Applications of e^- Linacs, From Very Low to Very High Energy, and From Warm to SC Technologies

Sami G. Tantawi, and Collaborators

U.S. DEPARTMENT OF ENERGY
Office of Science

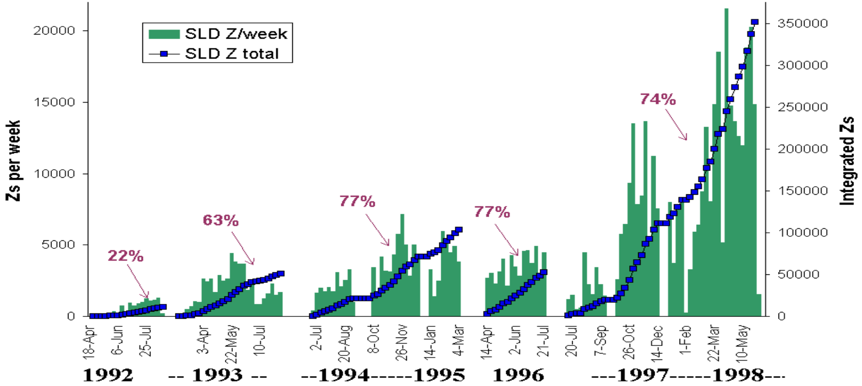
SLAC NATIONAL ACCELERATOR LABORATORY

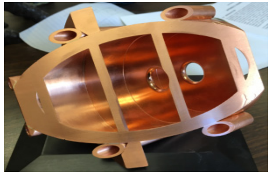
Outline

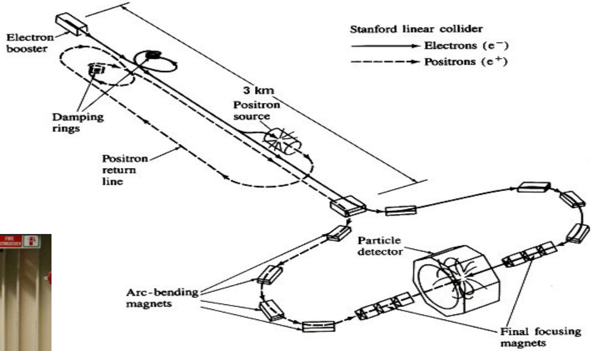
- Big science applications
  - Linear colliders
  - 4th generation light sources
- Advances in linear accelerator technology
  - High gradient phenomena
  - Distributed coupling accelerator structures.
- Applications Impacted by recent linear accelerator technology developments
  - Security applications
  - Compact light sources
  - EUD/EUM
  - **Medical linacs for radiation therapy**

SLAC Linear Collider (SLC): First Linear Collider for HEP

SLC construction: 1982-1987
SLC operation: 1987-1998
Z^0 Meson (**45.6 GeV e- x 45.6 GeV e+**)
Luminosity reached 3 x 10^{30} /cm^2/sec
~4x10^{10} particles per bunch at 120 Hz
80 % average e- polarization
About 0.7 million Z^0s produced
MARK-II and SLD detectors



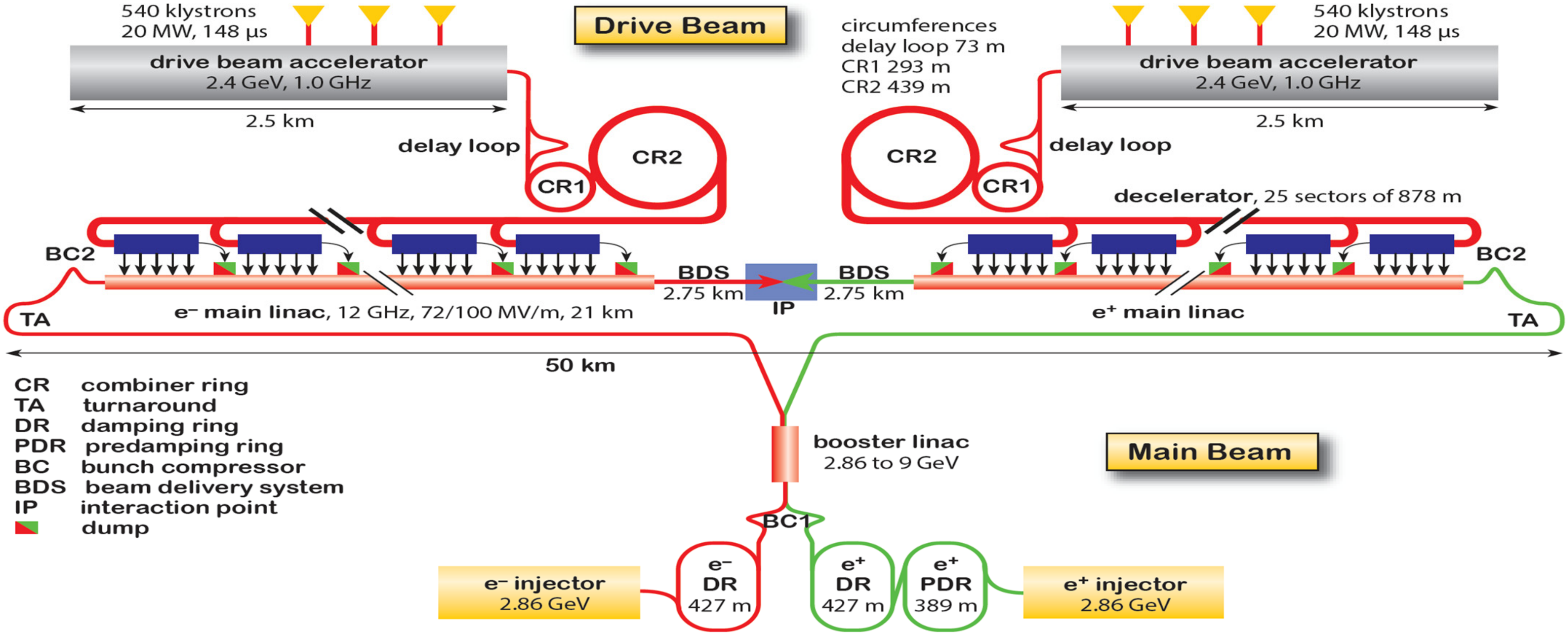




SLAC linac

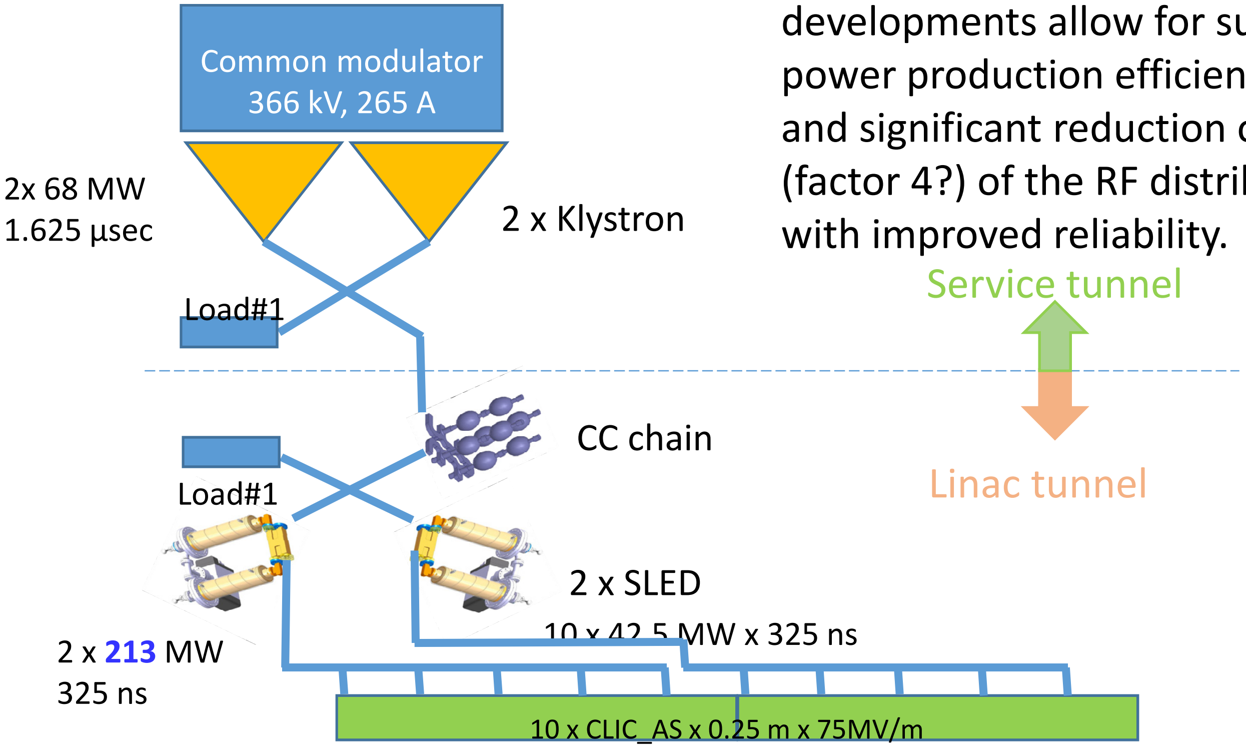
SLD Detector

CLIC layout at 3 TeV

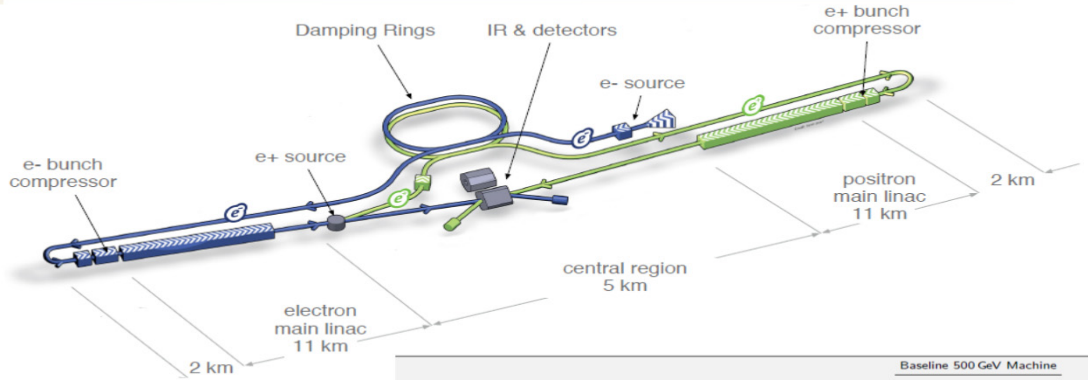


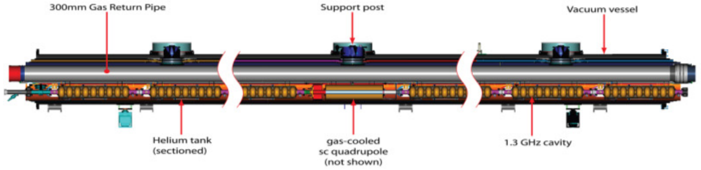
New CLIC’k RF unit layout

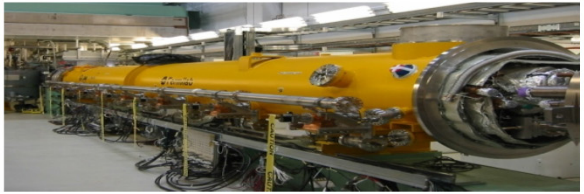
In a given (not yet optimised) example, the resent developments allow for substantial increase of RF power production efficiency (from 21.8% to 30.5%) and significant reduction of the complexity and cost (factor 4?) of the RF distribution system together with improved reliability.



Linac Applications-Big Science-ILC





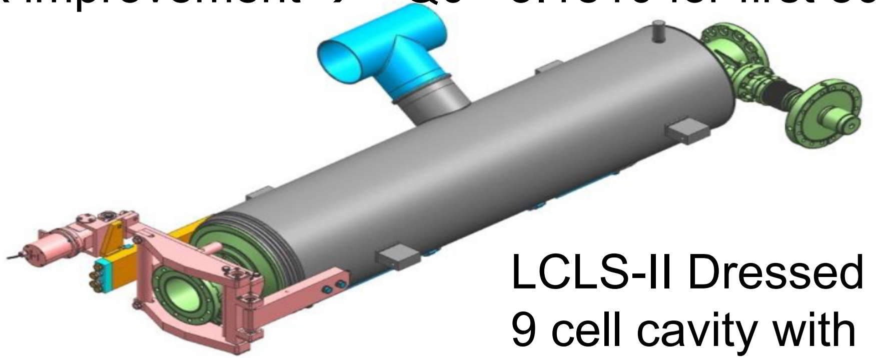


			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade A	E_{CM} Upgrade B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ $cm^{-2}s^{-1}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

Ultra-low cryogenic loss (High Q0) from N2 doping
Developed at Fermilab (Grassellino, 2012)

→ industrialized ←

3x improvement → <Q0> 3.1e10 for first 80 cavities

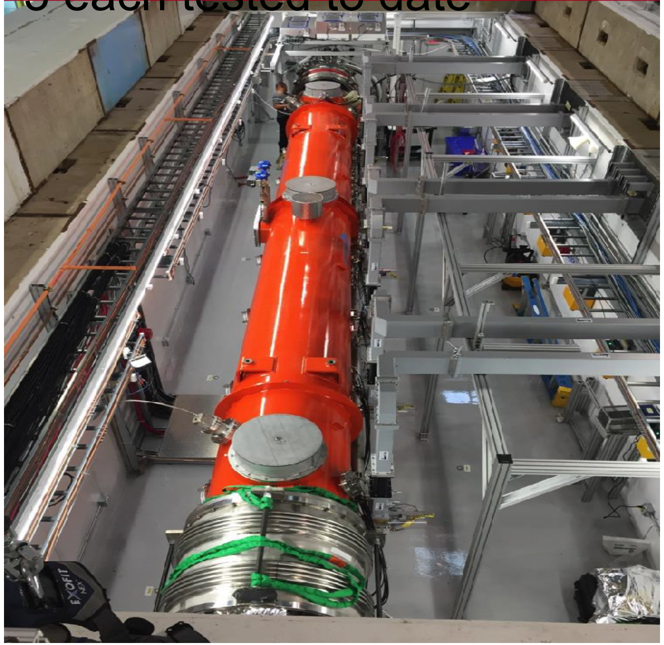


LCLS-II Dressed
9 cell cavity with
coupler and tuner

Cryomodules are assembled
and tested at both Fermilab
and Jefferson Lab
→following XFEL scheme ←

CM02 complete and at CMTS1

3 each tested to date



CM test results:

Q0; E_acc meet expectations

3.0 e10 and 19 MV/m

Each facility will produce 1CM/6 weeks until fall 2018

LCLS-I (2009) and LCLS-II (2020)

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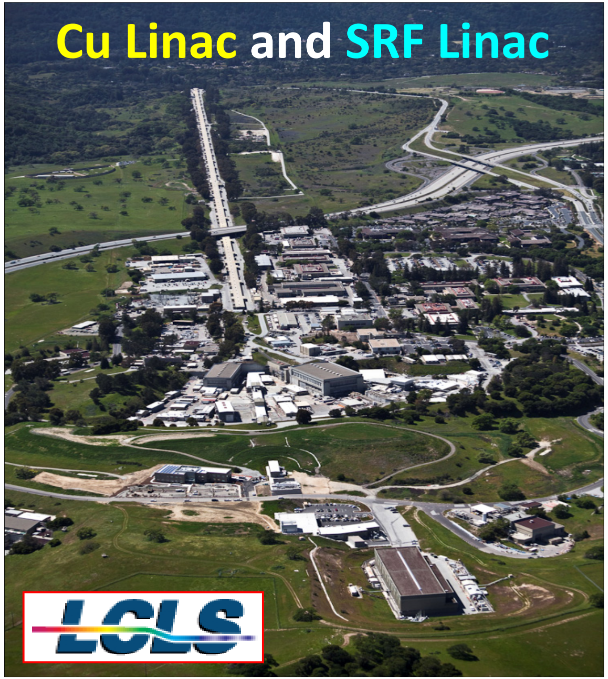

LCLS-I (uses 1-km existing SLAC linac)

- Repetition rate = **120 Hz**
- Electron energy = **3 - 15 GeV**
- Photon energy = **0.3 - 11 keV**
- X-ray pulse length = **5 - 500 fsec**
- Operations: **2009 - 2017**

