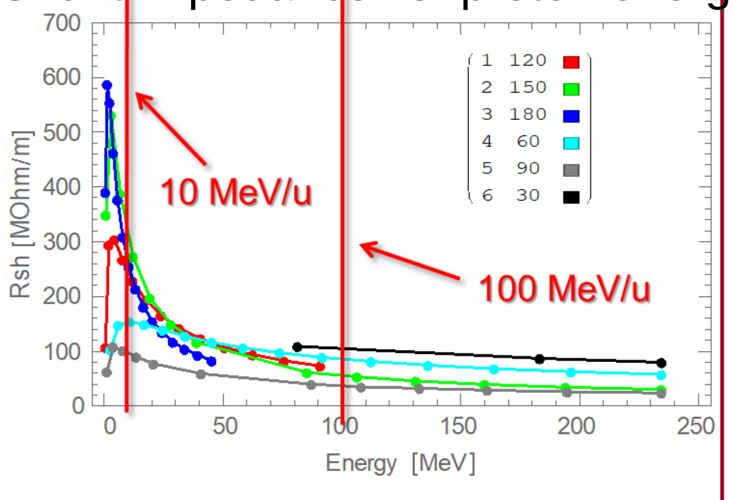


U. Ratzinger, H-Type Linac Structures,CAS 2000

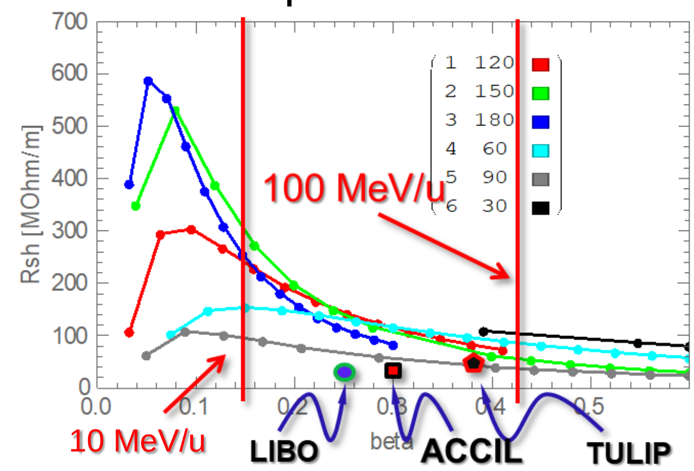
- Shunt impedance characterizes the structure efficiency for converting RF power to accelerating gradient.
- Here traditional ion linacs of different types are compared with Interdigital H-structures (IH) and Cross-Bar-H structures (CH).
- ***From our research, we concluded that higher shunt impedance structures can sustain higher gradients***

