

X-Band Deflectors

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Cavity Applications in Accelerators
Cockcroft Institute, 1-3 September 2010*

Acknowledgments

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- Pietro Musumeci of UCLA
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- Craig Wilsen of L3 Communications

Outline

- Introduction
- SLAC 11.4 GHz traveling wave (TW) deflector for Linac Coherent Light Source (LCLS)
- Radiabeam Tech. 11.4 GHz TW deflector for BNL Accelerator Test Facility (BNL-ATF)
- The Cockcroft Institute / Lancaster University TW deflectors for linear collider
 - 11.4 GHz prototype for high power tests
 - 12 GHz
- UCLA 9.6 GHz standing wave (SW) deflector
- Hiamson Research 17 GHz circularly polarized SW deflector
- New X-band rf power sources

Introduction

Why X-band for rf deflectors?

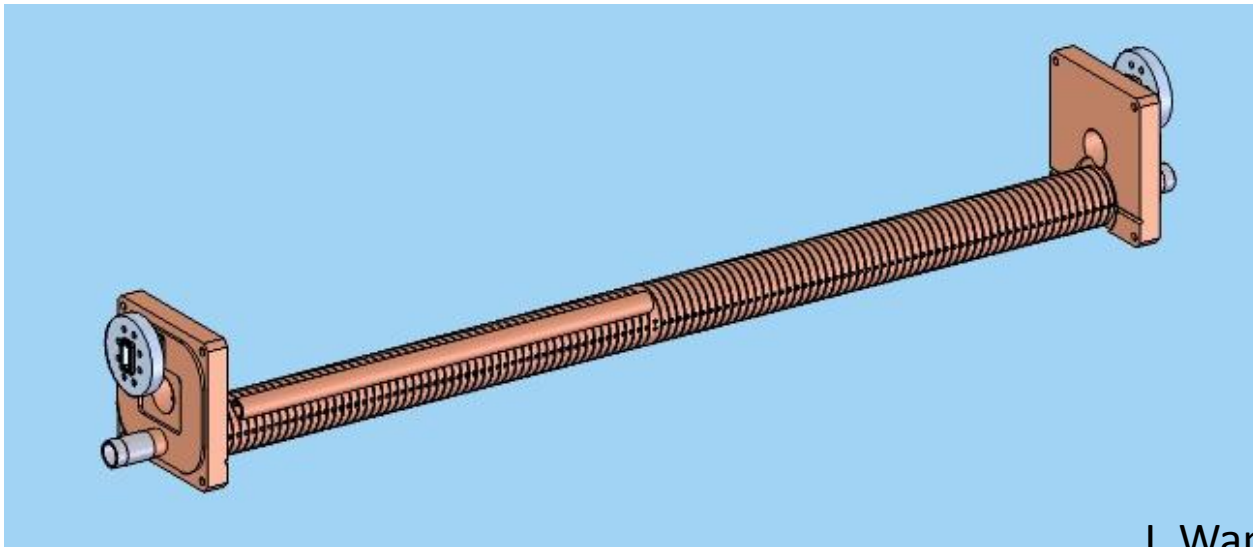
- Compact
- Practical devices that allow extreme timing resolution, such as ~ 10 fs at 14 GeV
- Practical way to build portable \sim fs beam diagnostics for \sim MeV beams

Difficulty:

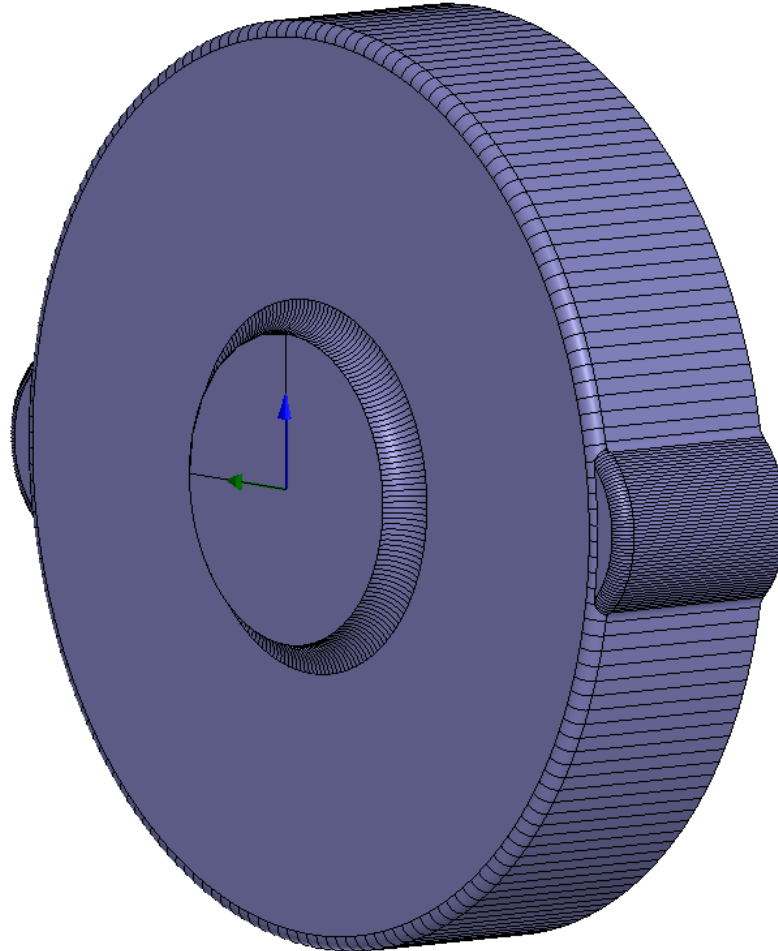
Need expensive rf power sources,
from 0.1 to 10th MW of X-band rf power

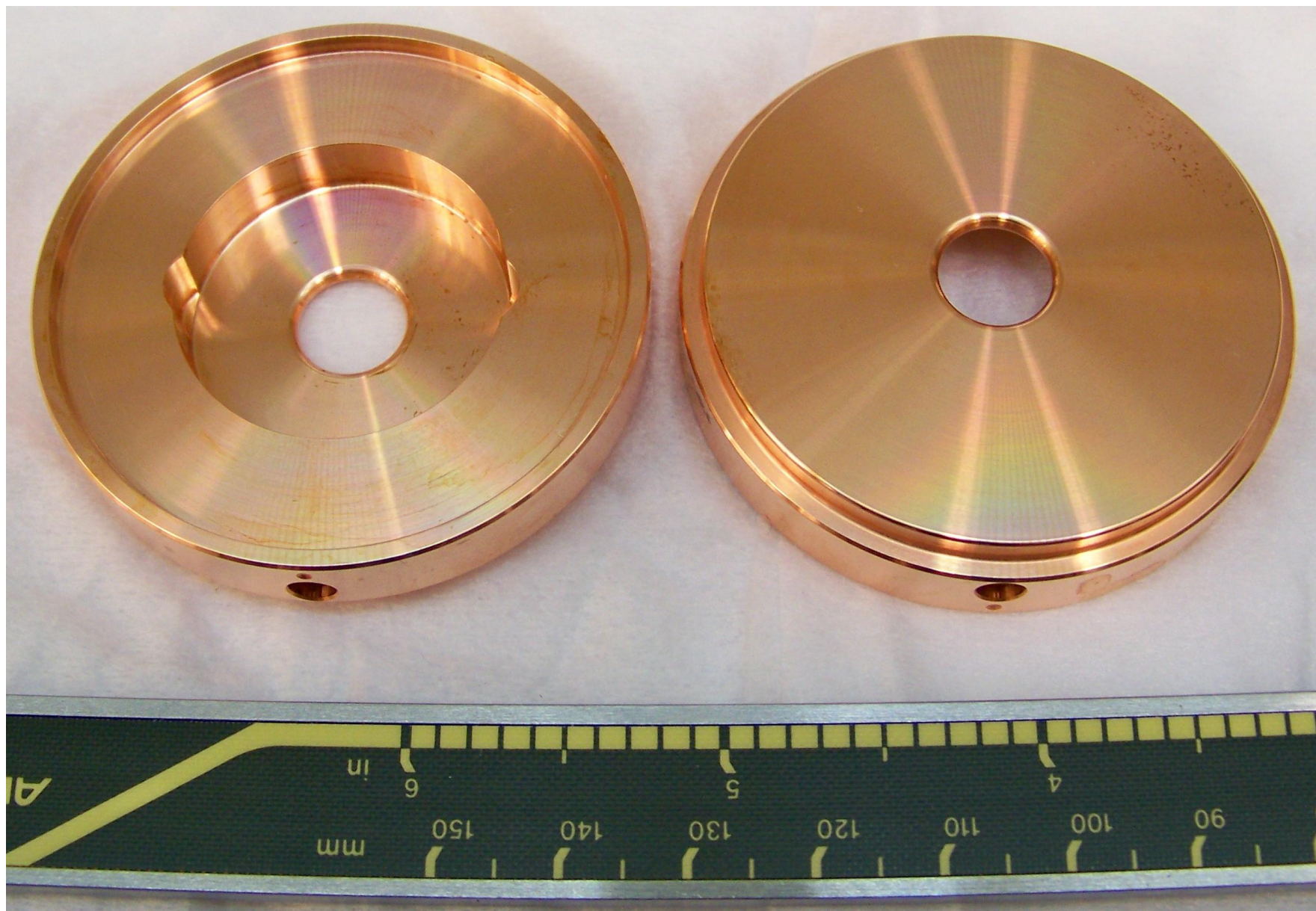
11.424 GHz Traveling Wave Deflector for LCLS