LCLS-II (2 FELs, 2 Linacs, CW-SRF)

- Repetition rate = **1 MHz**
- Electron energy = **4 GeV** & **3-15 GeV**
- Photon energy = **0.2 - 25 keV**
- X-ray pulse length = **5 - 200 fsec**
- Operations: **2019 - ?**

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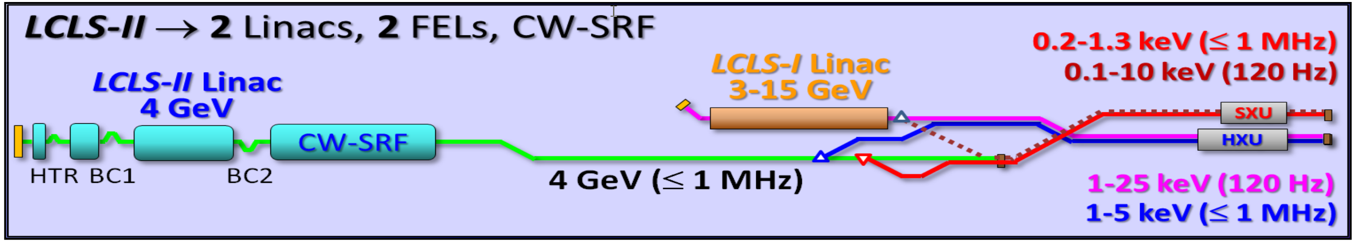
Fermilab



Planned/Existing X-ray FELs

- ***FLASH at DESY***, De (4.2-51 nm) (2001)
- ***LCLS*** at ***SLAC***, USA (0.11-4.4 nm) (2009)
- ***Fermi*** in *Trieste*, Italy (4-80 nm) (2010)
- ***SACLA*** at ***SPring-8***, Japan (0.1-3.6 nm) (2011)
- ***PAL-XFEL*** in ***Korea*** (0.1-10 nm) (2016)
- ***Swiss-FEL*** at ***PSI***, Ch (0.1-7 nm) **2017**
- ***European X-FEL*** at ***DESY***, De (0.05-6 nm) **2017**
- ***LCLS-II*** at ***SLAC***, USA (0.05-6 nm) **2019**
- ***XFEL at Shanghai***, China (0.1-1 nm) ? **202?**

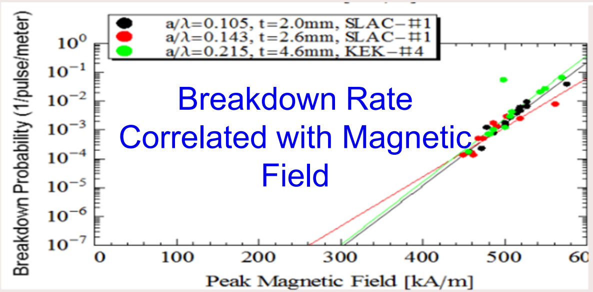
Core Areas of Research for the Advancement of RF Accelerator Technology

SLAC

Physics of Breakdown

Discovery of Magnetic Field's Role in Breakdown Triggered New Research Initiative

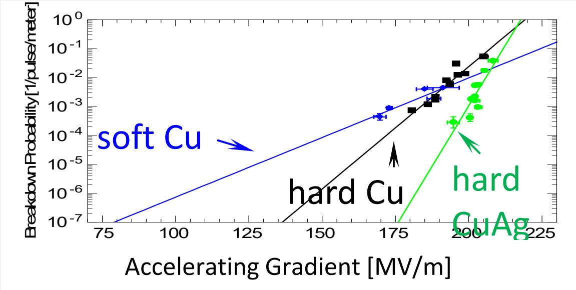
- Achieved through studies of surface electric and magnetic fields, processing techniques, surface finish



Materials Science

Investigate Materials to Improve the Performance of High Gradient Accelerating Structures

- Enhanced performance with increasing material strength
- Low temperature operation also increases the



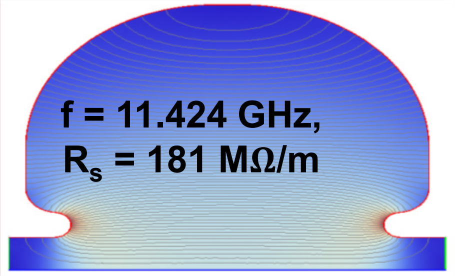
Innovative Electrodynamics

Geometry of Accelerating Structures Optimized Accounting for:

1. ***Our New Understanding of the Physics of Breakdown (magnetic fields, materials etc.)***

AND

2. ***The Beam Parameters Required for a Specific***

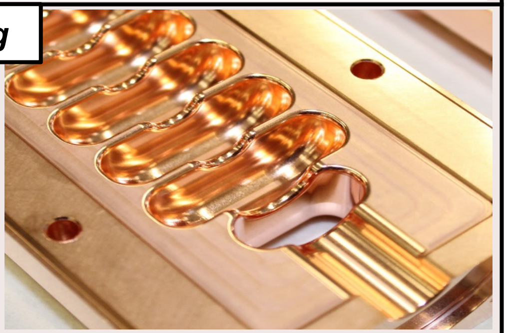


Geometry optimizations for accelerator structures based on reduction of the magnetic surface field

Manufacturing Engineering

Manufacturing Techniques that are Compatible with Superior Materials and Unique Geometries

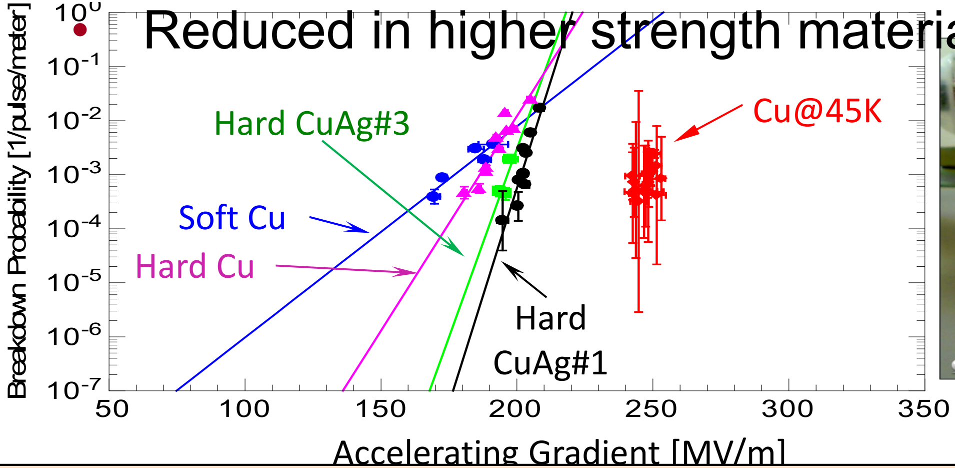
- Low temperature assembly with clamped structures and welding
- Split-block machining for increased flexibility in fabricating advanced structures and reducing

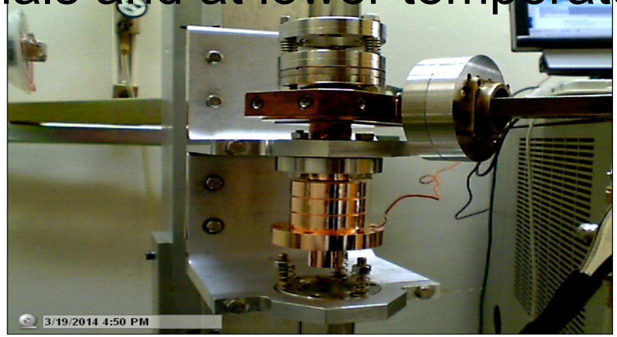


Novel split-block assembly for novel gap accelerator

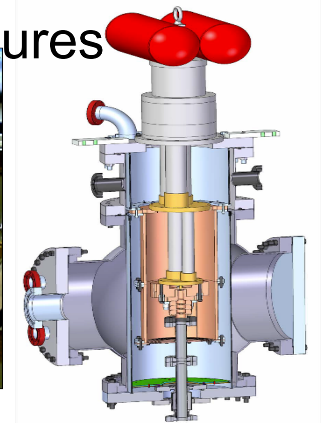
Understanding the Physics of Breakdown at High Gradients has Established the Limits Normal-Conducting Copper Structures

- Material properties determine the performance of accelerating structures at high gradient
- Dislocations caused by stress from fields form protrusions
- Reduced in higher strength materials and at lower temperatures





Bead Pull Test

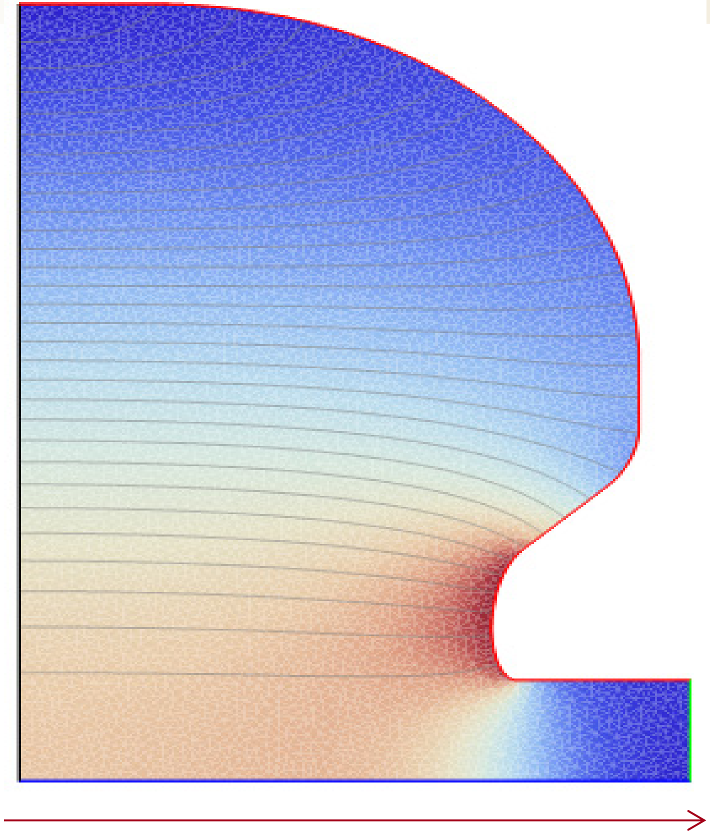


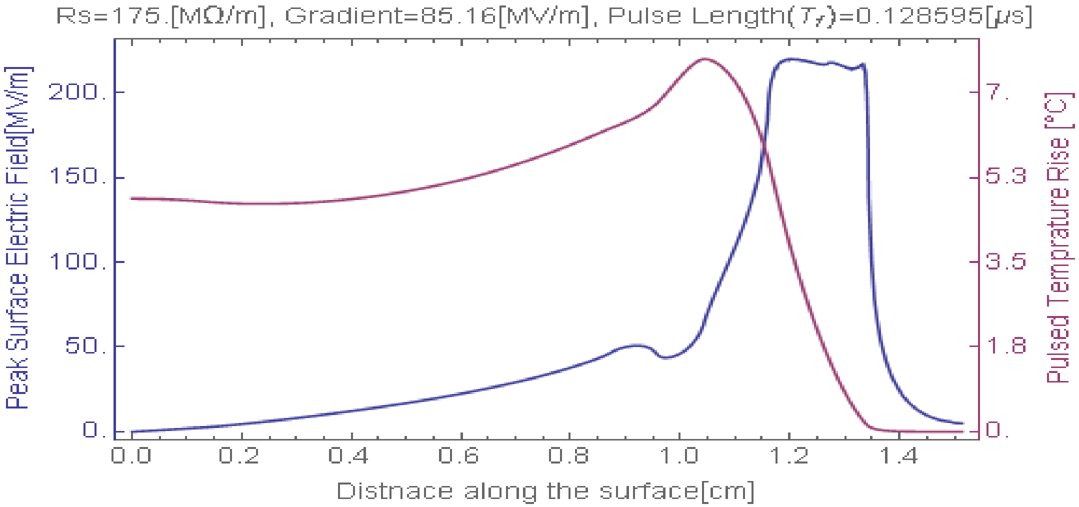
Cryostat assembly

- Controlling material properties for accelerating structures has produced dramatic improvements in the achievable accelerating gradient

V. Dolgashev, S. Tantawi

Optimization of cavity shapes



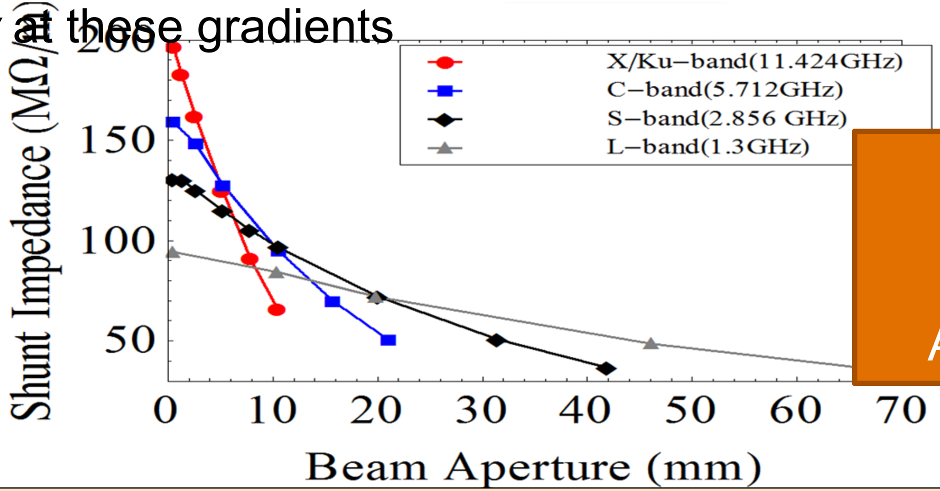


e Beam

Highly Optimized Standing-Wave Structures with Distributed Feeding Allow for New Possibilities

SLAC

- Distributed coupling, split-block fabrication, high-shunt impedance and suppression of breakdown combine to form new architecture for future facilities
- Cost effective implementation of accelerator structures capable of operating *efficiently* at these gradients



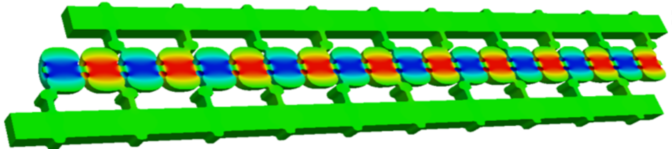
New Scaling Laws Determine the Best Performance for Accelerating Structures

- Scalable technology with enhanced shunt impedance capable of reaching high duty factors

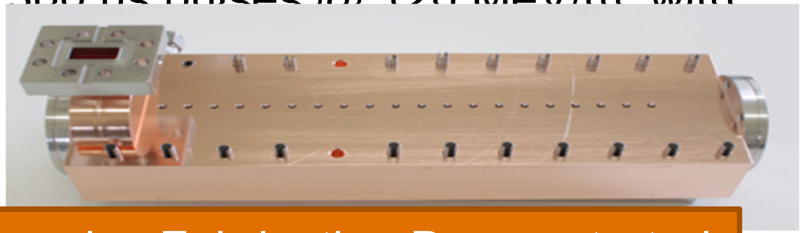
S. Tantawi

Novel Distributed Coupling to Each Accelerator Cell Enables *Doubling* RF to Beam Efficiency and Ultra-High-Gradient Operation

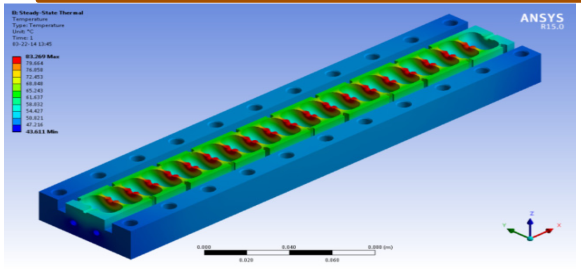
- Structure is much more efficient, easy to build and tune
- Successful High-Gradient Demonstration: 300 ns pulses @ 120 MeV/m, with ter ~50 hours