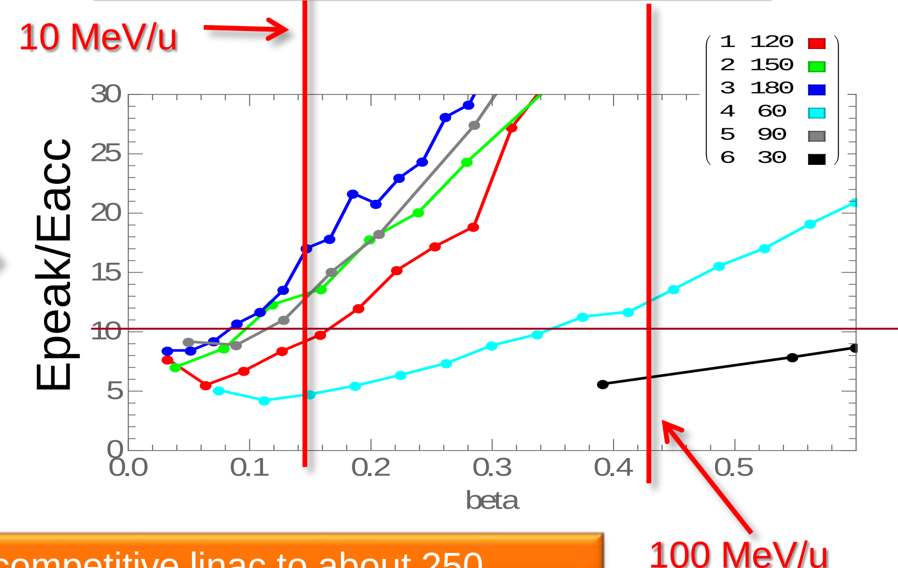
2856 MHz Traveling Wave Proton Linac

Shunt impedance *vs.* proton energy



Shunt impedance *vs.* beta

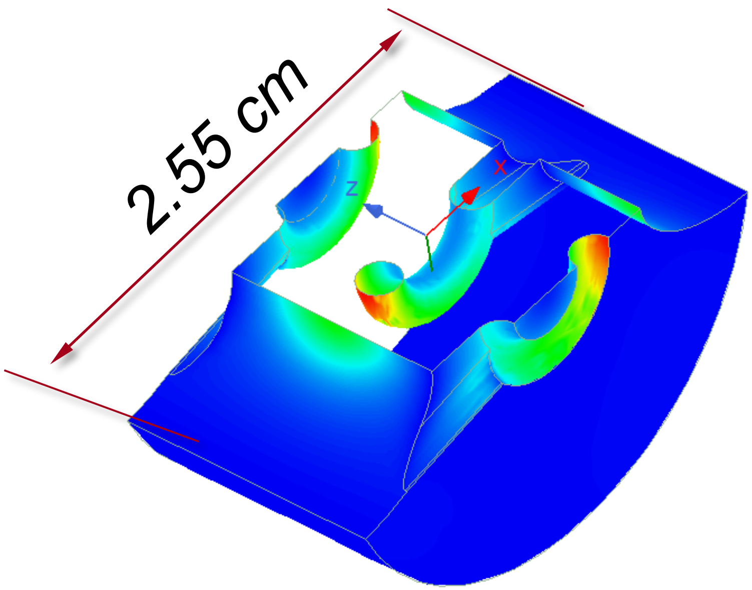




- ,
- Assuming max Epeak ~200 MV/m
- low phase per cell traveling wave linacs
- allow for ~20 MV/m accelerating
- gradient up to 250 MeV/u

Traveling Wave IH structure have higher efficiency then any competitive linac to about 250 MeV/u

Traveling Wave Interdigital-H Ion linac



Traveling Wave opens parameter space that allow highly efficient high gradient low-beta linacs.

Parameter	Value
Beam aperture diameter, 2a	4 mm
Inside diameter, 2b	25.5 mm
Half period, *d*	6.33 mm
Beta	0.14484
Accelerating gradient, Eacc	**20 MV/m**
Peak Surface electric fields, Emax	165 MV/m
Kilpatrick limit	135 MV/m
Ion energy	**10 MV/u**
Peak RF lost power	**3.4 MW/m**
RF power loss at 0.1% duty	34 W/cm
Frequency	2856 MHz
Phase advance per half period	150 deg.
Shunt Impedance	**118 MOhm/m**
Emax/Eacc	8.25
Vg/c	26%
Qo	3800

The combination of SLAC efforts in High gradient and modern design tools for IH structure could lead to extremely efficient high gradient Ion Linac

SLAC

High Gradient Low-β Structures

radiabeam SYSTEMS

- Comparison with other hadron therapy linac projects

Structure	ACCIL	TULIP[1]	LIBO[2]	CABOTO[2]	*Possible SLAC design* TW IH, 5pi/6
Ion types	p^+ and $^{12}C^{6+}$	p^+	p^+	$^{12}C^{6+}$	$^{197}Au^{54+}$
Minimum beta	0.30	0.38	0.25	0.65	**0.145**
Frequency, MHz	2856	2998.5	2998.5	2998.5	2856
Structure type	BTW	BTW	SCL	SCL	BTW
Spatial harmonic	-1st	Fund.	Fund.	Fund.	Fund.
Accelerating gradient, MV/m	50	50	10	~15	**20**
Shunt impedance, MΩ/m	32	52	29	100	**118**
Peak electric field, MV/m	160	220	-	-	**165**
Modified Poynting vector, MW/mm²	1.3	1.55	-	-	-
Beam pulse width, μs	1.0	2.5	3.0	3.0	-
Filling time, μs	0.5	0.9	1.5	1.5	0.2
Repetition rate, pps	120	-	200	400	1000

1. S. Benedetti et al."RF Design of a Novel S-band Backward Travelling Wave Linac for Proton Therapy", Proceedings of Linac'14, Geneva, Switzerland p. 992.
2. U. Amaldi et al. "High Frequency Linacs for Hadronotherapy"., Rev. Accl. Sci. Tech. 02, 111 (2009)