Frequency	11.424 GHz
Beam pipe diameter	10 mm
Phase advance per cell	$2\pi/3$
Kick per meter	31 MeV/m/Sqrt(20 MW)
102 cell structure kick	21.3 MeV/Sqrt(20 MV)
Maximum Electric field (input coupler)	100 MV/m / Sqrt(20 MW)
Maximum Magnetic field (input coupler)	400 kA/m / Sqrt(20 MW)
Group velocity/ speed of light	3.2 %
Structure length (with beam pipes)	~94 cm

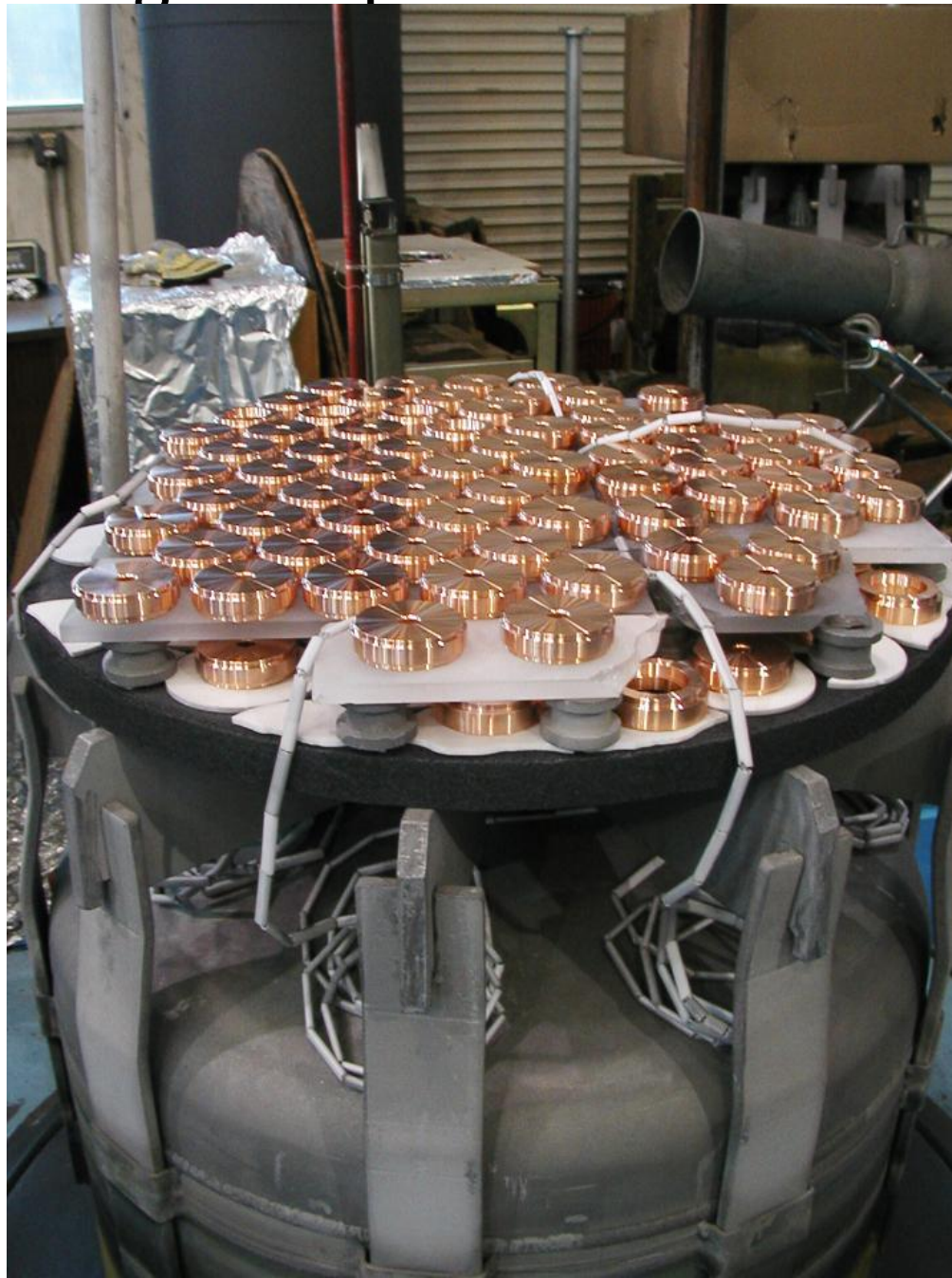


Regular Cell, HFSS Model

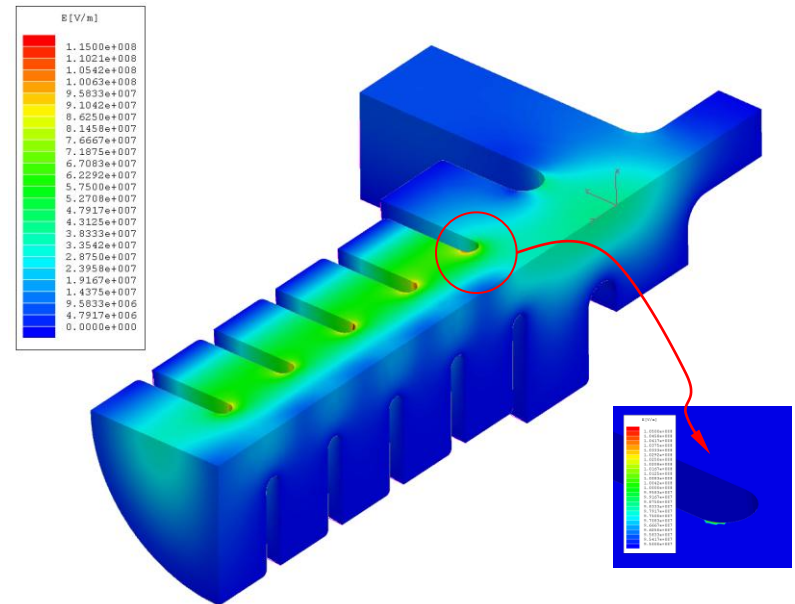
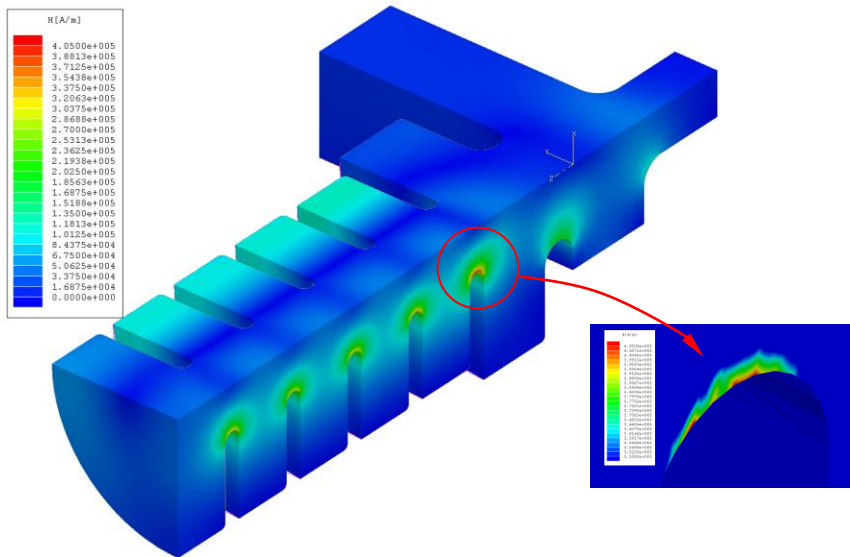




Annealing of Cups for Final Machining



Waveguide Coupler for TW X-band Deflector, 20 MW of Transmitted Power, or 21.3 MeV kick for 89 cm structure



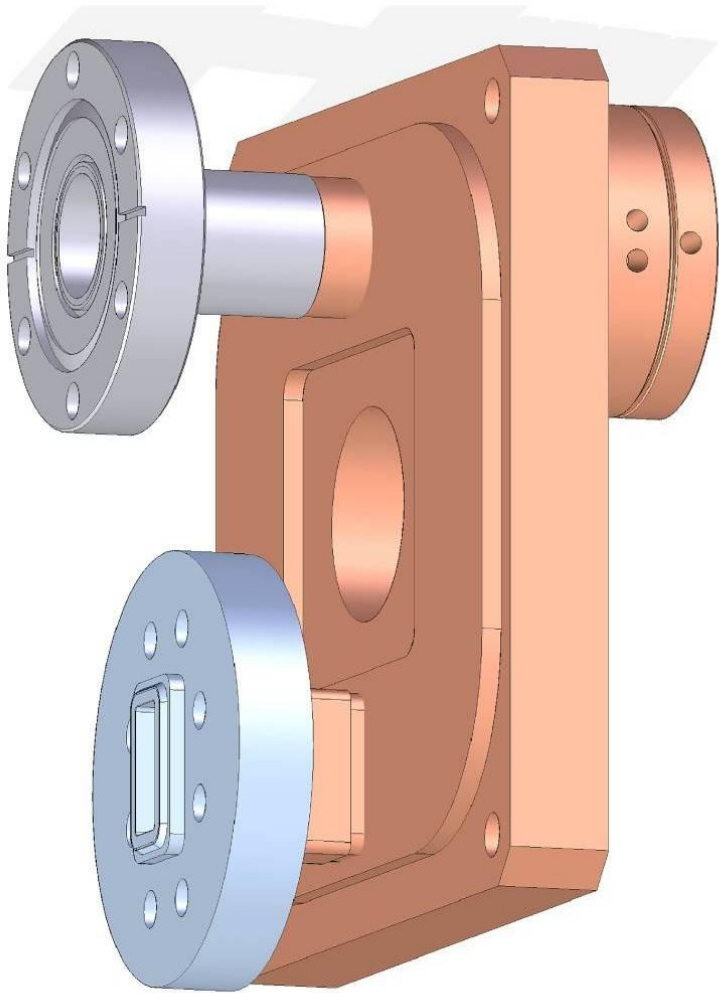
Maximum surface magnetic fields ~ 400 kA/m,
Pulse heating 22 deg. C for 100 ns pulse.