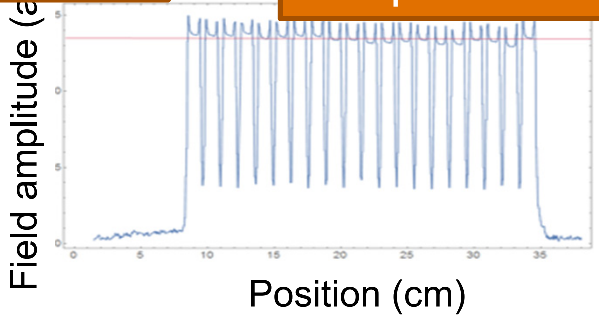
Distributed Coupling to Each Cell



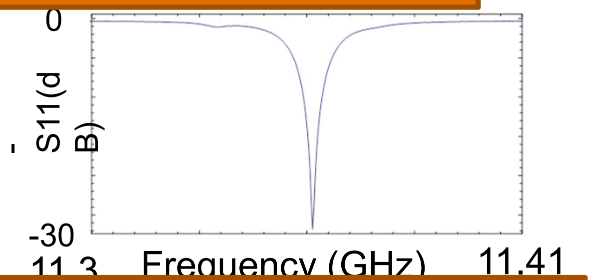
Inexpensive Fabrication Demonstrated



Solid-Model of Split-Block Assembly



Easy Tuning

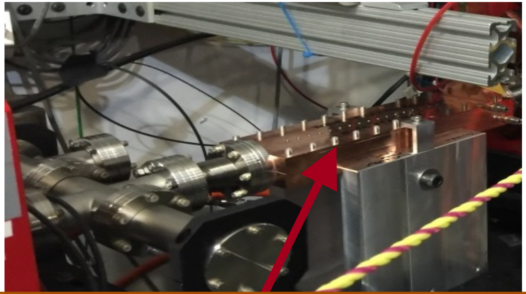


Single frequency rather than the traditional 20 resonances

- Only possible through modern virtual prototyping using high power computing

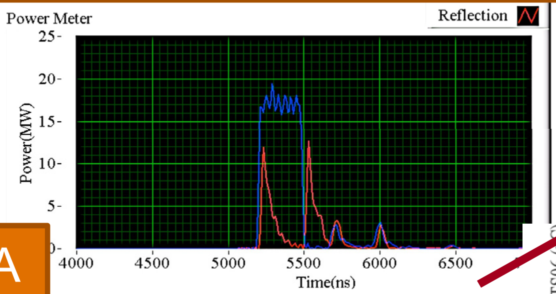
S. Tantawi, P. Borchard, Z. Li

Split Structure Accelerates Beam and Operates at High Gradient Demonstrating the Predicted Shunt Impedance

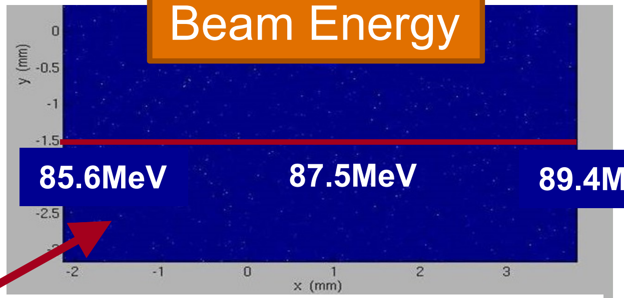


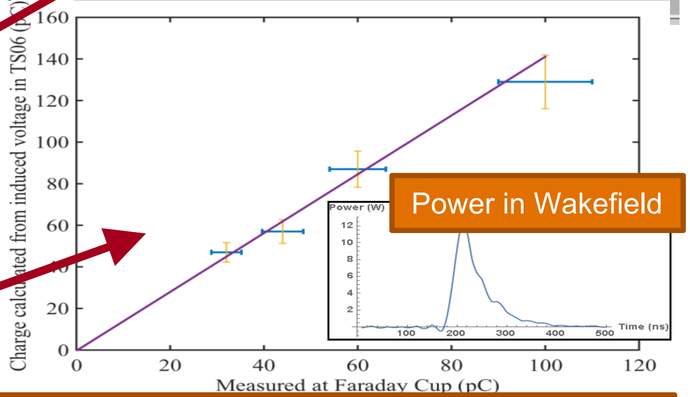
26 cm structure installed at XTA

Forward and Reflected Power



Beam Energy





Power in Wakefield

Measured Charge with Faraday Cup and Calculated from Induced Wakefield

- Confirmation of gradient by measuring 24 MeV energy gain
- Operating with ~100 MeV/m gradient with 16.5 MW of input power and 300 ns pulse length
- Additional confirmation of RF performance by measuring wakefield power to determine charge

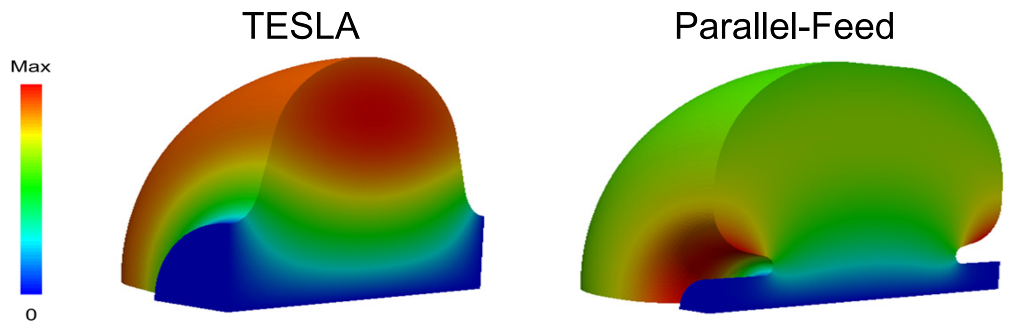
- The structure is being processed at XTA to go beyond 120 MeV/m

S. Tantawi, C. Limborg, A. Cahill, M. Nasr

Adapting the NC X-band Structure for SC L-band

	1.3 GHz TESLA	1.3 GHz Parallel-Feed
R/Q	984	2570
E_{surf}/E_{acc}	2.0	5.3
B_{surf}/E_{acc}	4.2	4.0
P_{loss}	101	43
Q_0	1.0e10	0.91e10

Magnetic Field Simulations

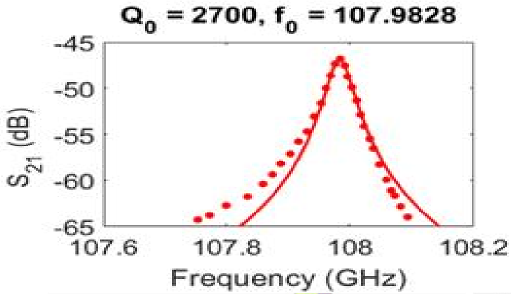


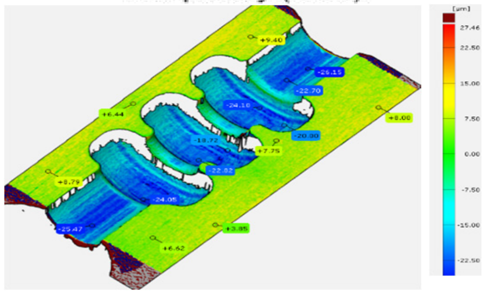
- X-band structure optimized for efficiency (high shunt impedance)
  - Translated to L-band with bulk-Nb surface resistance, dynamic RF cavity loss reduced by nearly 60% versus TESLA cavity.
- Surface magnetic fields reduced 5% for the same gradient. However:
  - Larger "packing ratio" possible with parallel-feed structure → active accelerating length is greater percentage of total length.
  - Utilizing multi-frequency acceleration will enable even higher gradients (> 70 MV/m) for the same max surface magnetic field.

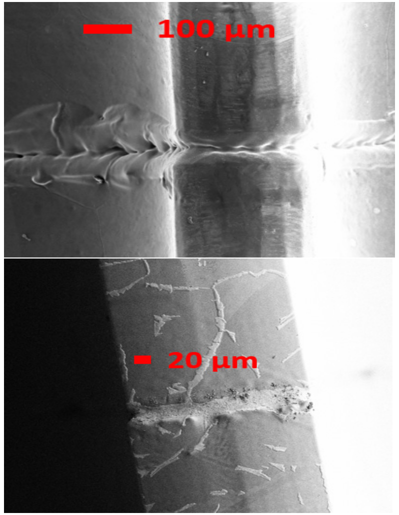
Modern Tools for Fabrication of mm-Wave Standing-Wave Accelerating Structures

- CNC machining tool provide rapid fabrication of prototype mm-wave accelerating structures
- <50 nm is state-of-the-art positional accuracy
- Unique approaches n… structu…

Standing-Wave Accelerating Structure @ 110 GHz





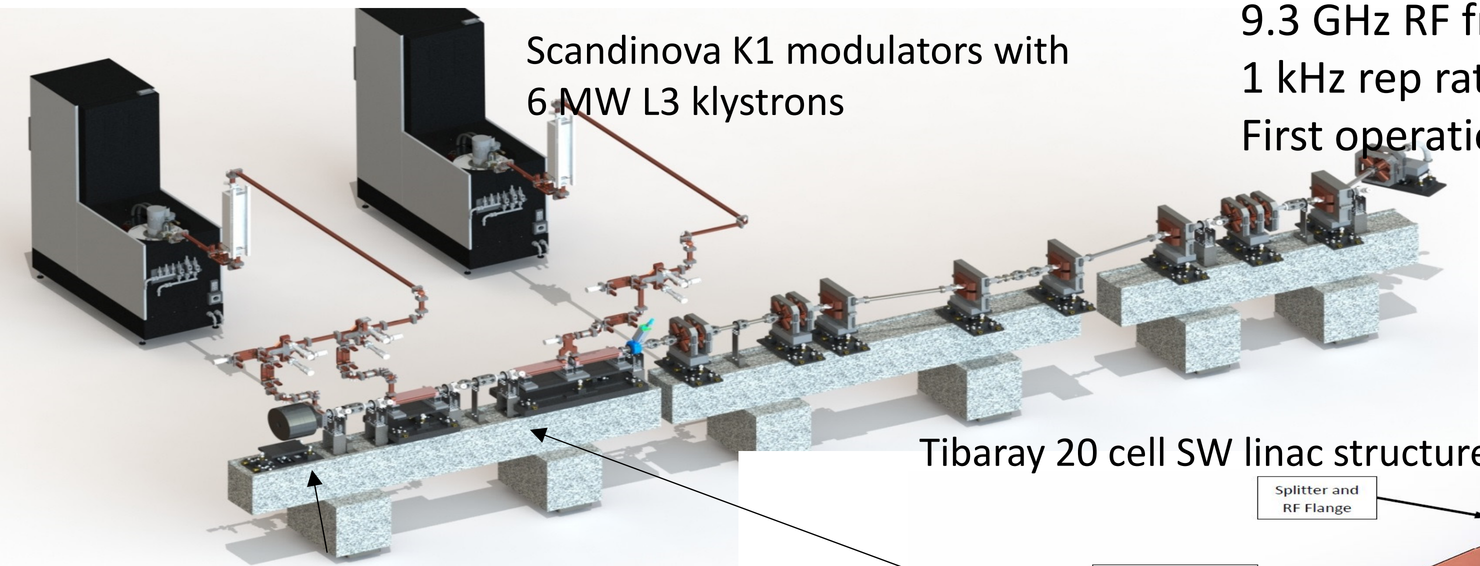


E. Nanni, V. Dolgashev

ASU Compact X-ray Light Source

9.3 GHz RF frequency
1 kHz rep rate @ 100 pC
First operations Fall 2017

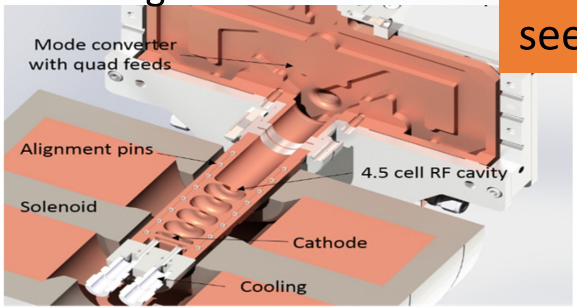
Scandinova K1 modulators with 6 MW L3 klystrons

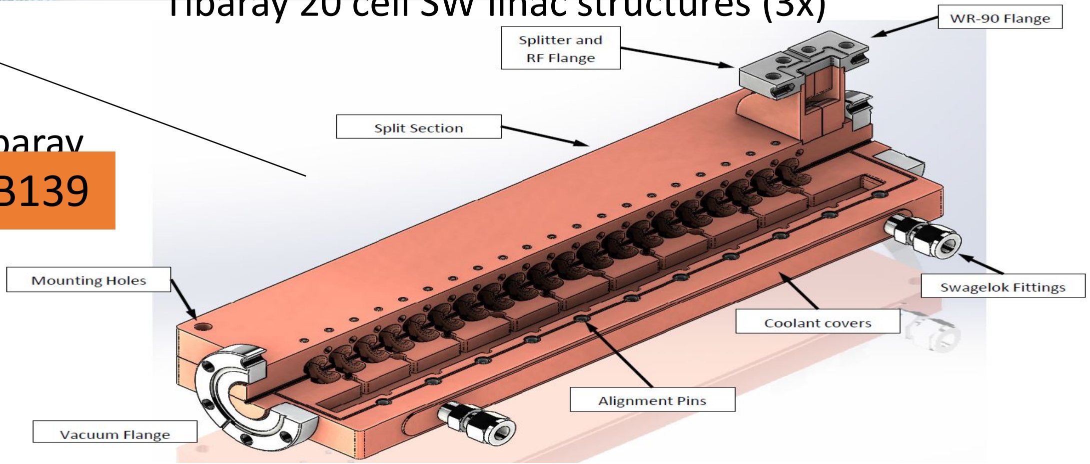


Tibaray 20 cell SW linac structures (3x)

4.5 cell SW gun structure developed with Tibaray

see TUPAB139

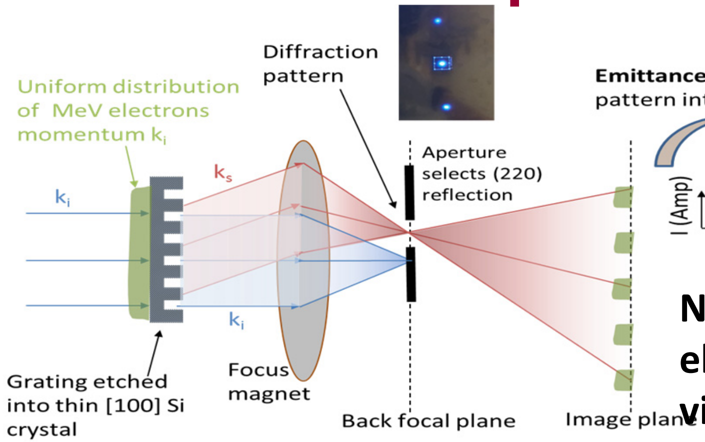




ARIZONA STATE UNIVERSITY

W.S. Graves, April 2017

ASU Compact XFEL: simple upgrade to CXLS

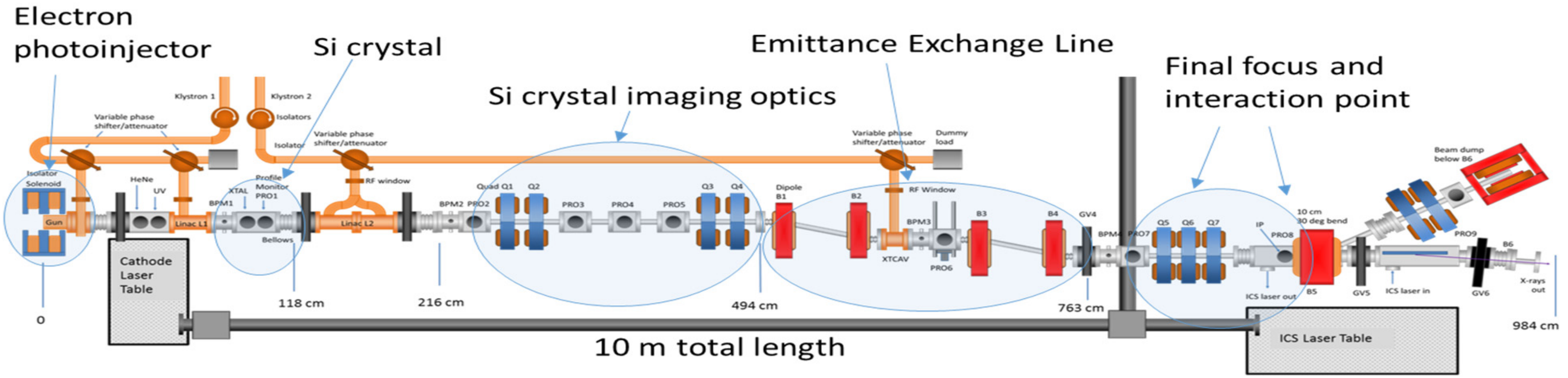


Nano-pattern electron beam via diffraction

Fully coherent phase and amplitude control

Proof-of-principle experiments underway at SLAC and UCLA
See MOPAB150, THPAB088

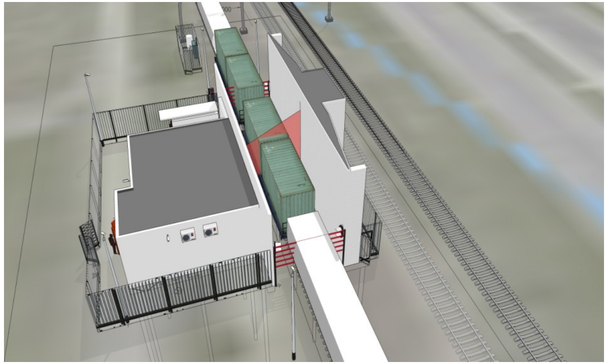
From attosecond pulses to .01% linewidth