Proposed linac with 20 MV/m accelerating gradient, Au^{54+} , B^{3+}, Ar^{11+}, mass-to-charge ratio ~3.6

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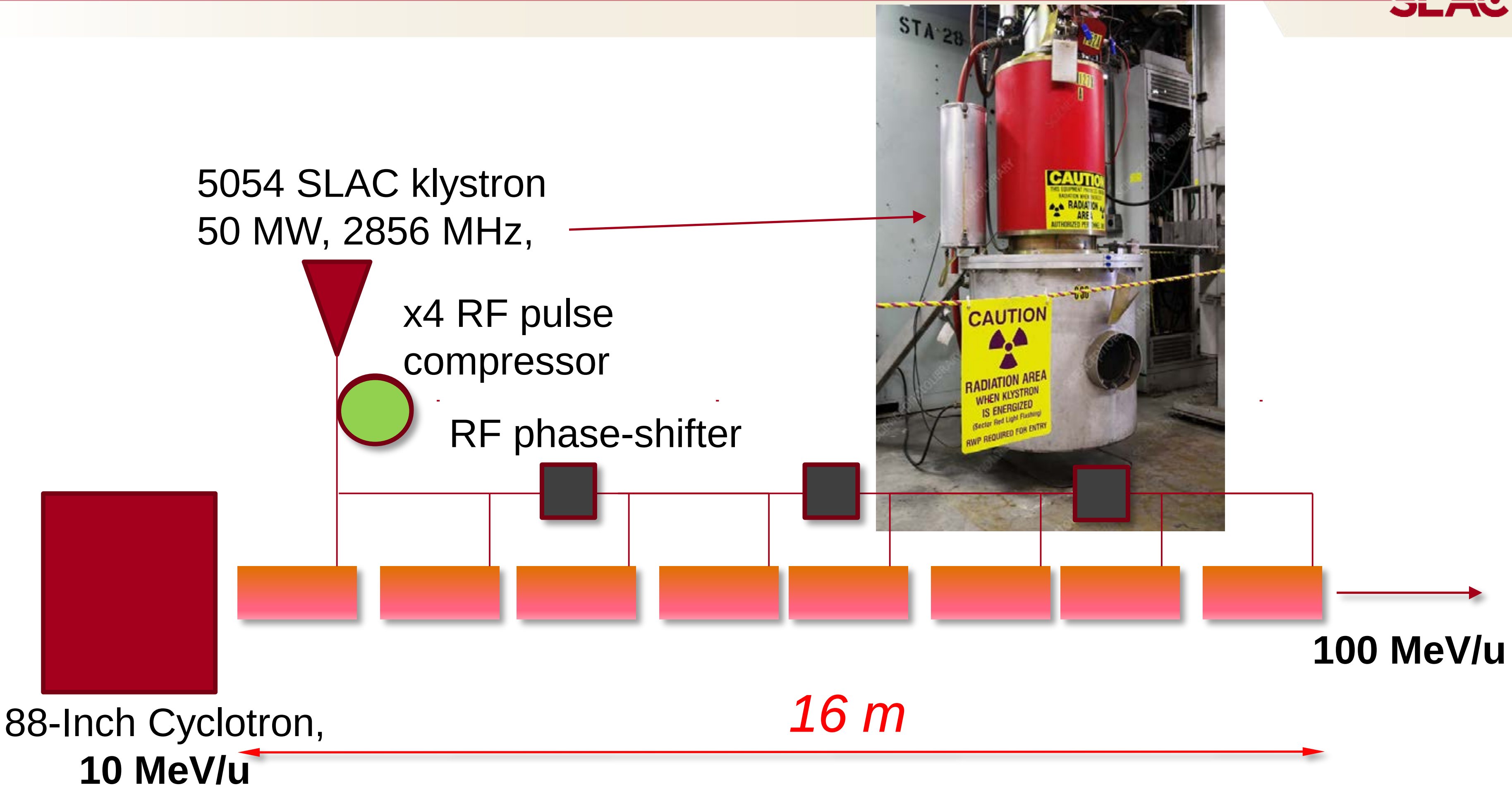


One possible configuration for a compact linac fed by a cyclotron

- Average power from the wall ~ 20 kW
- Cost ~ \$16M-\$20M
- RF source is a ubiquitous klystron (SLAC has been using these for more than 30 years)