Maximum surface electric fields ~ 100 MV/m.

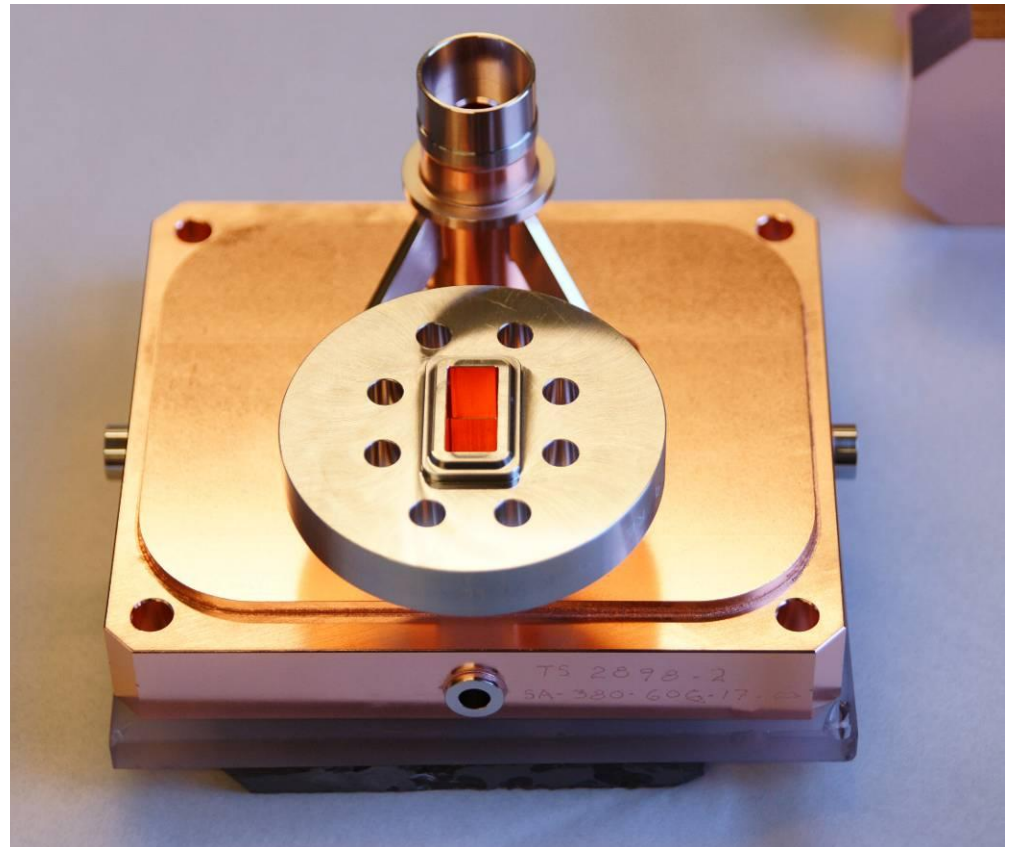
V.A. Dolgashev, **Waveguide Coupler for X-band Defectors**, *Advanced Accelerator Concepts Workshop 2008, Santa Cruz, CA, July 27 – August 2, 2008*:

<http://www.slac.stanford.edu/~dolgashev/x-rays/Waveguide%20coupler%20for%20an%20x-band%20defector%20Dolgashev AAC08 31jul08.pdf>

Input/Output Couple Assemblies



Mechanical Design Model



Completed Couple Assembly

Application: 10 fs Time Resolution for 13.6 GeV LCLS Beam

P. Emma, *An X-Band Transverse RF Deflector for the LCLS*, Oct. 18, 2006

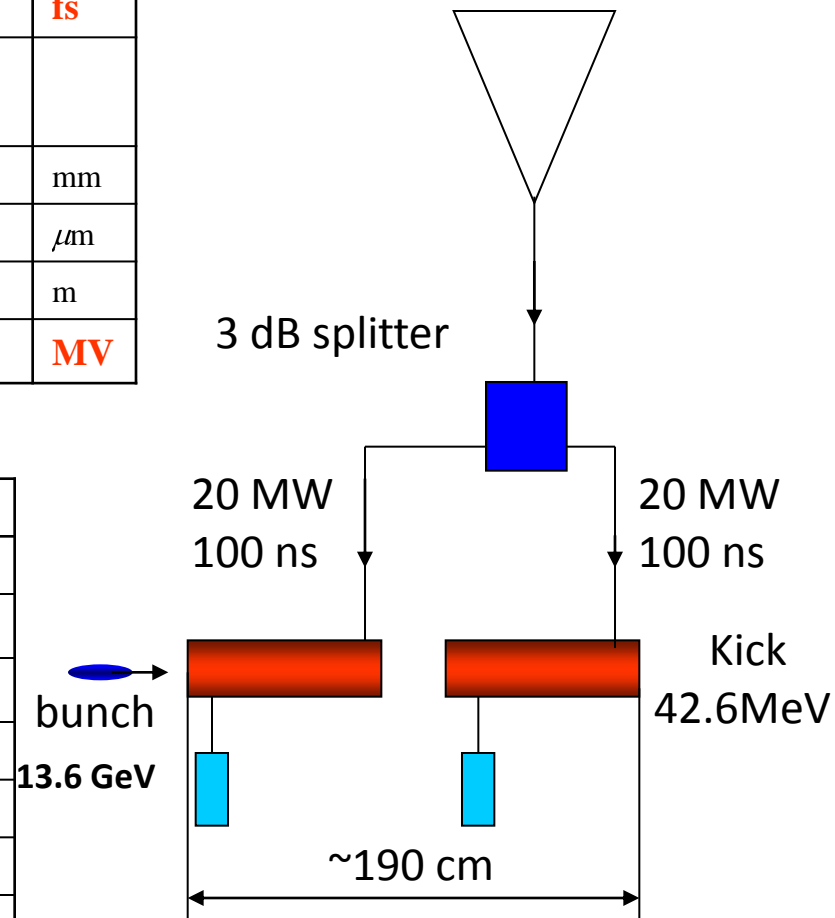
Table 1. Parameters for a 10-fs temporal resolution using an X-band RF deflecting cavity.

Parameter	symbol	value	unit
Electron energy	E	13.6	GeV
Desired temporal resolution	Δt	10	fs
Offset of Δt -particle on screen, in units of rms beam size	n	2	
RF wavelength of deflector (X-band)	λ	26	mm
Vertical normalized rms emittance	ε_N	1	μm
Vertical beta function at the center of the RF deflector	β_d	50	m
Peak vertically accelerating voltage seen by beam	V	33	MV

SLAC XL-4 Klystron, 50 MW, <1.6 μs

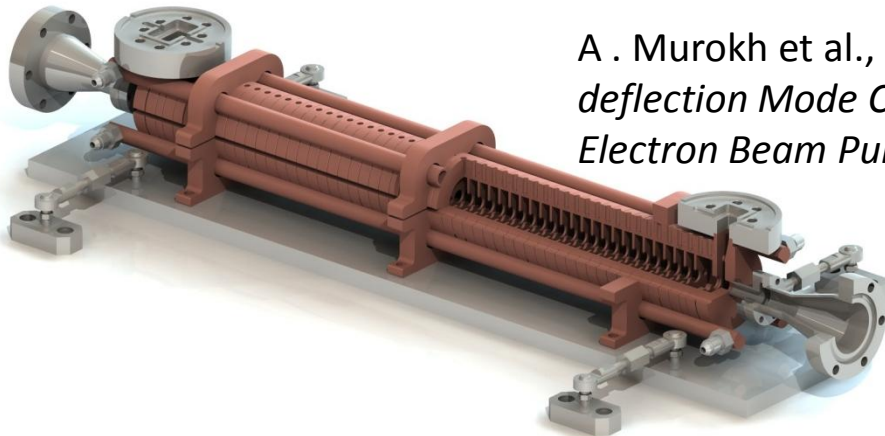
Table 3. Approximate specifications for an X-band RF deflecting cavity.

Parameter	symbol	value	unit
Maximum repetition rate	f	120	Hz
Minimum iris radius (if located after undulator)	r	5	mm
Maximum cavity length (approx.)	L	2	m
Minimum RF pulse length	$\Delta\tau_{RF}$	100	ns
RF frequency	f_{RF}	11.424	GHz
RF phase stability at $f > 1$ Hz (rms)	ϕ_{rms}	0.05	deg-X
RF relative amplitude stability (rms)	$\Delta V/V_0$	1	%



11.424 GHz Traveling Wave Deflector by Radiabeam Technologies

Frequency	11.424 GHz
Beam pipe diameter	10 mm
Phase advance per cell	$2\pi/3$
Kick per meter	38 MeV/m/Sqrt(20 MW)
53 cell structure kick	15 MeV/Sqrt(20 MV)
Maximum Electric field (first regular cell)	92 MV/m/Sqrt(20 MW)
Maximum Magnetic field (first regular cell)	345 kA/m/Sqrt(20 MW)
Group velocity/ speed of light	2.7 %
Structure length	~46 cm



A . Murokh et al., *Design and Fabrication of an X-band Traveling Wave deflection Mode Cavity for Longitudinal Characterization of Ultra-Short Electron Beam Pulses*, Proc. Of EPAC08, Genoa, Italy, 2008, pp. 1215-1217

A . Murokh, Radiabeam Tech.