W.S. Graves, April 2017

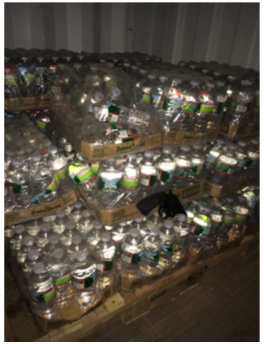
L3 Technologies
Security & Detection Systems

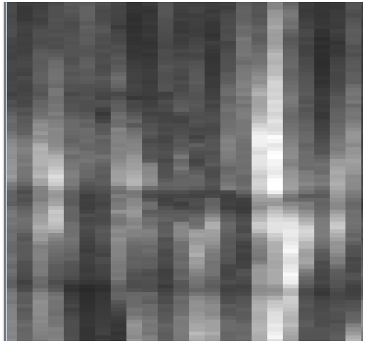
High speed/resolution scanning with SLAC linac



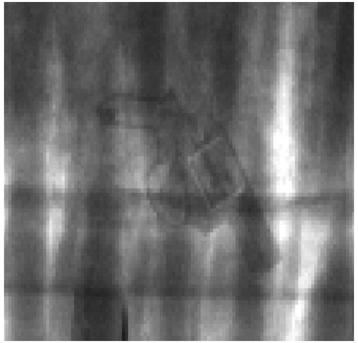
CX-Rail with <u>6000Hz</u>

- High resolution/ high speed
    - 2.5 mm at 30 mph
    - >360mm penetration
- Significant cost reduction over rail inspection systems with multiple detector arrays required by current linacs





400 PPS



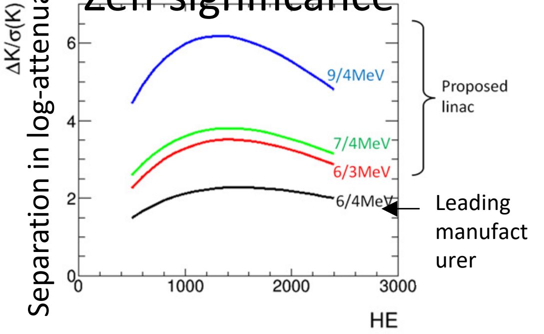
2000 PPS

- Significantly improved threat detection with high resolution images

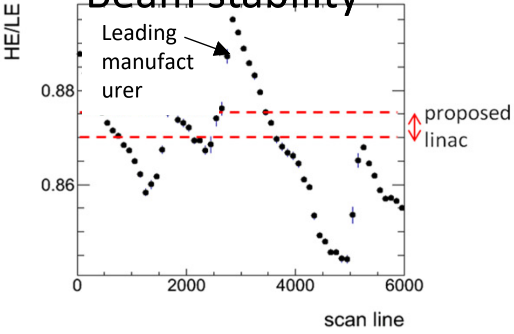
Improved SNM Detection with SLAC linac

- High-Z identification with pulse-to-pulse energy selection:
  - Much better Zeff due to wider energy separation and higher energy reach (3-9MeV)
  - More stable linac beams allow detection of thinner objects (<4mm)
- Photofission with 10MeV
- Single x-ray detection with high duty factor (3%):
  - Scatter reduction improves penetration and detection of shielded SNM’s
  - Zeff from average x-ray energy

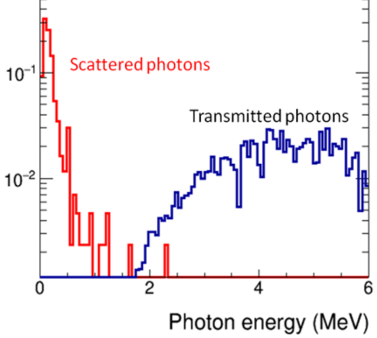
Zeff significance



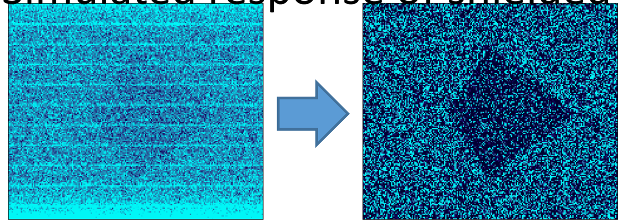
Beam stability



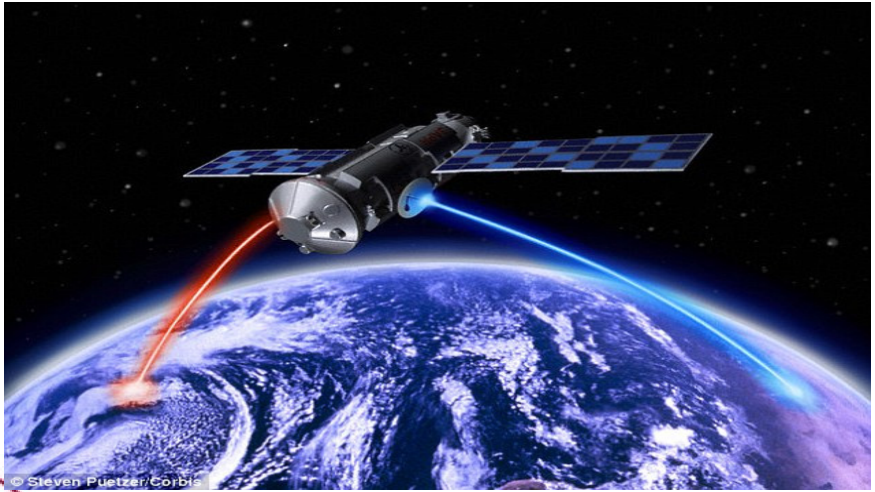
Scatter Reduction



Simulated response of shielded object



COMPact Accelerator for Space Science (COMPASS)



Jeff Neilson

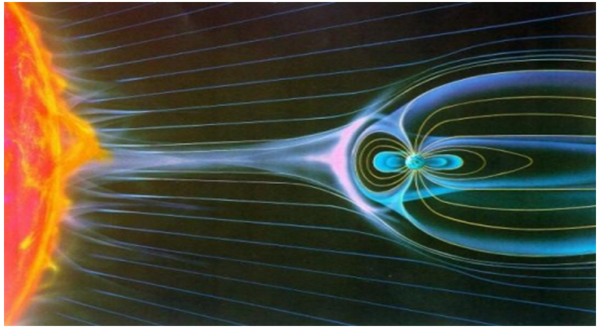
Emilio Nanni

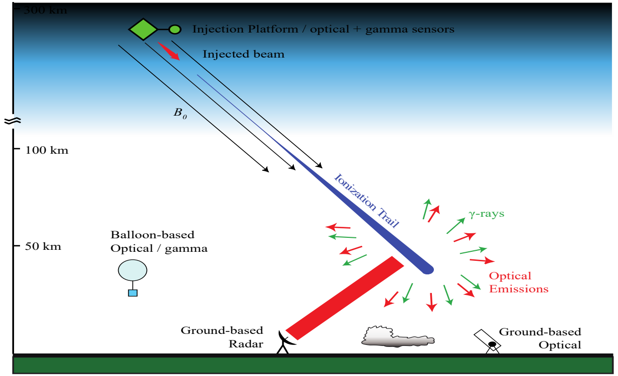
U.S. DEPARTMENT OF ENERGY
Office of Science

The Magnetosphere – Earth's Invisible Shield

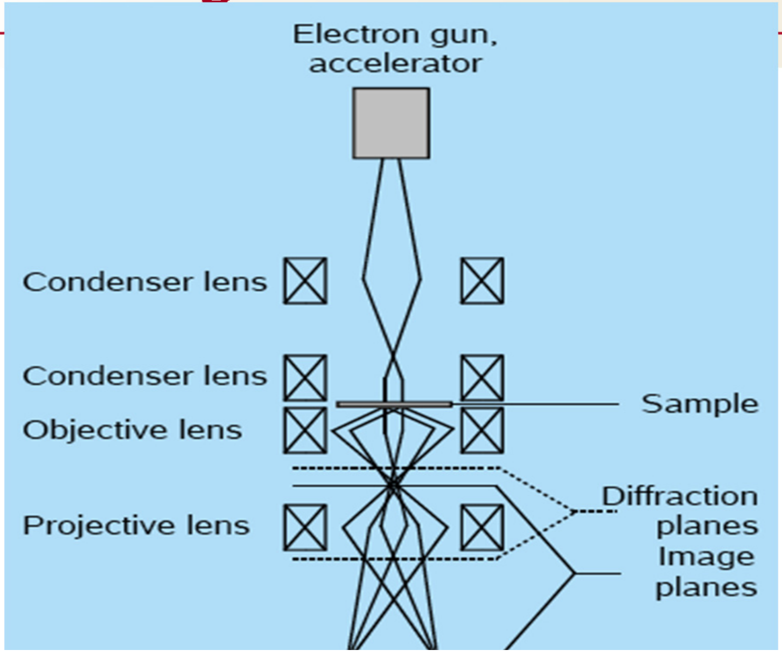
- The magnetosphere is a shield that protects us from dangerous charged particles from the Sun
- Knowledge of magnetosphere physics is important for anticipating and protecting against harmful effects of space storms
- Latest NASA Decadal Survey *"... an accurate mapping between the ionosphere and magnetosphere for all relevant conditions is lacking... Techniques to establish definitively the instantaneous mapping are thus urgently needed."*

Electron beam RF linac is primary method proposed to do this mapping

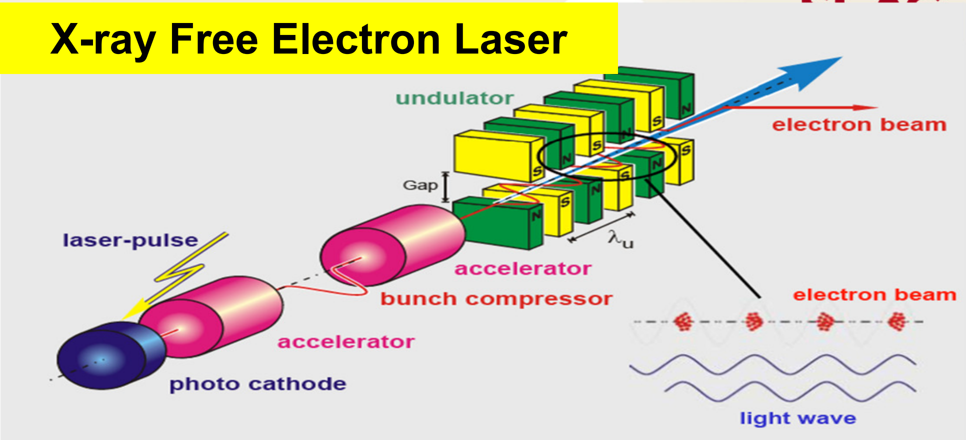




Brighter e⁻ Source → Better X-ray & Electron Instruments



X-ray Free Electron Laser



Electron source

$$\lambda_{\min}\,[\mathrm{A}] = 4\,\frac{\pi\varepsilon_n[mm-mrad]}{\sqrt{I[kA]\,L_w[m]}}$$

Source Brightness

Contrast and Pixel Count

Time Resolution

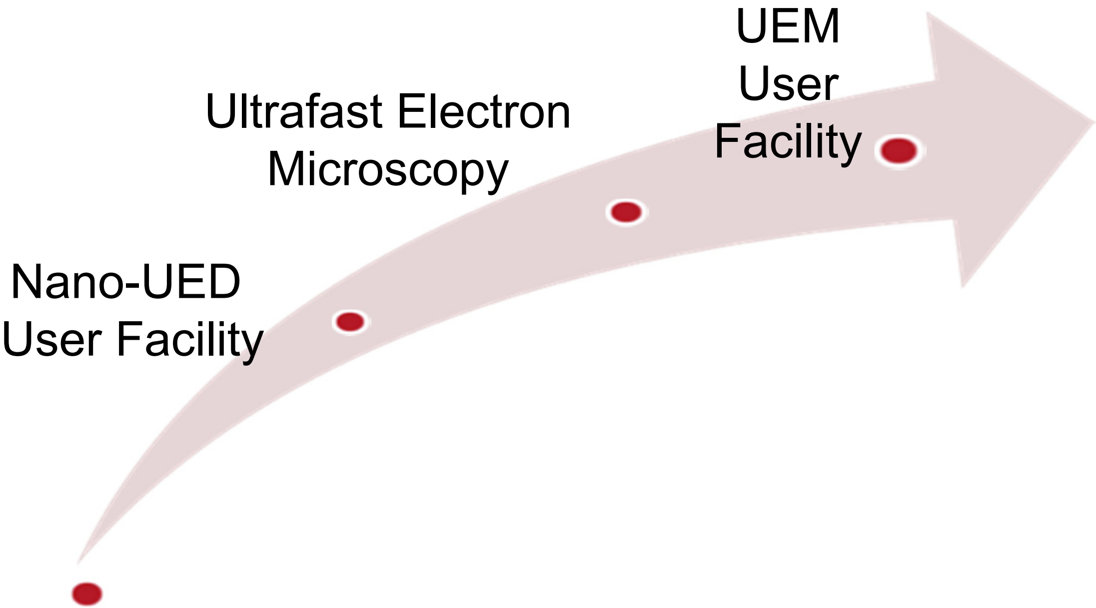
Brightness $B = \dfrac{Ne}{(\pi r^2)(\pi\alpha^2)\Delta t}$

Spatial Resolution

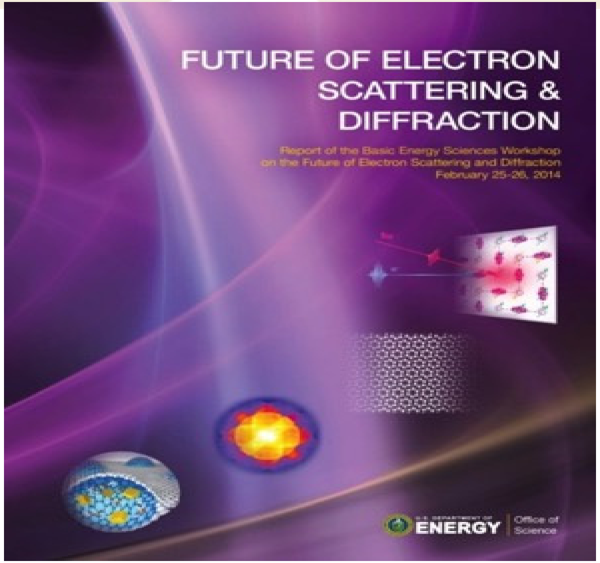
Spatial Coherence

XJ Wang

SLAC's Vision for Ultrafast Electron Scattering & Microscopy



The first step: MeV Ultrafast Electron Diffraction (UED)