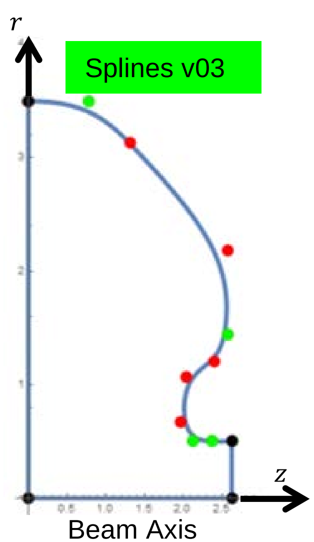
Going to 400 MV/u

- Beyond 100 MeV the speed is high enough; conventional TM01 accelerators are more efficient in this regime.
- At SLAC we invented a new type of accelerator structure that we call the “Distributed Coupling Linac,” that has about twice the sunt impedance of typical structures while capable of sustain extremely high gradients.

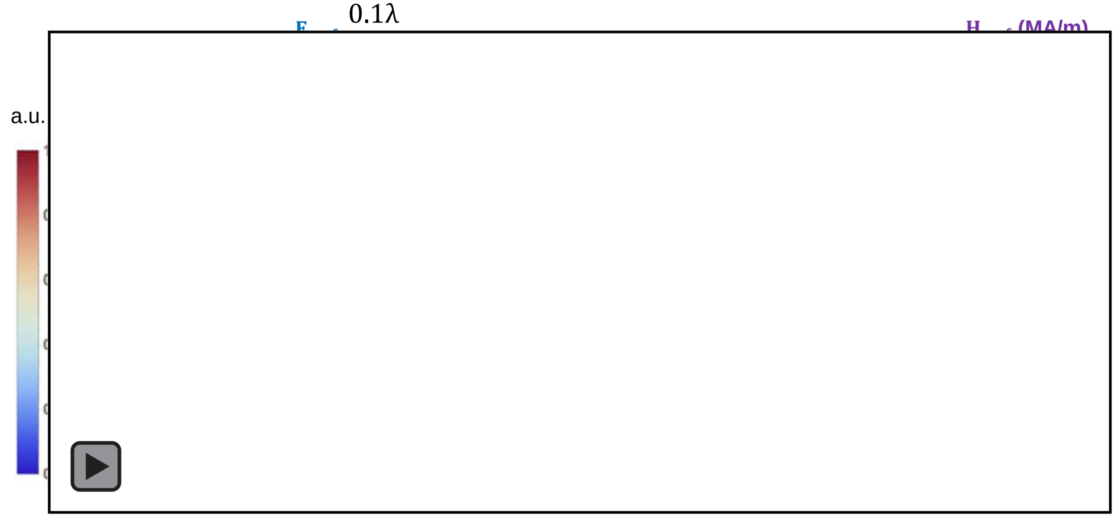
The cavity curvature is defined with a set of control points with variable positions to control splines which describes the cavity shape.

Evolution of an optimization example

X-band, 11.424 GHz, iris diameter 0.1λ



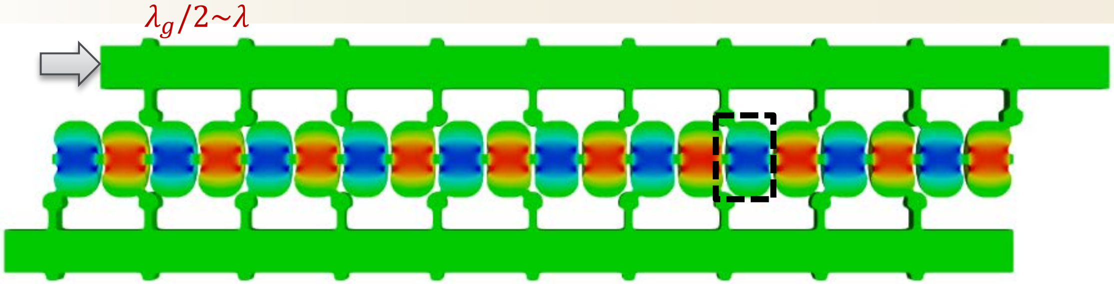
M. Nasr et al. New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities’ Performance, IPAC’18