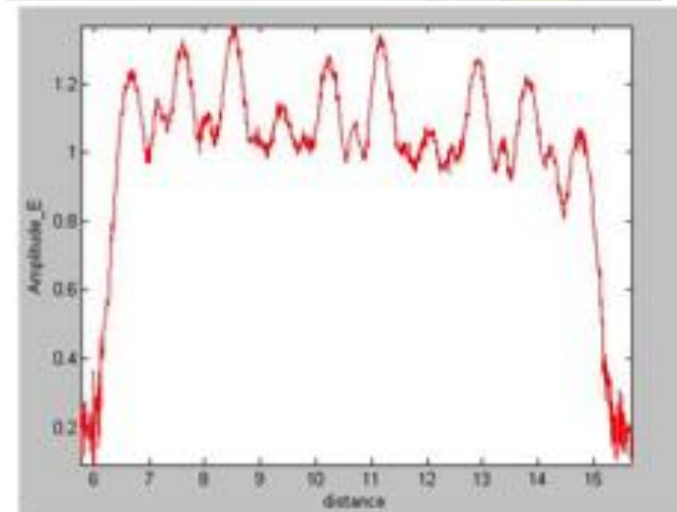
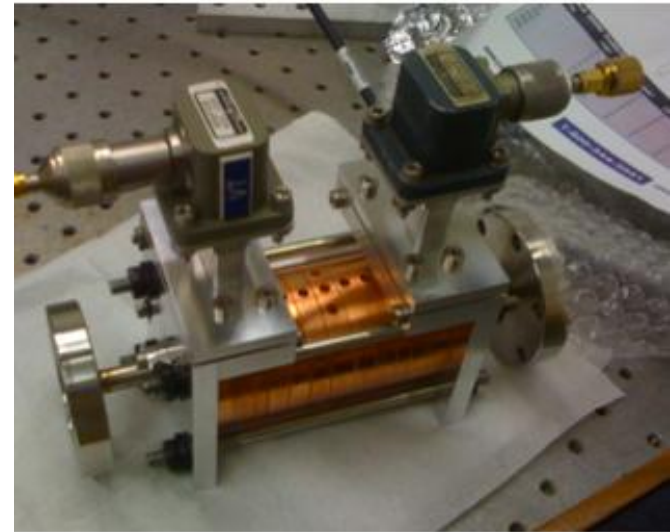
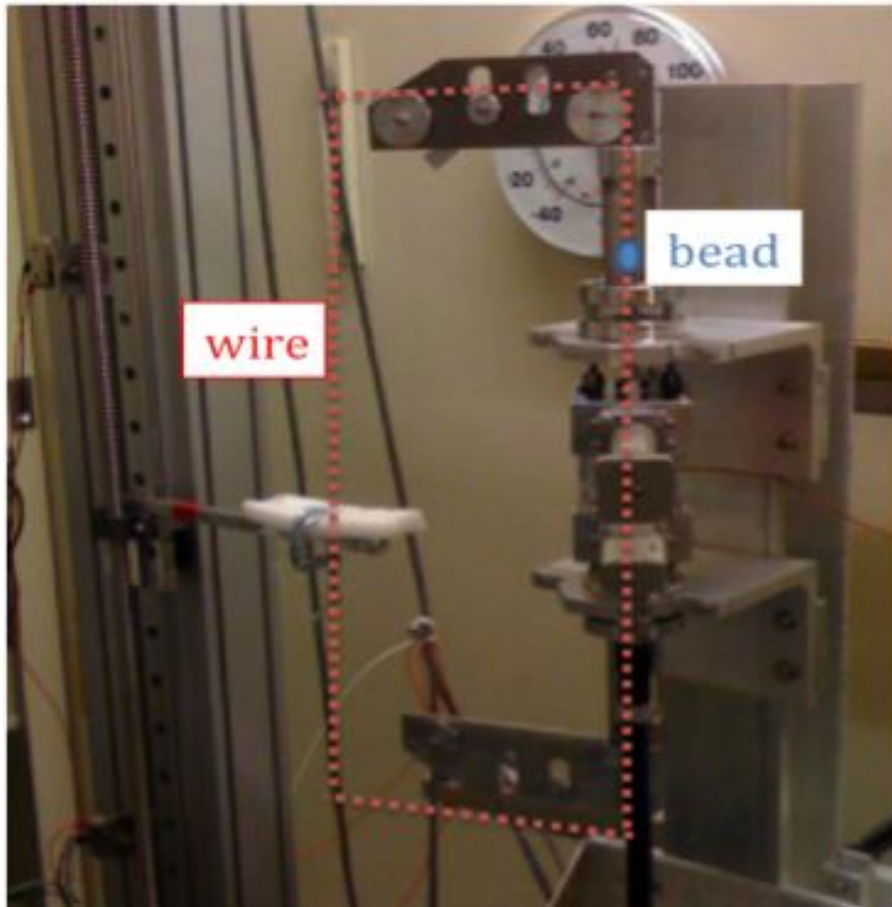
Manufacturing



Adapted SLAC cleaning and handling procedures developed for high gradient X-band structures

A . Murokh, Radiabeam Tech.

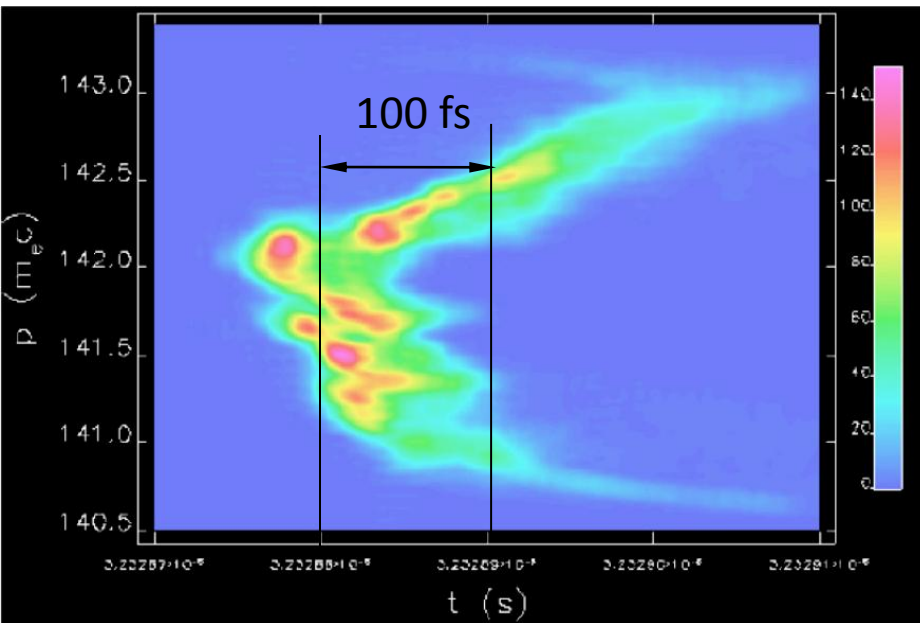
Bead pull Test of Clamped Structure at SLAC



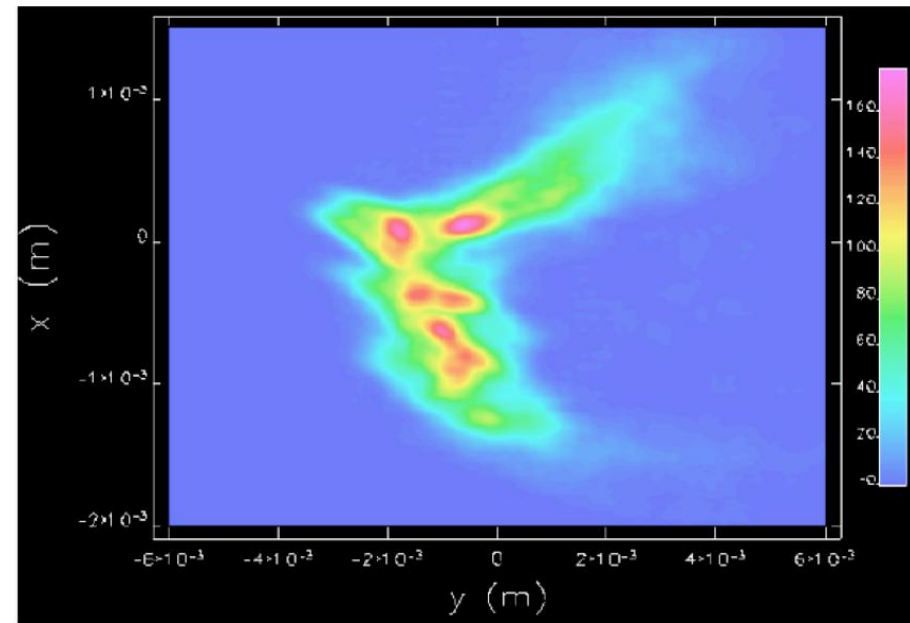
Fields measured along axis

Application: Measurements of Longitudinal Phase Space of BNL ATF Beam

Longitudinal resolution should be better than 10 fs for beam energy 75 MeV and transverse emittance $\sim 2 \text{ } \mu\text{m}$.