Recommendation: setup ultrafast electron scattering & microscopy facility

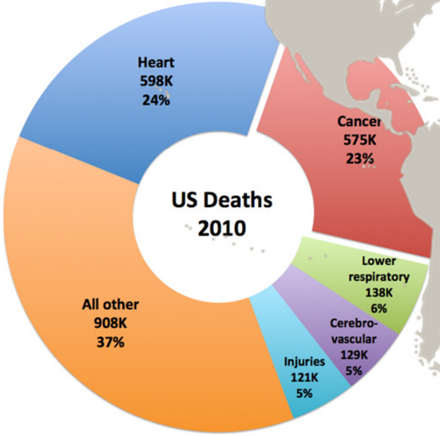
Opportunity to develop the complementarity of x-rays & electrons to access to the "Ultrafast" & "Ultrasmall"

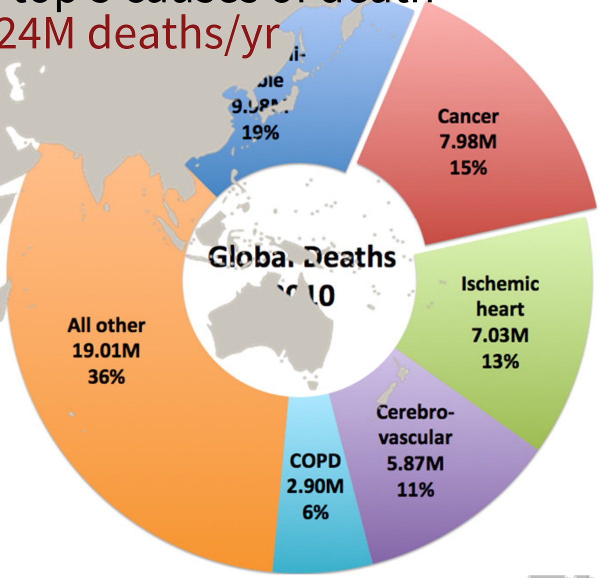
Scope of medical problem

Cancer is the **#1 single cause** of global deaths

13M cases, 8M deaths yearly & increasing epidemically

Cancer, Cardiac, COPD, Stroke in top 5 causes of death
both in US & worldwide: 24M deaths/yr

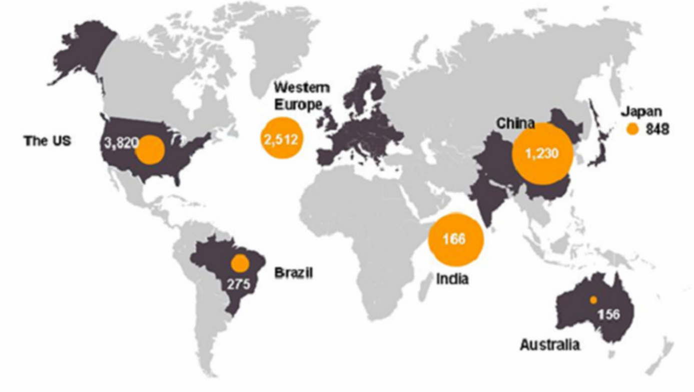




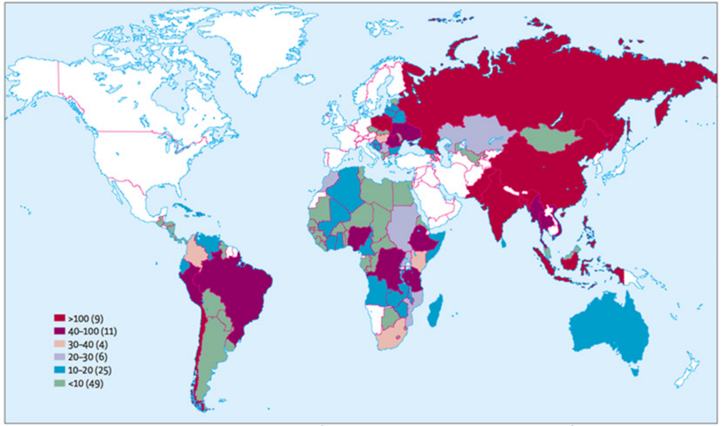
Siegel *CA: Ca J Clin* 2014
Lozano *Lancet* 2012

Importance of radiotherapy (RT)

- Cancer: **52-67% of patients benefit from RT**, 52% of those with potential for cure
- Cases will increase at least 45% in US & 60% worldwide by 2030 from demographic effects alone



2014 Installed base: ~11K linacs

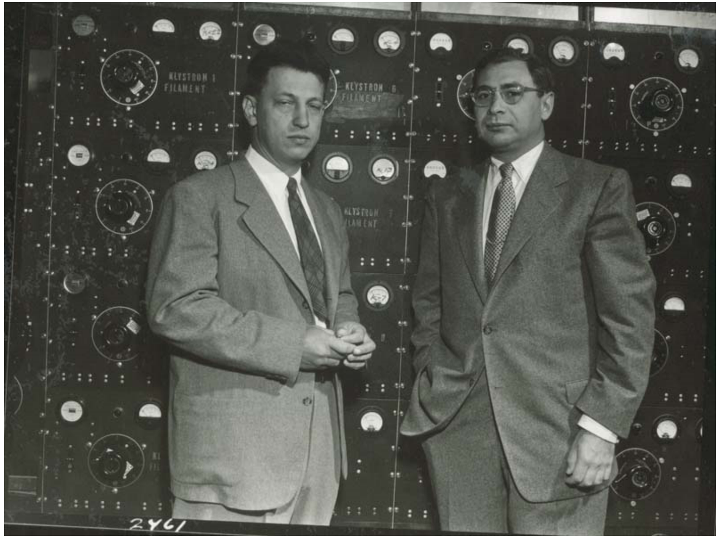


2011 shortfall in LMIC: >6.9K linacs

Barton *Lancet Oncol* 2006; Datta *IJROBP* 2014; Smith *J Clin Oncol* 2009
globocan.iarc.fr; www.rtanswers.org; www-naweb.iaea.org/nahu/dirac
GlobalData 2012 Report: Radiation Therapy Devices – Global Opportunity Assessment and Market Forecast to 2018

Stanford heritage

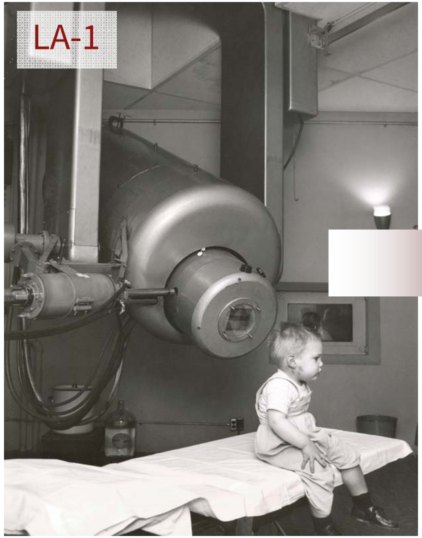
The first medical linear accelerator in the Western Hemisphere (LA-1) was invented at Stanford by Henry Kaplan (Radiology) and Edward Ginzton (Microwave Laboratory)

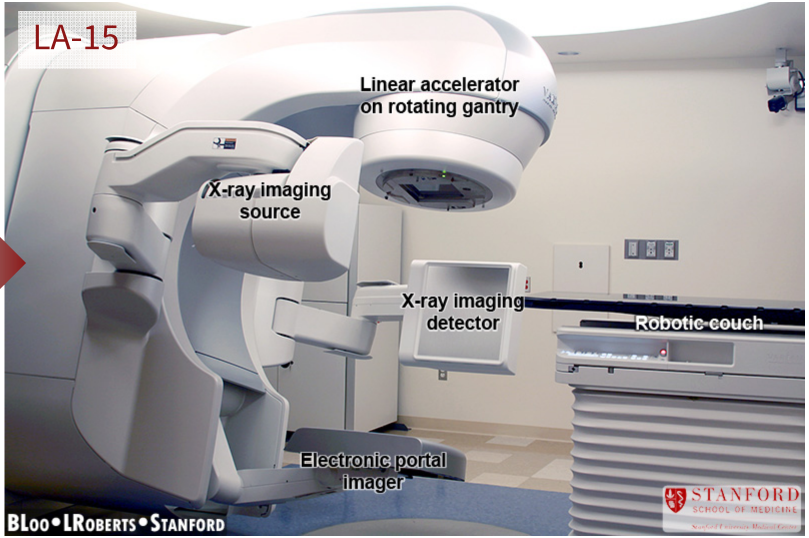


LA-1: the first patient, a child with retinoblastoma, was treated *and cured* in 1956.

Stanford heritage

The first medical linear accelerator in the Western Hemisphere (LA-1) was invented at Stanford by Henry Kaplan (Radiology) and Edward Ginzton (Microwave Laboratory)



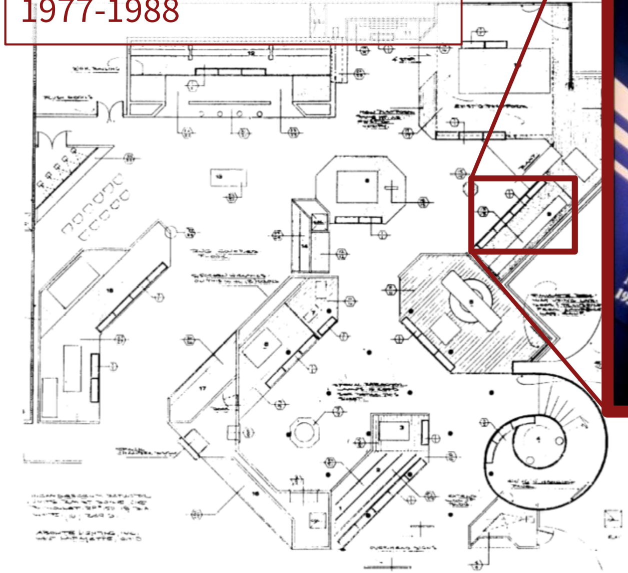


LA-1: the first patient, a child with retinoblastoma, was treated *and cured* in 1956.
Today, millions of patients are treated every year with the same basic technology.

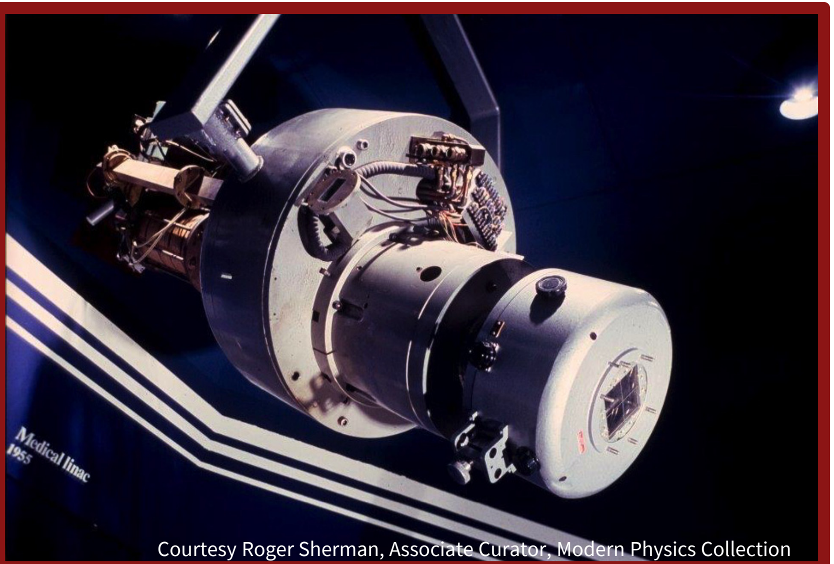
Stanford heritage

LA-1 on display at Smithsonian Institute

"Atom Smashers: 50 Years" at National Museum of American History 1977-1988



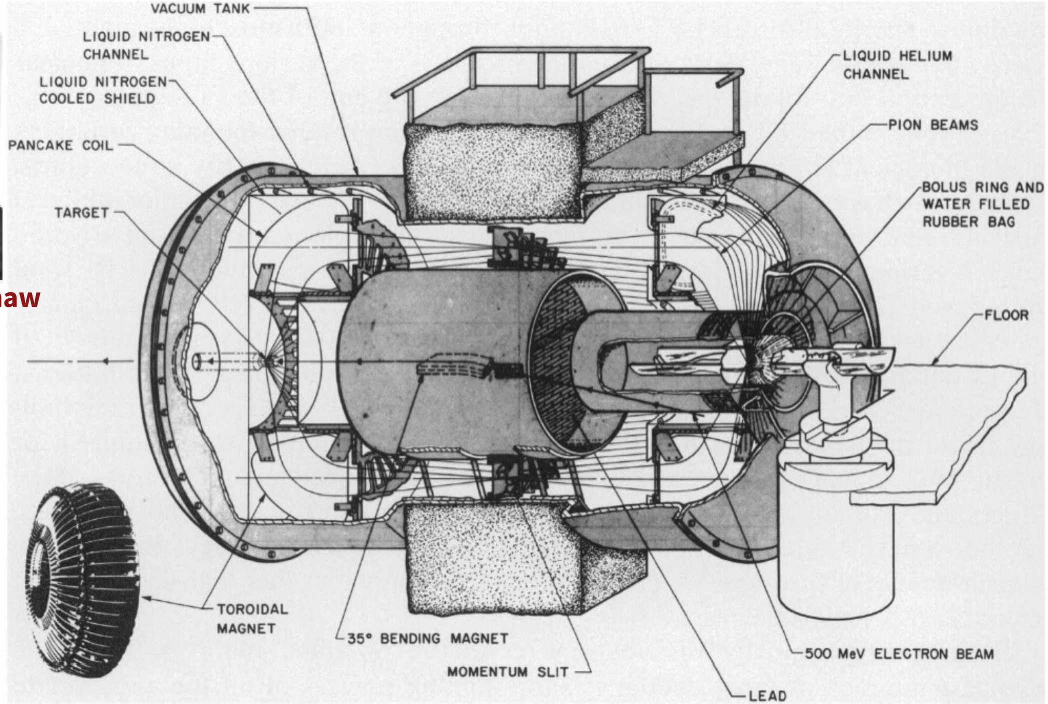
Forman *IEEE Trans Nucl Sci* 1977



Courtesy Roger Sherman, Associate Curator, Modern Physics Collection

Stanford heritage

Dr. Malcolm Bagshaw



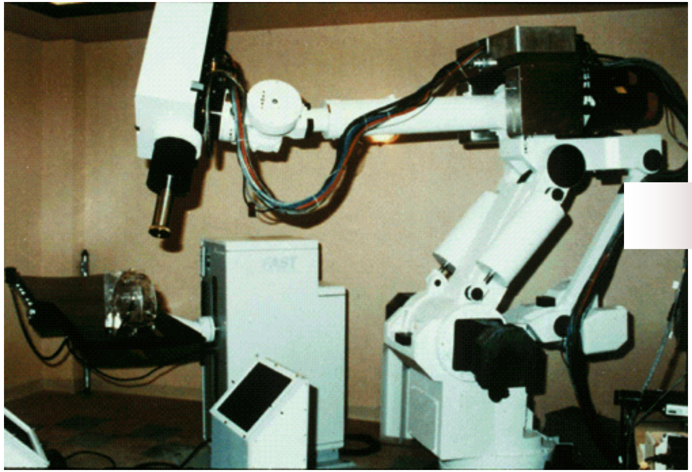
Pistenmaa
Radiology 1977

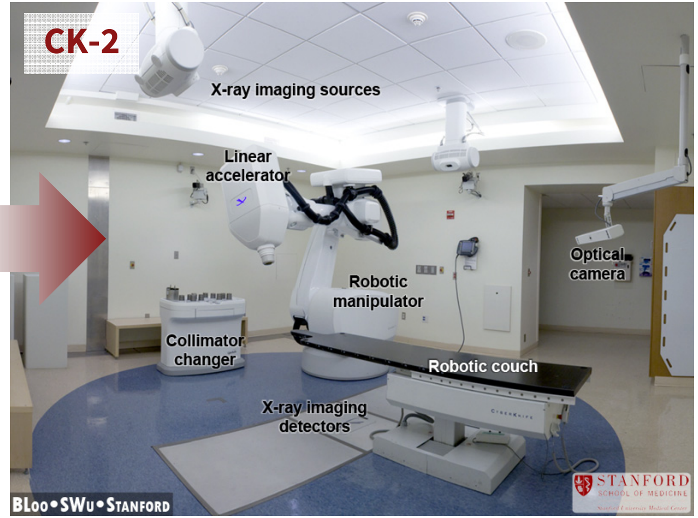
Stanford Medical Pion Generator (SPMG) at HEPL (Mark III) completed in 1974