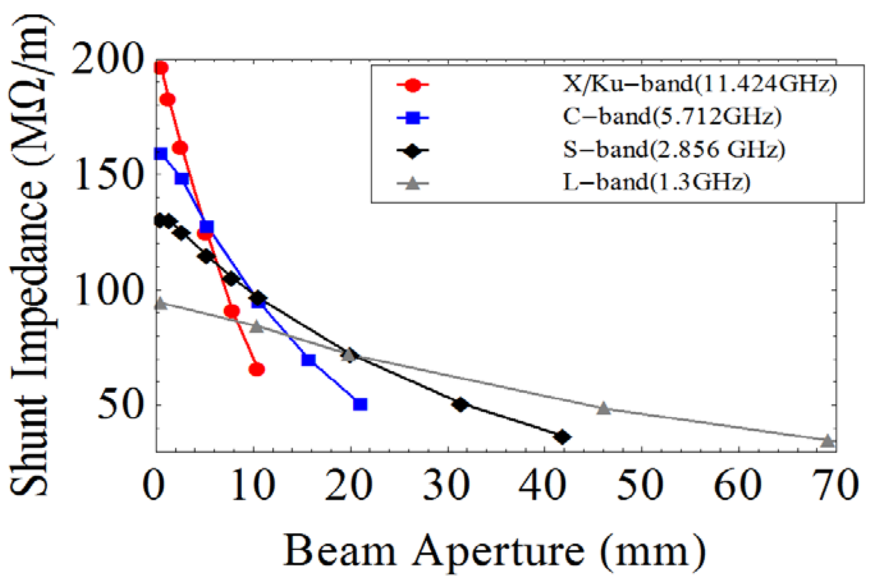


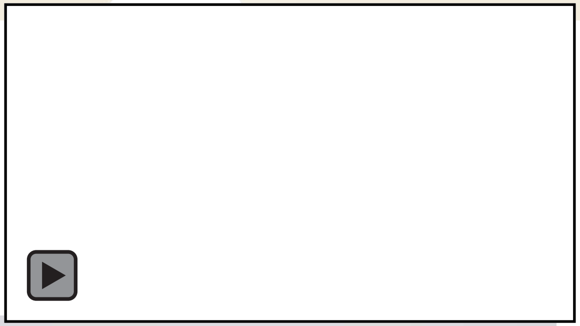
Peak surface field to gradient ratio reduction from 2.5 to 2 with even higher shunt impedance

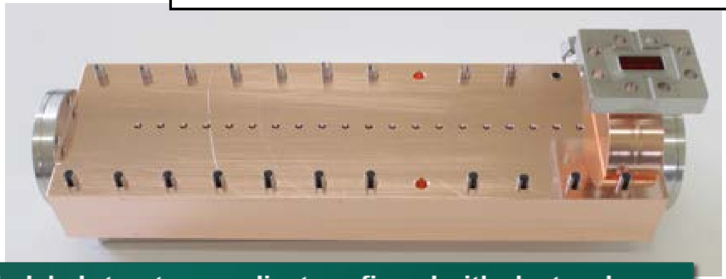
M. Nasr, S. Tantawi

Distributed-coupling: optimized accelerating cell

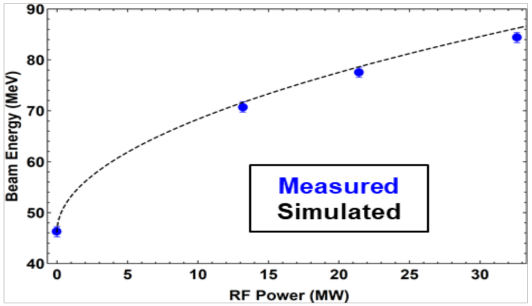


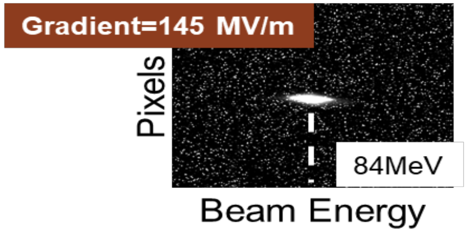






Modeled structure gradient confirmed with electron beam





Sami Tantawi, Mamdouh Nasr, Zenghai Li, Cecile Limborg, and Philipp Borchard, "Design and demonstration of a distributed-coupling linear accelerator structure," Phys. Rev. Accel. Beams 23, 092001 (2020) – Published 10 September 2020.

Summary

The unique parameter space for the ion accelerator, with extremely low current allows an economical high-frequency linear accelerator to accelerate an ion cocktail to energies of 100 MeV / u from a 88-inch cyclotron injection at 10 MeV / u