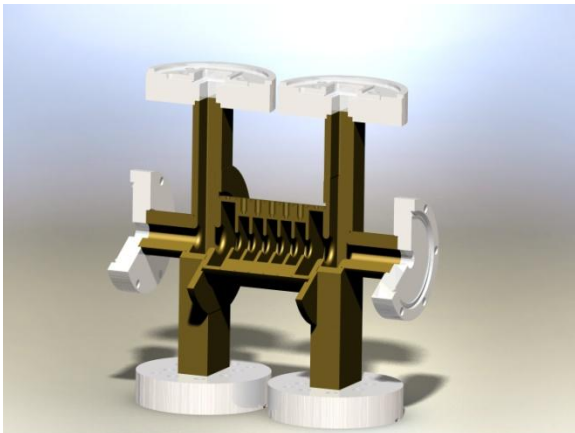
Numerical (ELEGANT) model of ATF X-band deflector experiment: a post-compressor beam longitudinal phase space in (p,t)-coordinates



(X,Y) map after the rf deflector and a bending magnet

11.424 GHz TW Deflector Prototype for Linear Collider CLIC

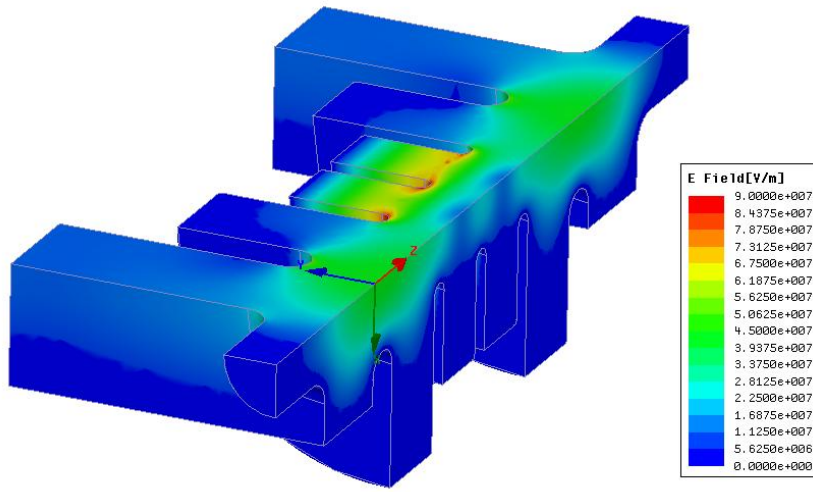
Frequency	11.424 GHz
Beam pipe diameter	10 mm
Phase advance per cell	$2\pi/3$
Kick per meter (regular. cell)	37 MeV/m/Sqrt(20 MW)
5 cell structure kick	1.62 MeV/Sqrt(20 MV)
Maximum Electric field	100 MV/m/Sqrt(20 MW)
Maximum Magnetic field	350 kA/m/Sqrt(20 MW)
Structure length (with beam pipes)	~18 cm



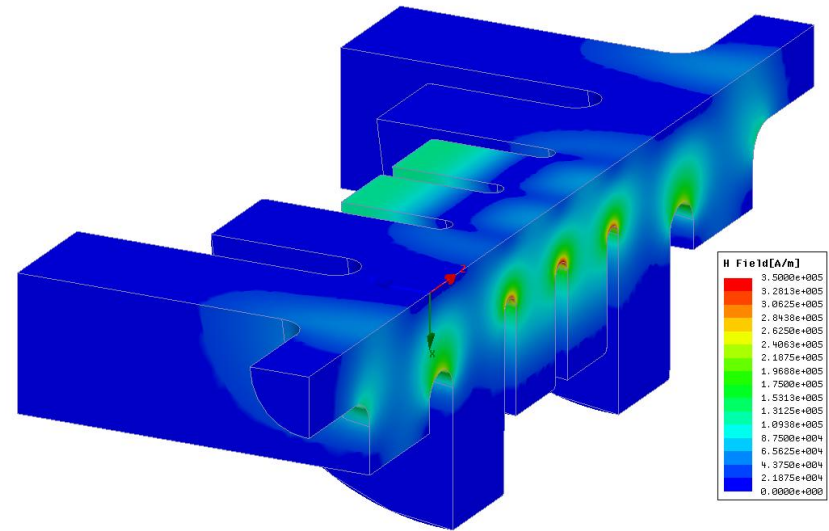
There are plans to test this prototype at SLAC to study high power aspects of its operation.

G. Burt et al., *X-band crab cavities for the CLIC beam delivery system*, Proceedings of X-Band Structures and Beam Dynamics Workshop (XB08), Cockcroft Institute, UK, 1-4 dec. 2008, arXiv:0903.2116v1

11.424 GHz TW Deflector Prototype for Linear Collider CLIC, HFSS Model for Two Regular Cells With Couplers



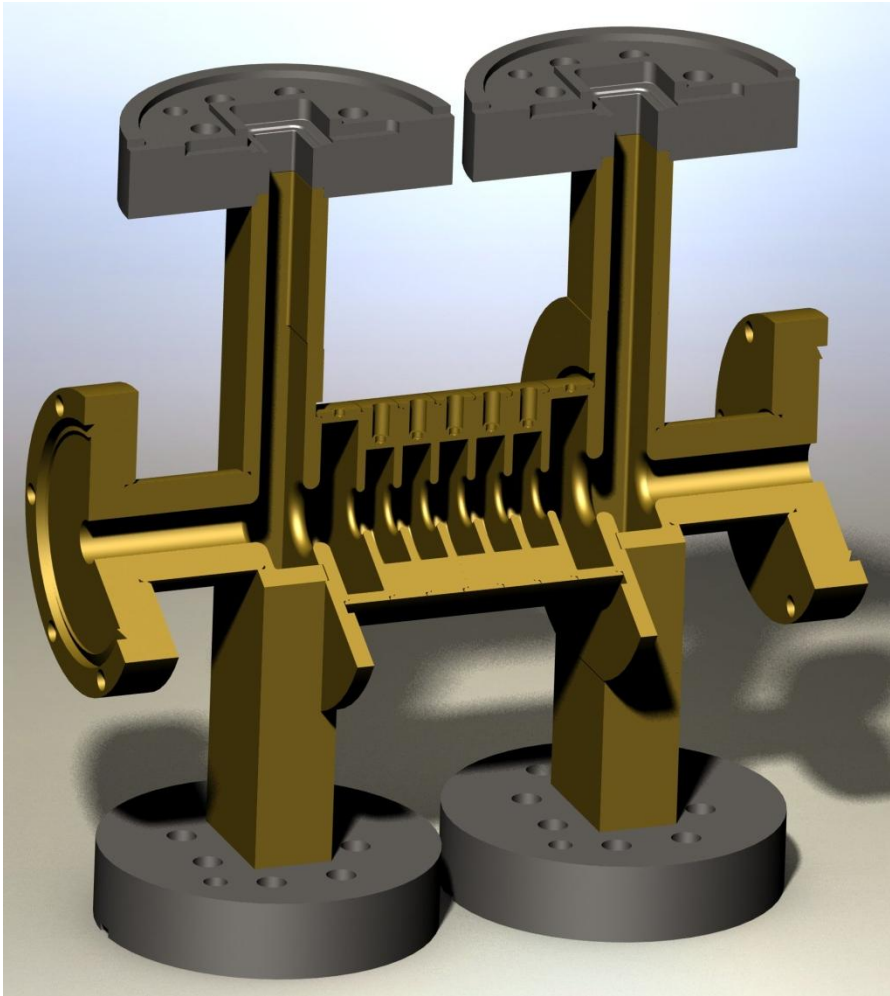
Maximum surface
electric field ~ 90 MV/m



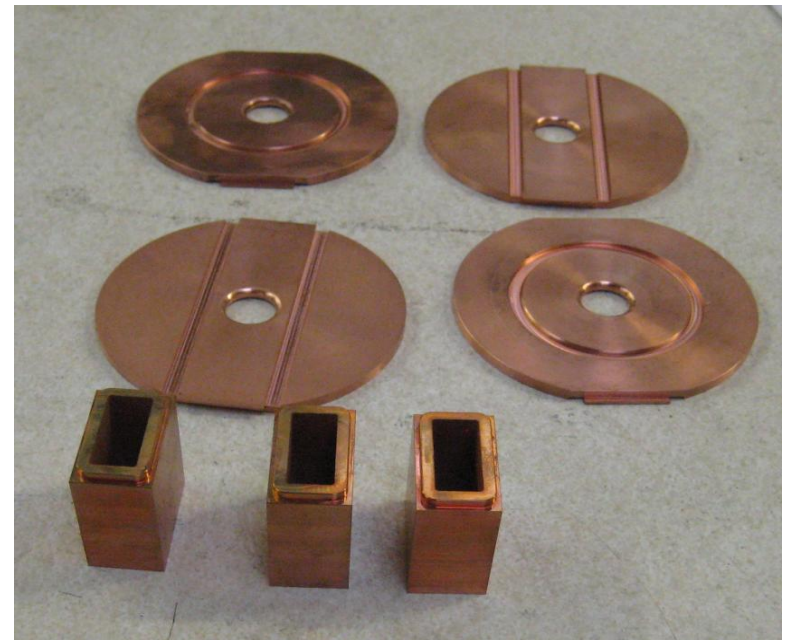
Maximum surface magnetic field ~ 350 kA/m,
pulse heating 24 deg. C for 200 ns pulse