Stanford heritage

Stanford conducted the **first clinical trials in Western Hemisphere or World** of stereotactic ablative radiotherapy (**SABR**) for:

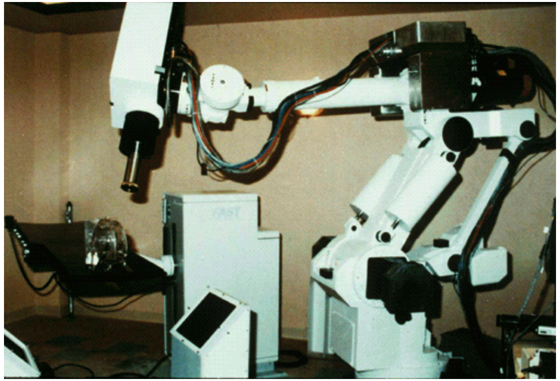
Pancreas, Nasopharynx, Lung, & Prostate cancers



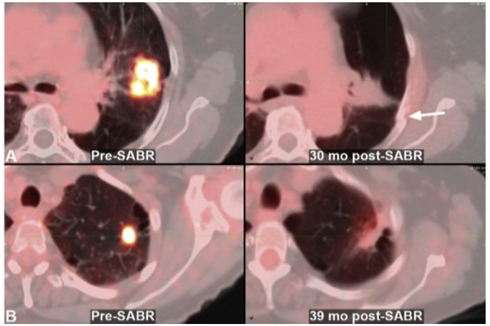


Invented at Stanford: CyberKnife robotic IGRT system, first patient treated in 1994

Pioneering new applications of RT

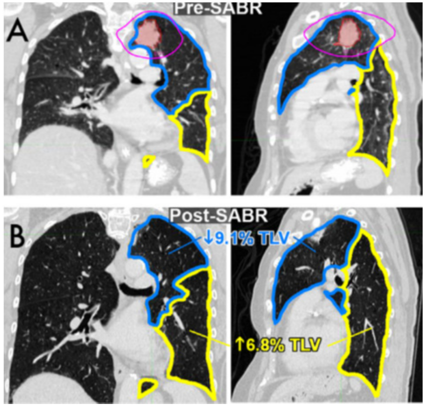


Lung cancer



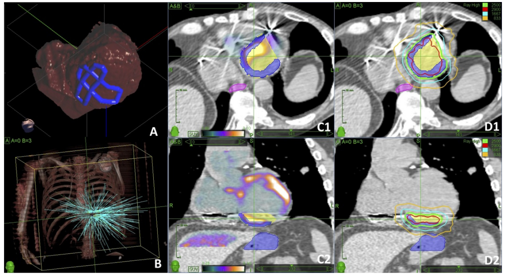
Trakul, Chang *IJROBP* 2012

Emphysema

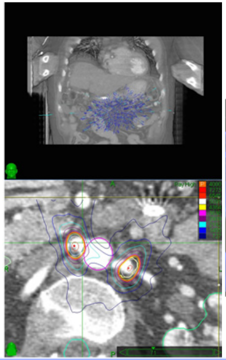


Binkley *IJROBP* 2014

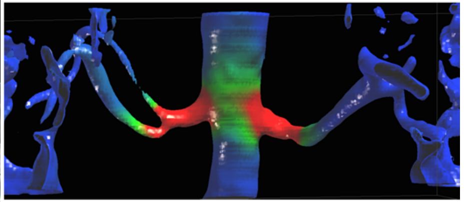
Cardiac arrhythmia



Loo, Soltys *Circ EP* 2015

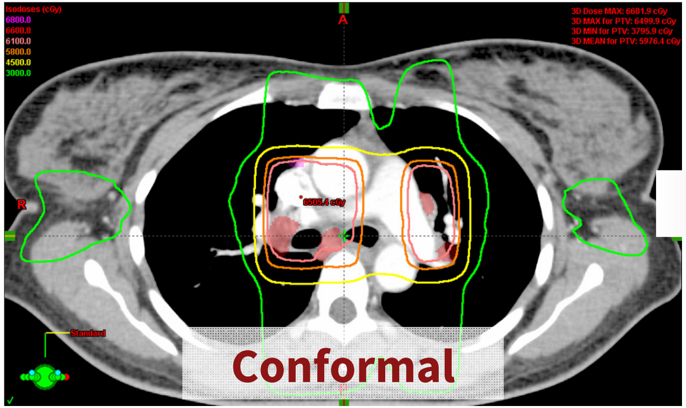


Hypertension

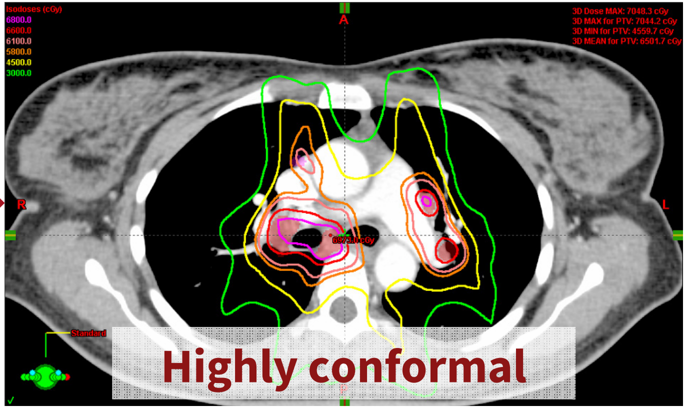


Maxim *AAPM* 2014

Push for conformity

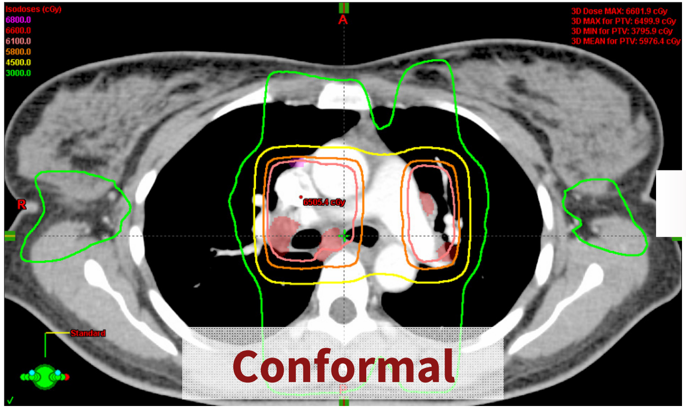


Conformal RT

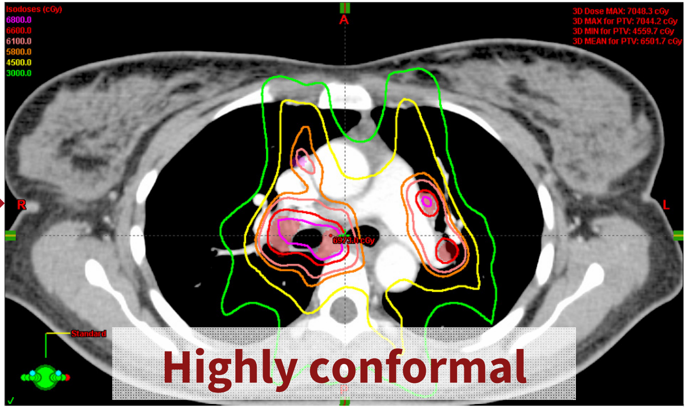


Highly conformal RT

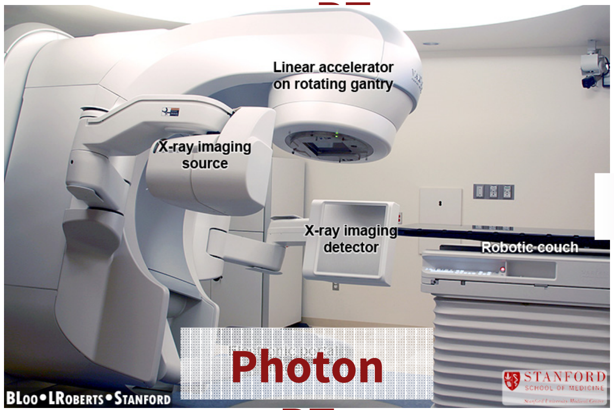
Push for conformity



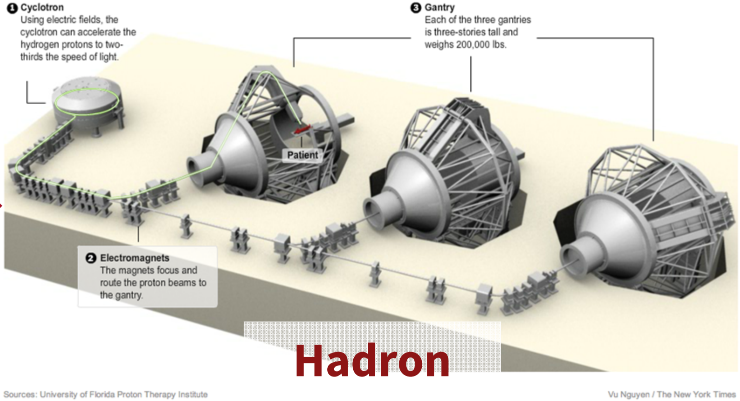
Conformal



Highly conformal



Photon RT



Hadron RT

Technical focus of RT in recent history

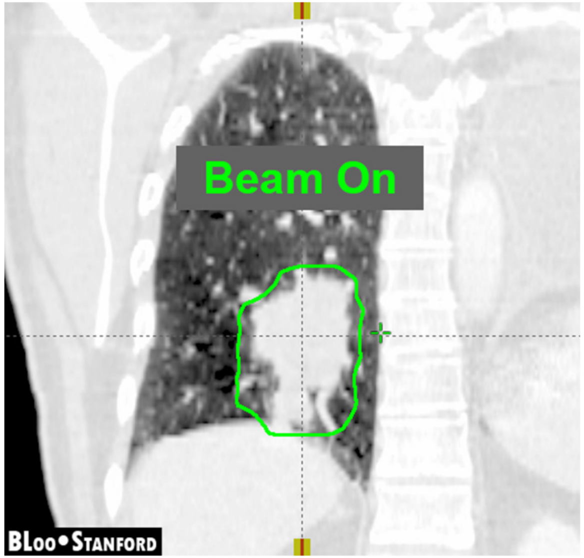
Push for conformity

Push for accuracy/precision

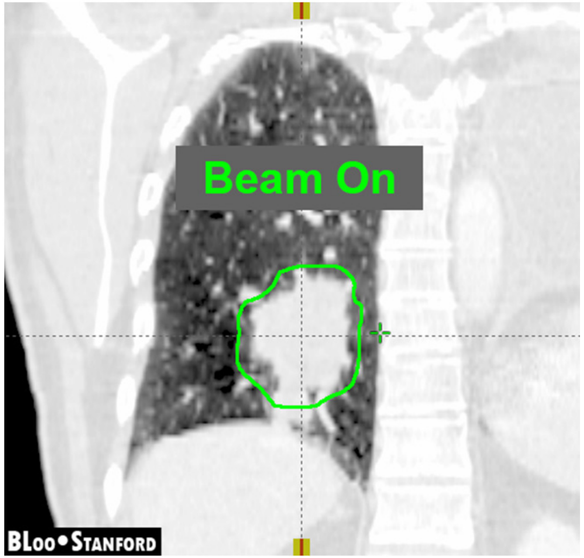
- New realizations:
  - Need to define role of RT in “precision medicine”
  - Need for cost-effectiveness/global access

Push for accuracy/precision

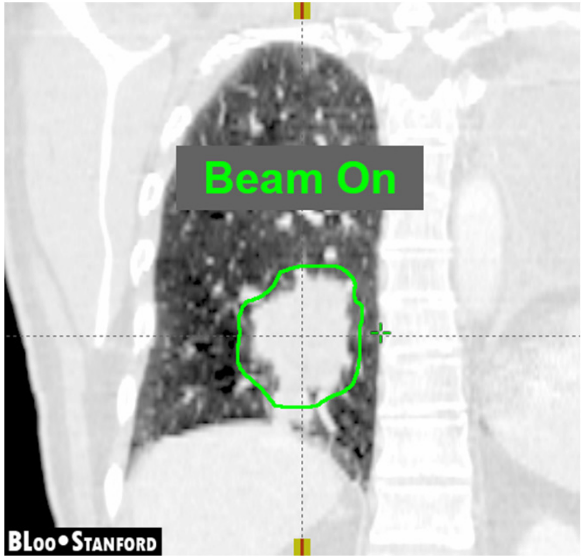
Motion Management



Motion inclusive

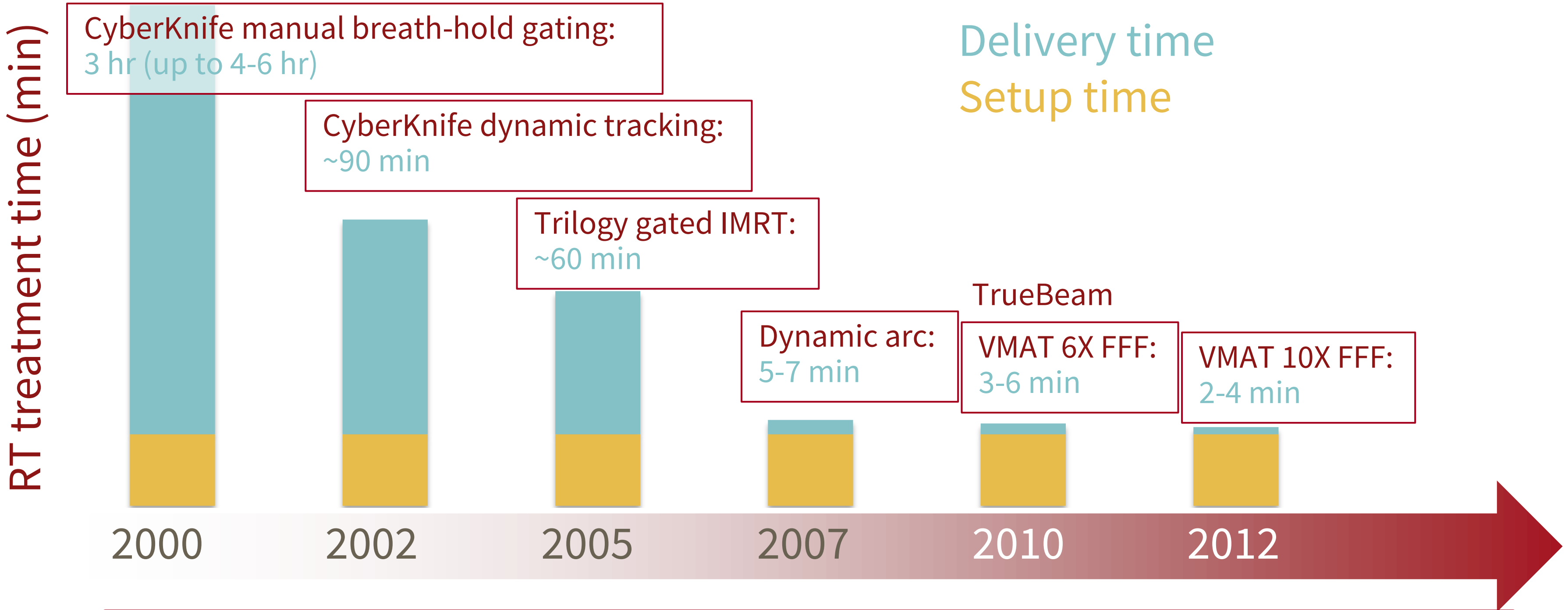


Respiratory gating



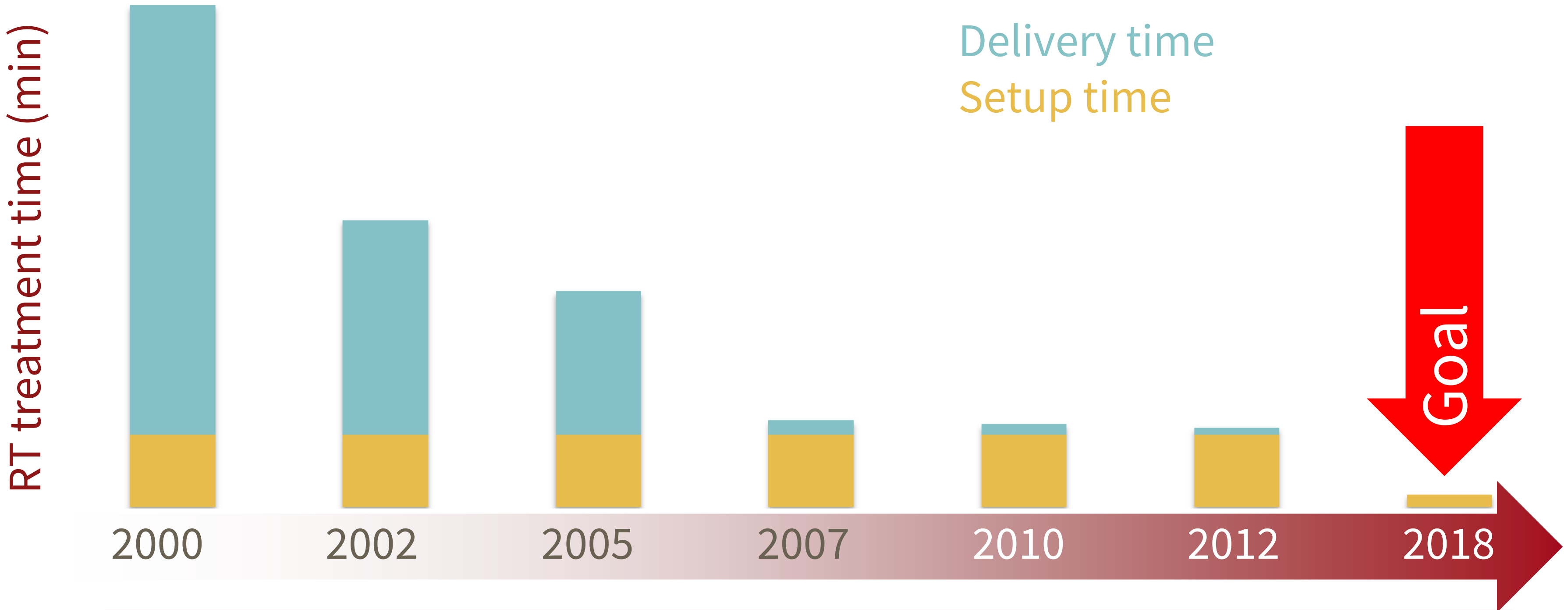
Tumor tracking

The Stanford experience – Need for speed



What if RT becomes fast enough to freeze motion?