Fields for 20 MW of transmitted power

11.424 GHz TW Deflector Prototype for Linear Collider CLIC



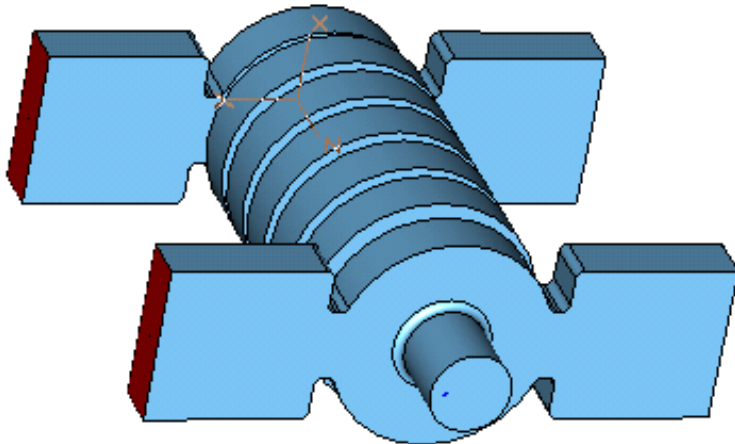
Solid model



Coupler parts

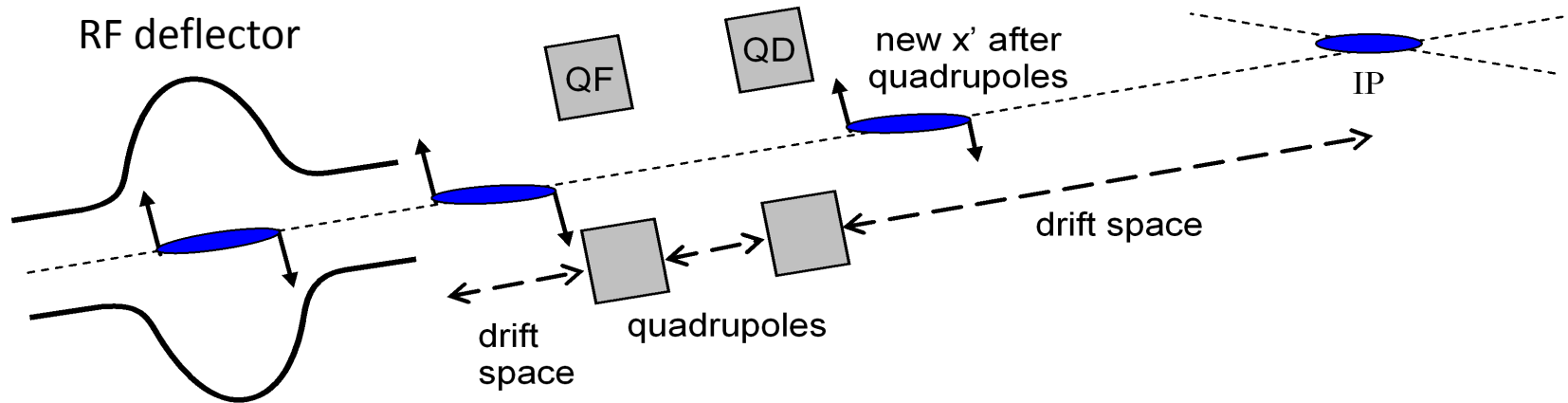
12 GHz TW Deflector for Linear Collider CLIC

Frequency	12 GHz
Beam pipe diameter	10 mm
Phase advance per cell	$2\pi/3$
Kick per meter (regular. cell)	33 MeV/m/Sqrt(20 MW)
9 cell structure kick	2.5 MeV/Sqrt(20 MV)
Maximum Electric field (regular cell)	90 MV/m/Sqrt(20 MW)
Maximum Magnetic field (regular cell)	314 kA/m/Sqrt(20 MW)
Group velocity/ speed of light	2.95 %
Structure length (without beam pipes)	~10 cm



Application: *Crab Crossing* Using RF Deflectors Near Interaction Point in a Linear Collider

Ref.: R. B. Palmer, *Energy scaling, crab crossing and the pair problem*, SLAC-PUB-4707, 1988

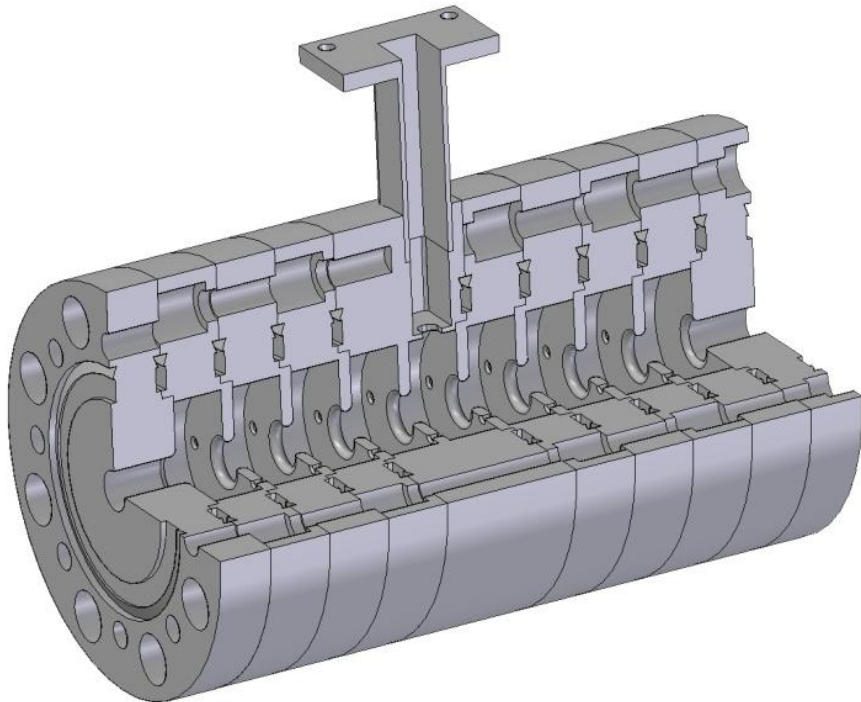


- RF deflector is placed in each beamline
- Cavity is phased that there is no net deflection at the interaction point, the bunch rotated around its centre

Operation of the rf deflectors for the crab crossing puts tight requirements on phase and amplitude jitter between both deflectors and on wakefield damping. In case of 12 GHz deflector the jitter has to be $< 2.1\%$ for amplitude and < 0.018 deg. phase.

9.6 GHz SW deflector at UCLA

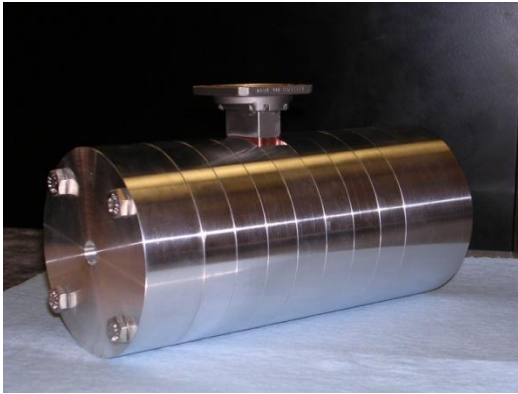
Frequency	9.596 GHz
Beam pipe diameter	10 mm
Phase advance per cell	π
9 cell structure kick	0.528 MeV/Sqrt(50 kW)
Unloaded Q	13043
External Q	13517
Structure length (without beam pipes)	~14 cm



R. J. England et al., *X-Band Dipole Mode Deflecting Cavity for the UCLA Neptune Beamline*, in Proc. of PAC 2005 , Knoxville, Tennessee

Design Evolution

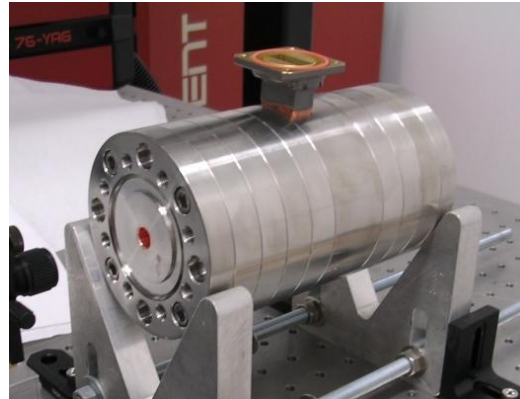
2004



cold test prototype

Aluminum
9-cell
9.3 GHz
cold-test only
clamped
no polarization separation

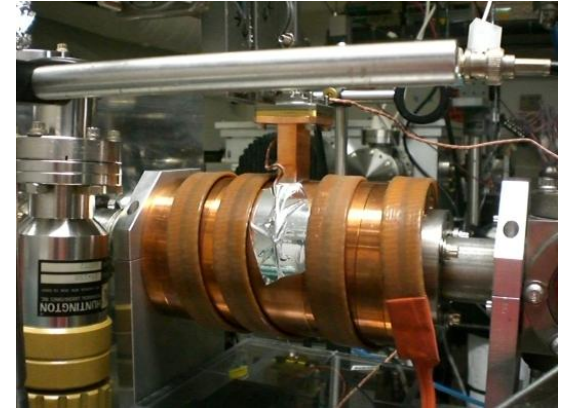
2005



steel prototype

Steel with Cu coating
9-cell
9.5 GHz
cold-test only
conflat flange design
no polarization separation

2006



final design

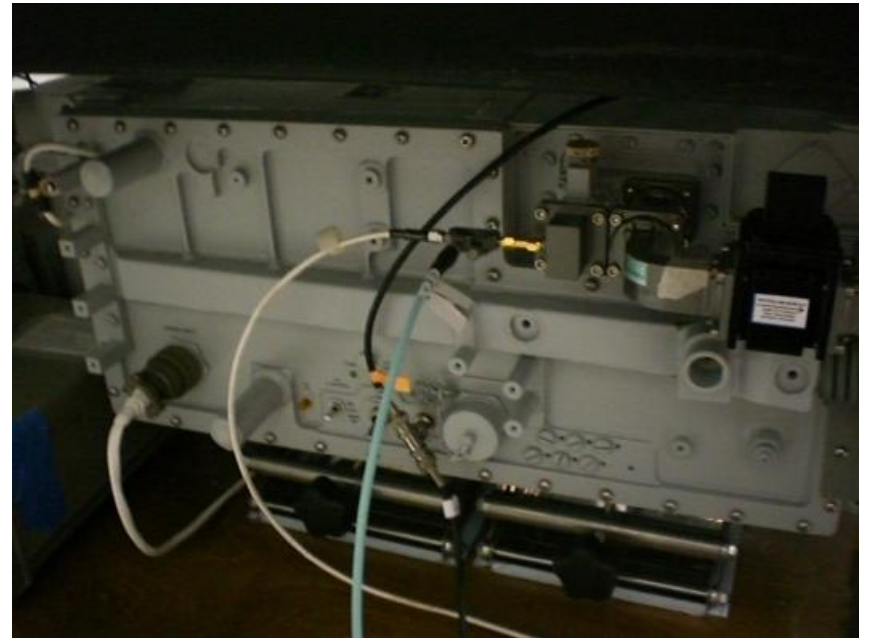
GlidCop Al-15
9-cell
9.59616 GHz
tested up to 50kW peak power
conflat flange design
EDM'd polarization holes

Final Cavity Design

- 9-cell standing wave structure
- center-fed input rf
- reconditioned 50 kW VA-24G klystron
- no brazing between cells
- cells are stacked ConFlat vacuum flanges

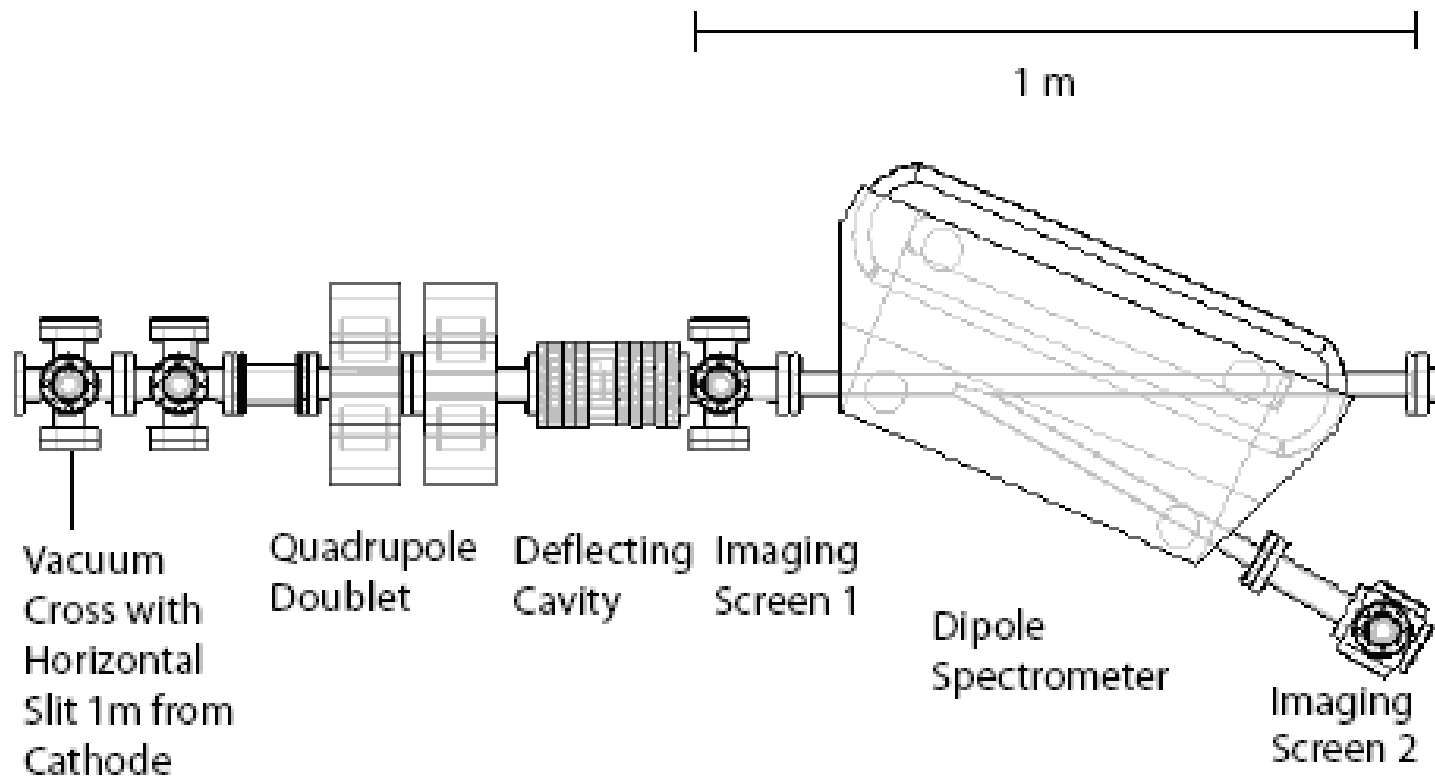


one cell with polarization holes



X-band klystron (50 kW peak)

Application: Measurement of Longitudinal Phase Space

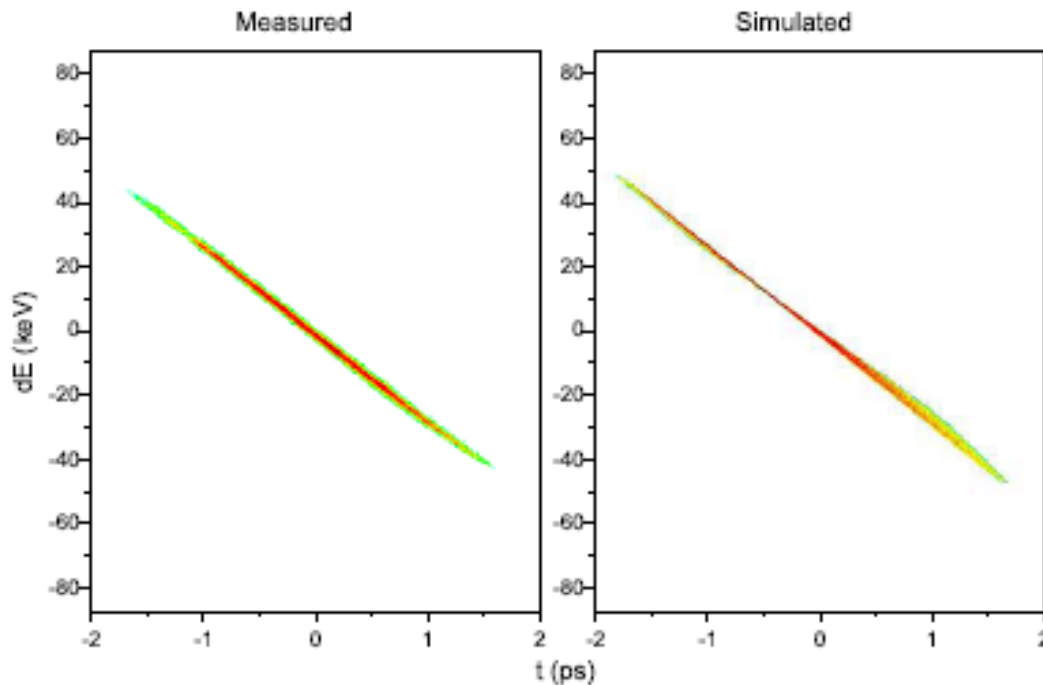


Application: Measurement of Longitudinal Phase Space

Measurements of 3.5 MeV beam:

- Time resolution is 50 fs
- Energy resolution is 1 keV, determined by energy spread introduced by rf deflector

J. T. Moody et al., *Longitudinal phase space characterization of the blow-out regime of rf photoinjector operation*, Phys. Rev. STAB 12, 070704 (2009)