The Stanford experience – Need for speed



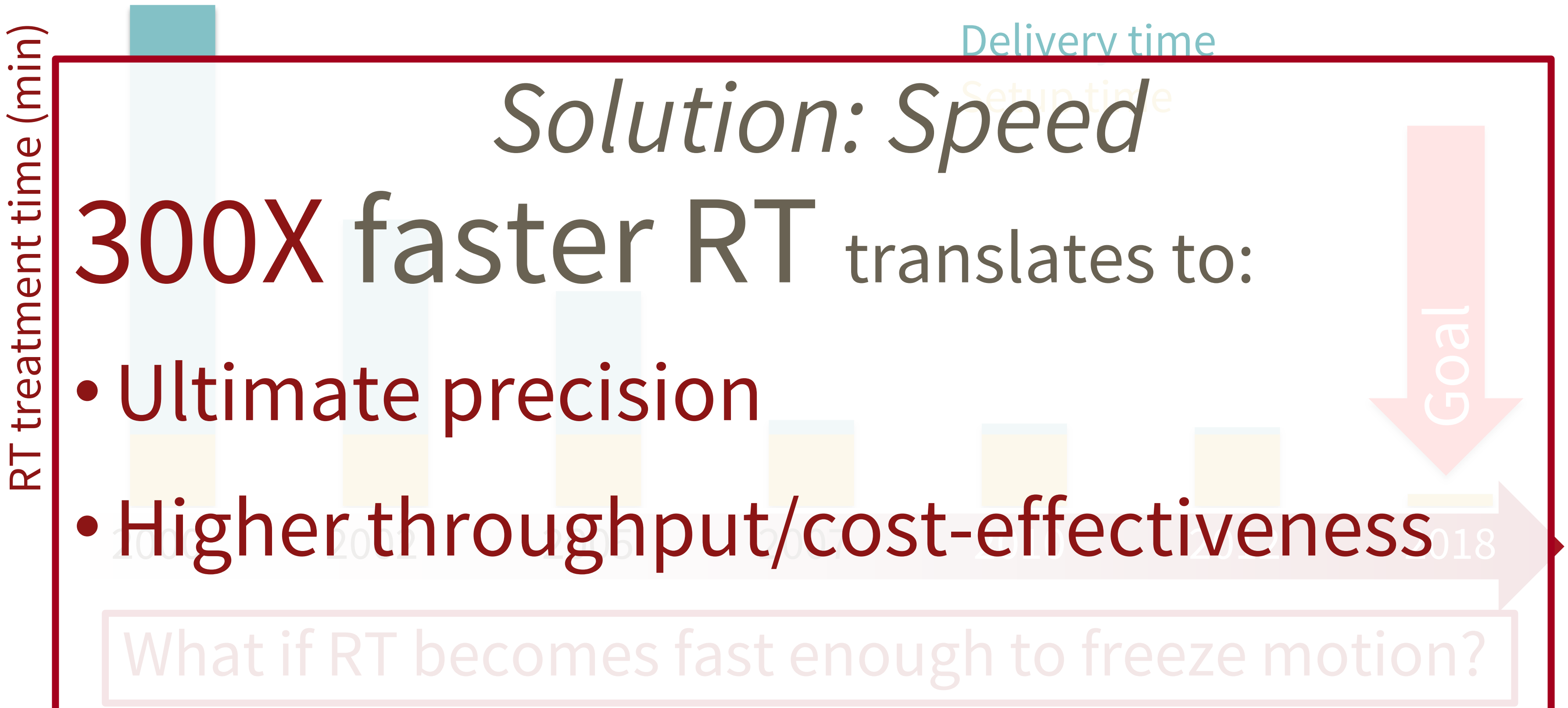
What if RT becomes fast enough to freeze motion?

The Stanford experience – Need for speed

Solution: Speed

What if RT becomes fast enough to freeze motion?

The Stanford experience – Need for speed



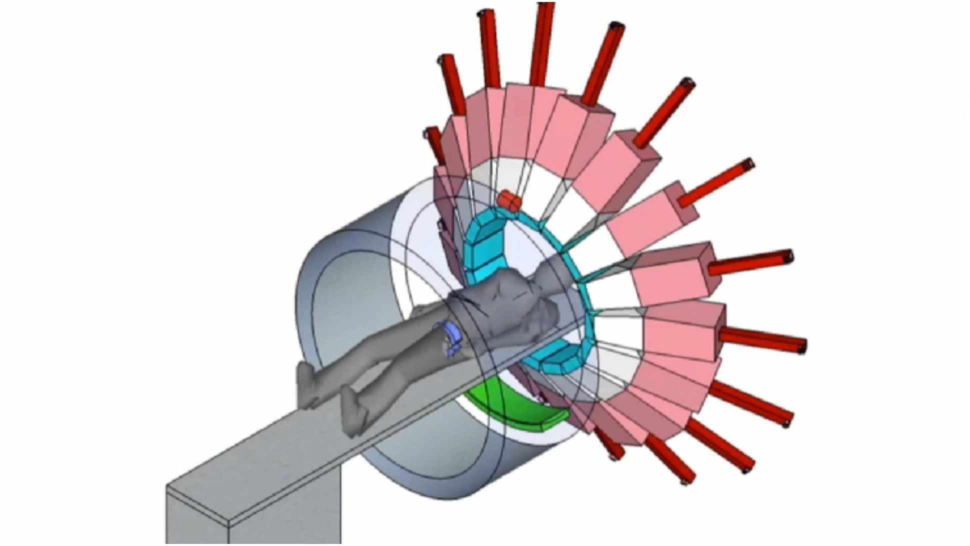
Solution: Speed

300X faster RT translates to:

- Ultimate precision
- Higher throughput/cost-effectiveness

The PHASER solution

Current state-of-the-art



Pluridirectional High-energy Agile Scanning Electronic Radiotherapy (PHASER)

The PHASER solution

Ultra-fast ➔ Ultimate precision
Compact, hi throughput ➔ Global access

Current state-of-the-art

Pluridirectional High-energy Agile Scanning Electronic Radiotherapy (PHASER)

Achieving extreme speed

Requirements:

- 300X beam output
- Eliminate mechanical motion
  - Gantry
  - MLC
- Fast, high-quality volumetric imaging

Constraints:

- Compact – fits in existing vaults
- Power efficient
- Economical to manufacture and operate

PHASER team


Historic radiation medicine & technology team-up
STANFORD CANCER INSTITUTE
Stanford University Medical Center
A NATIONAL CANCER INSTITUTE-DESIGNATED CANCER CENTER
Stanford School of Medicine – Rad Onc/
B Loo
P Maxim
R Fahrig
SLAC National Accelerator Lab
S Tantawi
V Bharadwaj
P Borchard
SLAC NATIONAL ACCELERATOR LABORATORY
Junipero Serra Fwy
Sand Hill Rd
Sharon Heights Golf & Country Club
SLAC National Accelerator Laboratory
Starbucks
STANFORD HILLS
Siebel Varsity Golf Training Complex
Stanford Medical Cer

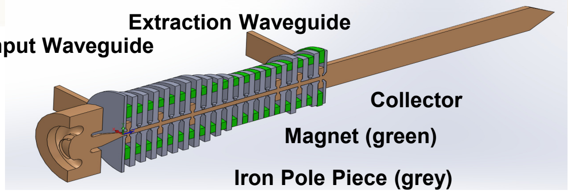
Reducing the cost of RF power is necessary to realize high gradient and or high duty cycle accelerator operation.

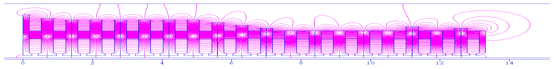
- The prohibitively high cost of traditional RF sources are derived from both:
  - Sources are complicated to built
  - High voltage power supplies
  - Limited by efficiency at high power

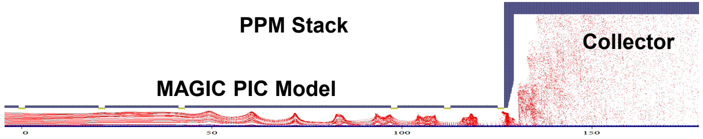
- Simplifying the RF system to reduce capital cost
  - Standardized *modular* design to scale to higher power, ***enabled by multiplexing***
    - Exploit manufacturing and engineering advantages
    - Utilize integrated low voltage electron beams (~60 KV)
    - Reduce size, weight, and cost of modulator

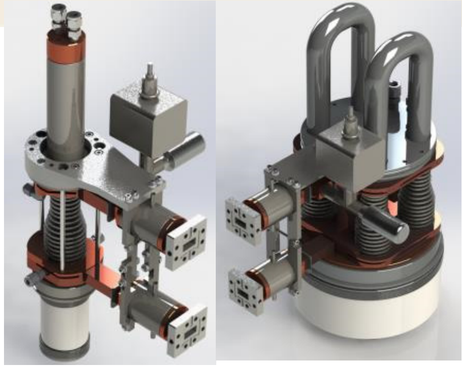
Reducing the cost of accelerators requires reimagining the topology of the RF source

Our Solution: MA-MBK takes advantage of low space charge system to attain high efficiency at low voltages





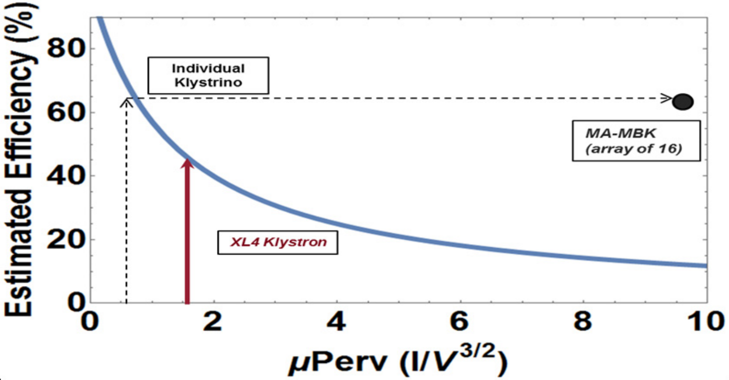




Modular klystrinos:

- allow for permanent periodic magnet focusing system
- Low voltage operation
- High efficiency
- Overall reduced cost

Parameter	Near Term Goal
Beam Voltage (kV)	60
Frequency (GHz)	11.424
Output Power for 16 devices(MW)	5
Beamlets	16
Efficiency (%)	60+

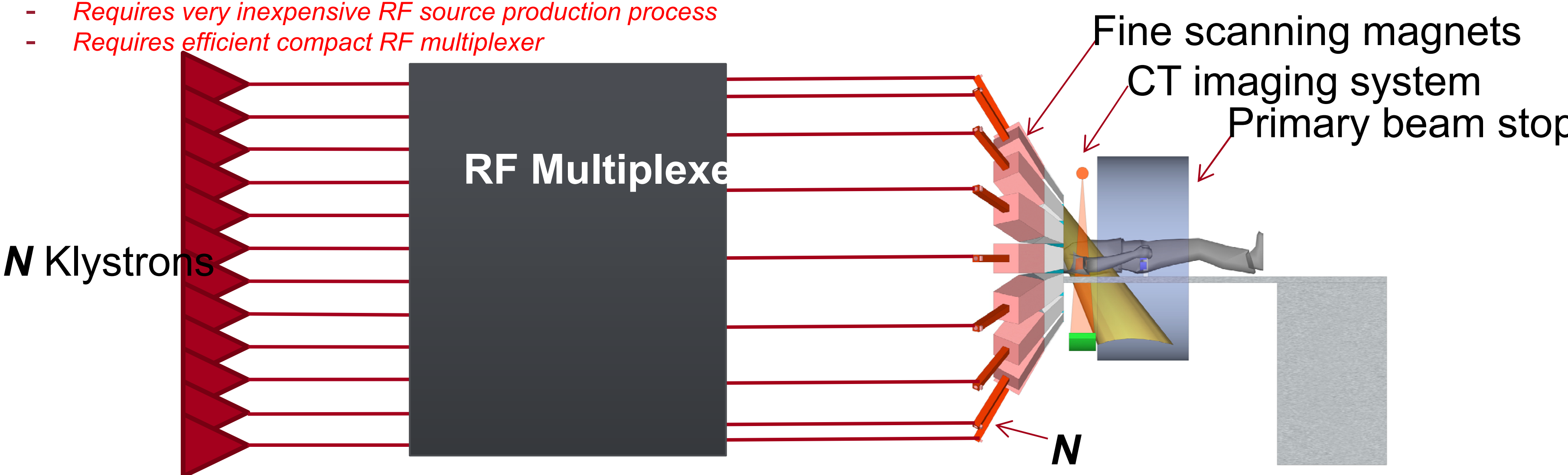


The MA-MBK is not restricted to the geometric limitations of a classic MBK

A. Jensen, S.Tantawi

The PHASER System Architecture: Multiple Linacs, Multiple RF sources-multiplexed

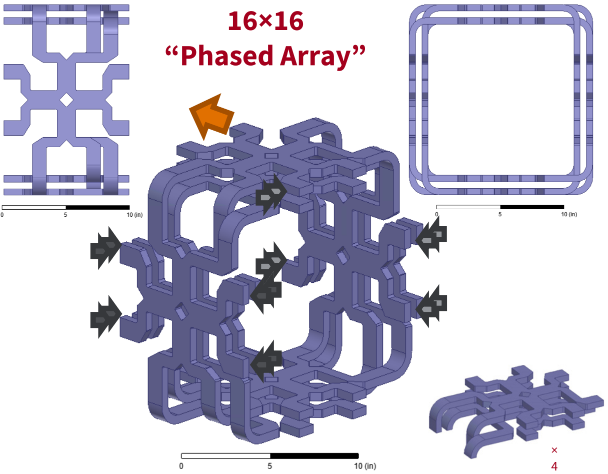
- Multiple Linacs (minimum 16 Linacs)
  - Effectively scan the beam around the patient, finer scan from each linac achieve desired resolution
  - Linac are arranged on the surface of a cone to allow for in situ imaging system
  - Distribute the average power for both the linac and target
  - *Requires very inexpensive linac production process*
- Multiple RF sources
  - Needed to deliver the power to each linac
  - If multiplexed, the ***peak*** power from each source can be reduced
    - Reduced power from each source implies reduced modulator voltage, hence less expensive system
    - *Requires very inexpensive RF source production process*
    - *Requires efficient compact RF multiplexer*

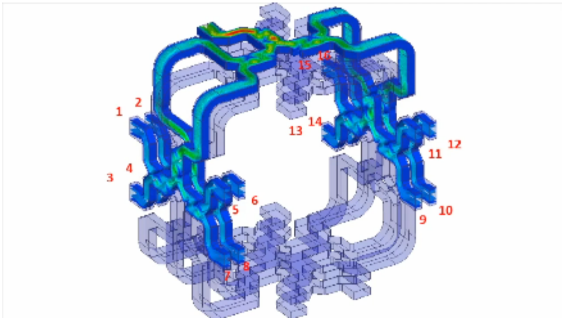


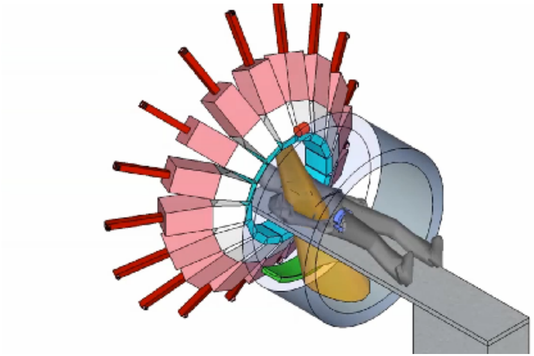
The Multiplexer scans the beam around the patient without any mechanical motion

~30 cm @ f=11.4 GHz

Scanning the beam through scanning the phases of the RF sources



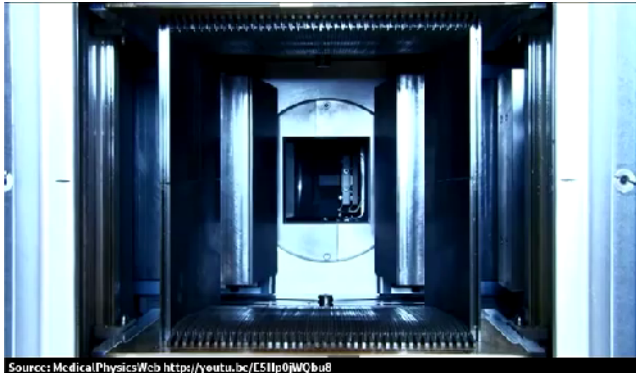




Inputs are numbered from 1-16

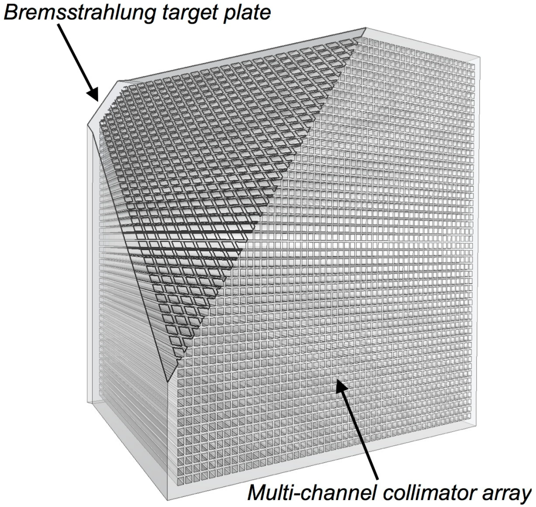
SPHINX – replacement for moving MLC

All-electronic intensity-modulation



SPHINX – replacement for moving MLC

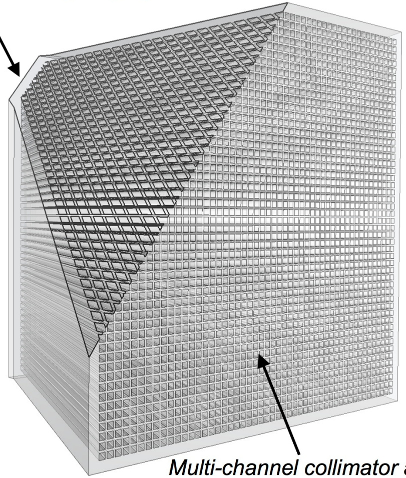
All-electronic intensity-modulation



Scanning Pencil-array-collimated High-speed
Intensity-modulated X-ray source (SPHINX)

SPHINX – replacement for moving MLC

All-electronic intensity-modulation

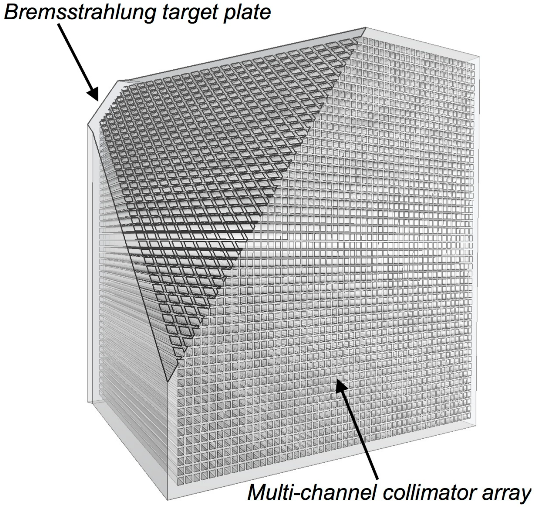


Scanning Pencil-array-collimated High-speed Intensity-modulated X-ray source (SPHINX)

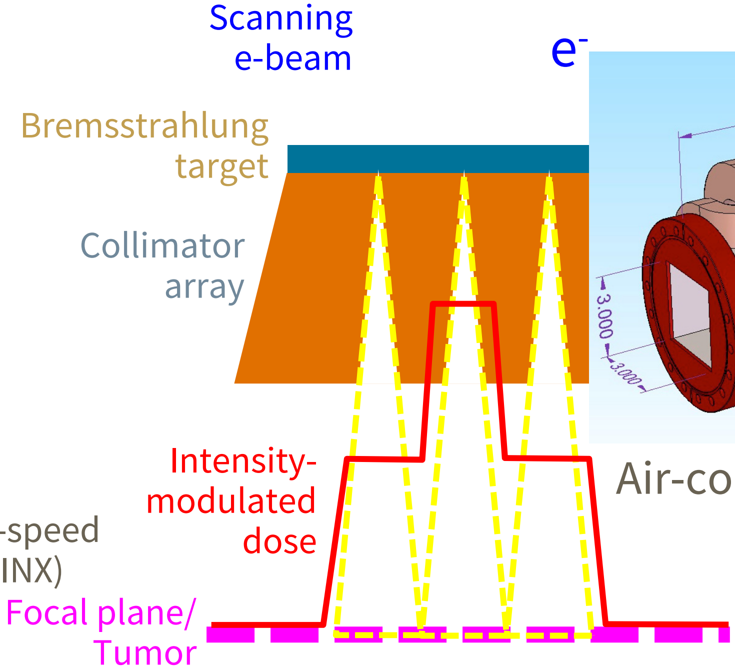
B Loo, L Nicolas – Stanford/SLAC

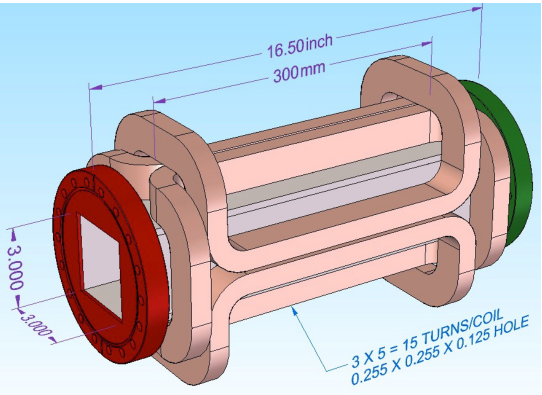
SPHINX – replacement for moving MLC

All-electronic intensity-modulation



Scanning Pencil-array-collimated High-speed Intensity-modulated X-ray source (SPHINX)



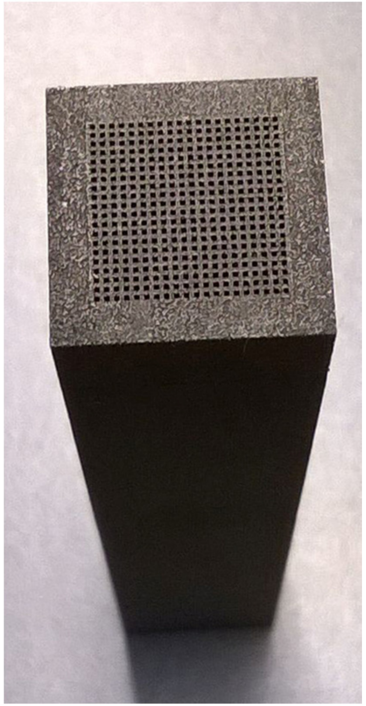


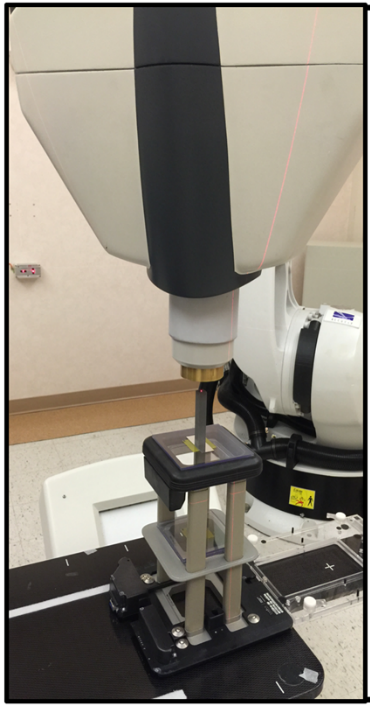
Air-core scanning magnet design

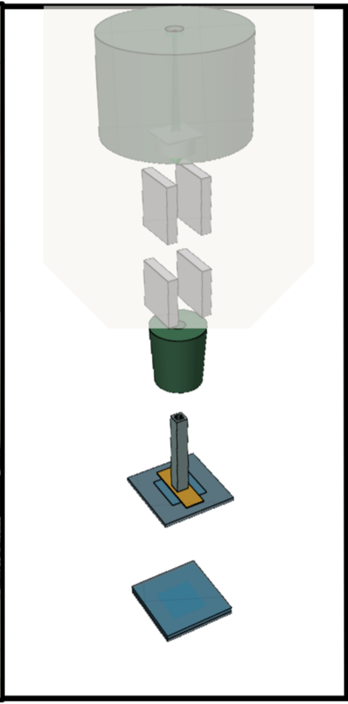
B Loo, L Nicolas – Stanford/SLAC

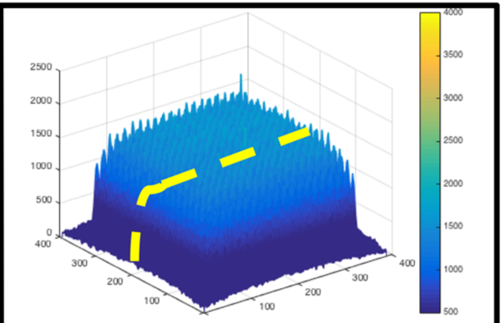
SPHINX – replacement for moving MLC

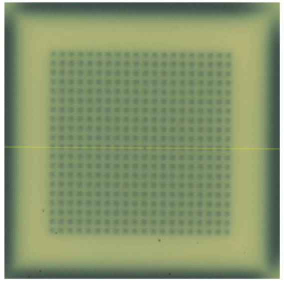
Geometrical accuracy of prototype

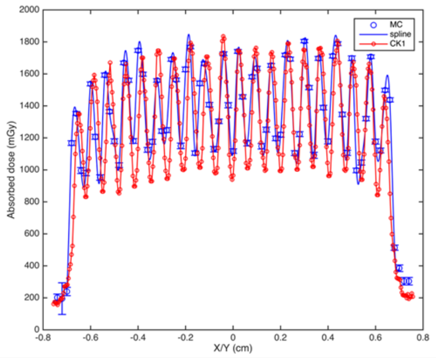


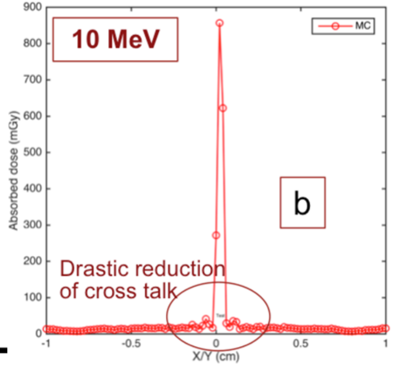












Conclusions

Next generation accelerator and RF power designs provide much higher performance, compactness, and lower cost, and can bring RT to low resource settings

Combined with CT, multi-beamline/RF multiplexer, electronic pencil beam scanning (SPHINX) → ultra-rapid PHASER

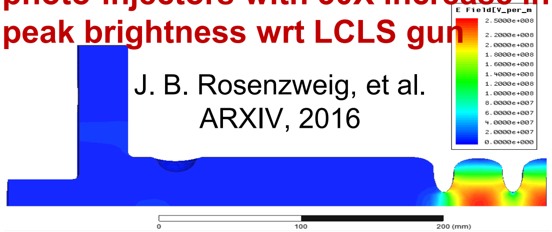
- Ultimate motion management/precision
- High clinical efficiency/throughput/cost-effectiveness
- Potential paradigm-shifting biological advantage (FLASH)

Broader Impacts Resulting from Advancements in RF Accelerator Technology

SLAC

Cryogenic RF Photoinjector (UCLA/SLAC)

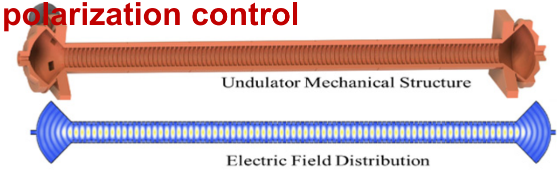
- **Cryogenic Cu with surface fields nearly twice room temperature Cu, rf photo-injectors with 30X increase in peak brightness wrt LCLS gun**



J. B. Rosenzweig, et al.
ARXIV, 2016

RF Undulator (NSF)

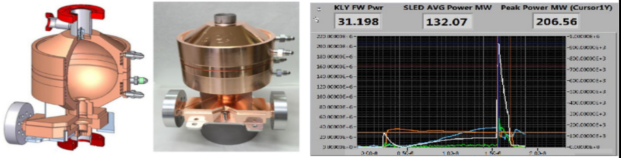
- **Microwave undulators with large aperture, short period and active polarization control**



S. Tantawi, et al. *PRL* (2014)

Pulse Compressors (LCLS/BES)

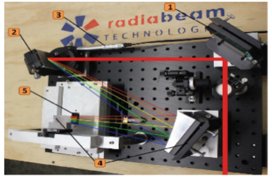
- **Super compact X-Band SLED system, doubles the kick in transverse deflector at LCLS**

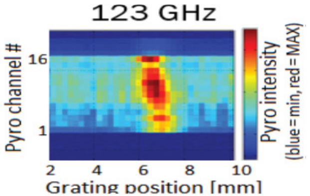


J.W. Wang, et al. IPAC 2016

Single Shot THZ Spectrometers (SBIR/HEP)

- **SBIR with Radiabeam in support of THz acceleration experiments**

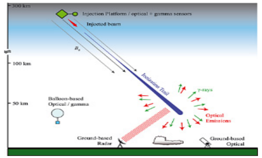




S.V. Kutsaev, et al. IPAC 2016

Accelerators Deployed on Satellites (NSF)

- **Requires extremely efficient and compact accelerator to produce MeV beams**

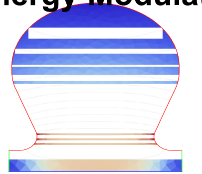


R. A. Marshall, et al. JGR: Space Physics, 2014
E. A. Nanni, et al. SLAC-R-1058, 2016

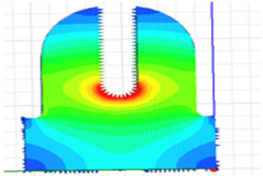
Proton Acceleration (Stanford Med./UCSF/SLAC)

- **Efficient accelerating structures to modulate beam energy and deflect beams for proton radiation therapy**

Energy Modulation



Beam Deflection



- **Collaborations and Investments have Advanced HEP GARD Mission**