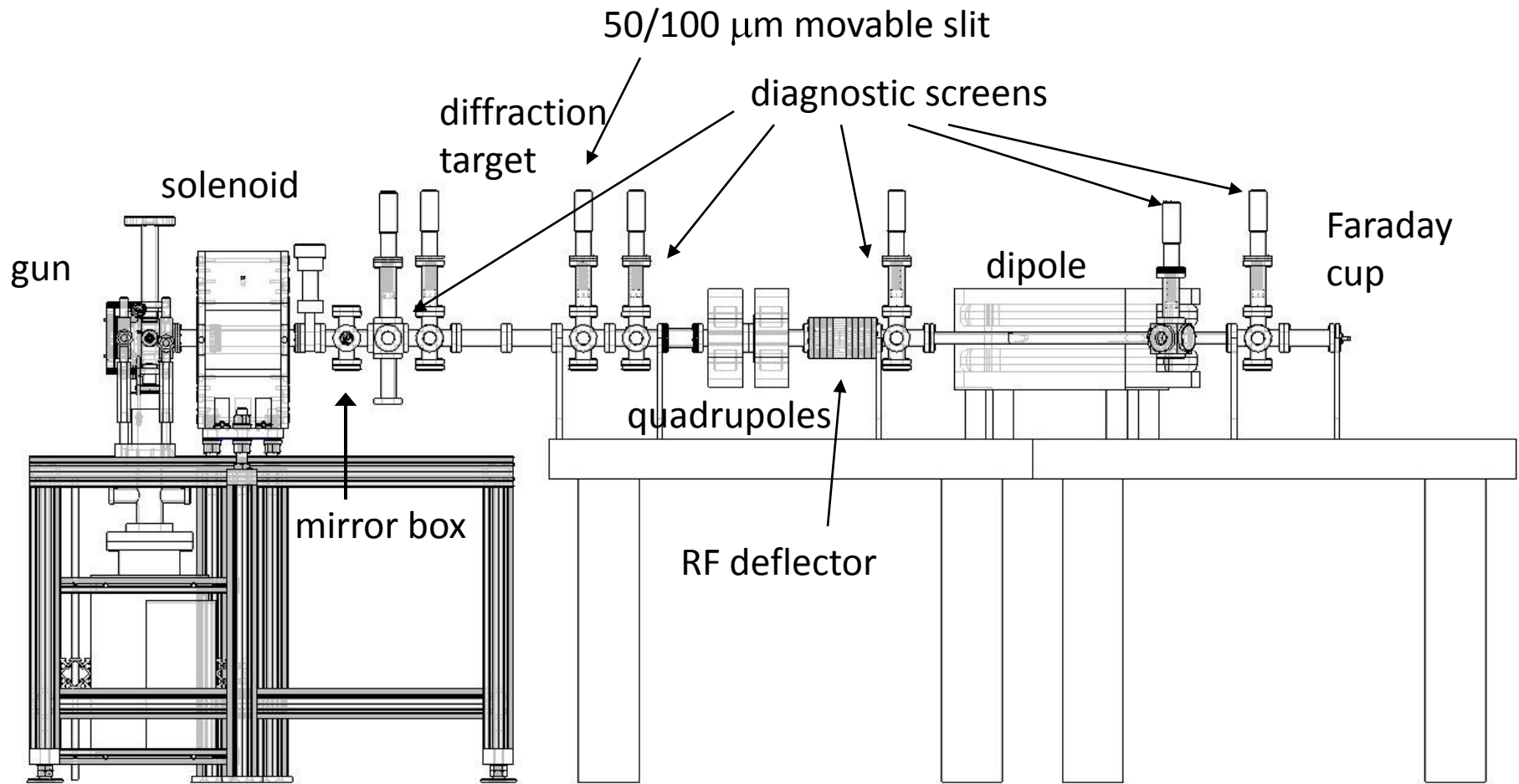
Very linear phase space

High 6D beam
brightness

Ultralow longitudinal
emittance ($<0.5 \text{ } \mu\text{m}$)

Longitudinal phase space measurement compared with simulation.
Bunch charge 20pC, 500 micron rms laser spot size on the cathode.

Application: Single Shot Ultrafast Electron Diffraction (UED)



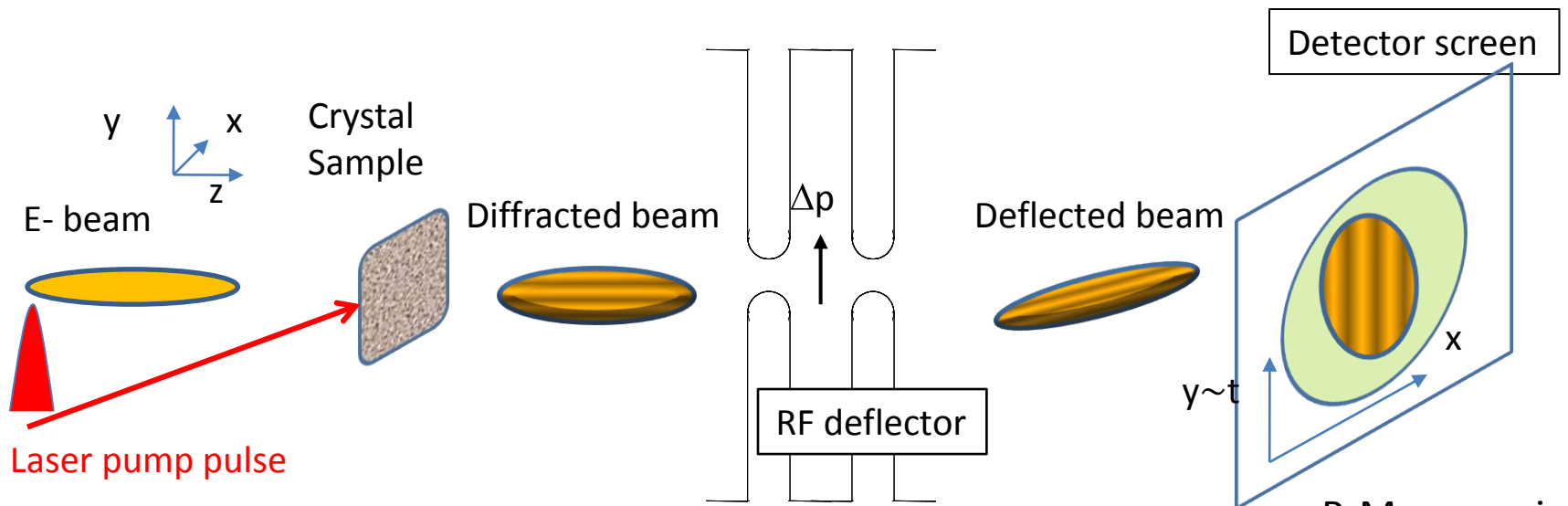
P. Musumeci et al., *Relativistic electron diffraction at the UCLA Pegasus photoinjector laboratory*, *Ultramicroscopy*, Volume 108, Issue 11, October 2008, Pages 1450-1453

P. Musumeci, UCLA

Application: Single shot Ultrafast Electron Diffraction

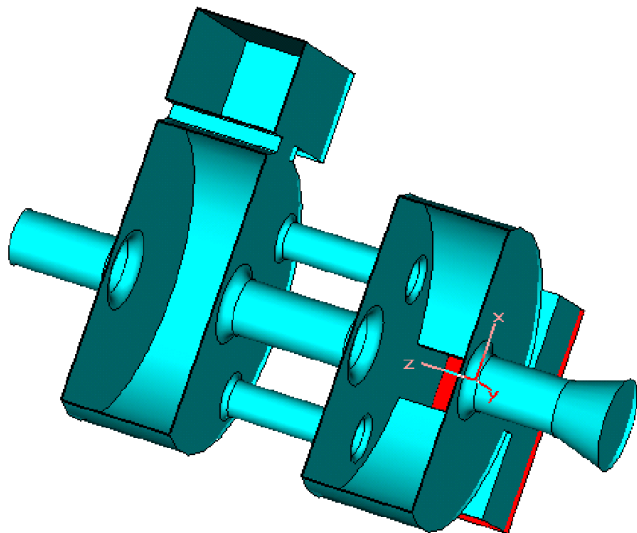
- Use RF deflecting cavity as a streak camera to time-resolve a relatively long (10s of ps) electron beam after its interaction with the diffraction sample.
- Advantages
 - Eliminates limitation of the time resolution due to the length of the electron beam and therefore significantly improves the temporal resolution of the technique.
 - Yield true single-shot structural change studies revolutionizing the approach of the conventional pump-probe experimental procedure.

By using an X-band deflector powered by 5 MW X-band klystron the Ultrafast Electron Diffraction could be done with <5 fs resolution



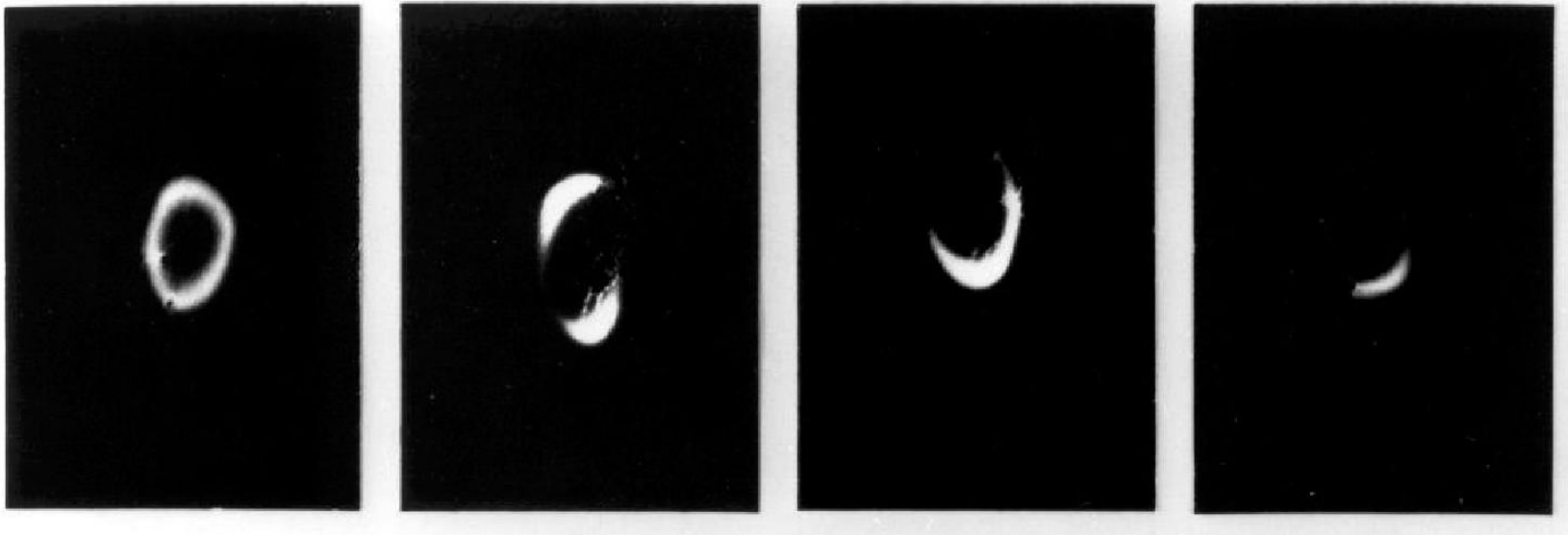
17 GHz circularly polarized SW deflector by Haimson Research Corporation

Frequency	17.136 GHz
Beam pipe diameter	4.96 mm
One polarization kick	0.42 MeV/Sqrt(734 kW per cavity)
Unloaded Q	3500
External Q	3500
Maximum electric field	89 MV/m/Sqrt(734 kW per cavity)
Maximum magnetic field	204 kA/m/Sqrt(734 kW per cavity)



Advanced Accelerator Concepts, AIP Conference Proceedings, 647, (New York: AIP Press, 2002) , pp. 810-820
Advanced Accelerator Concepts , AIP Conference Proceedings, 737, (New York: AIP Press, 2004), pp. 95-108

Method

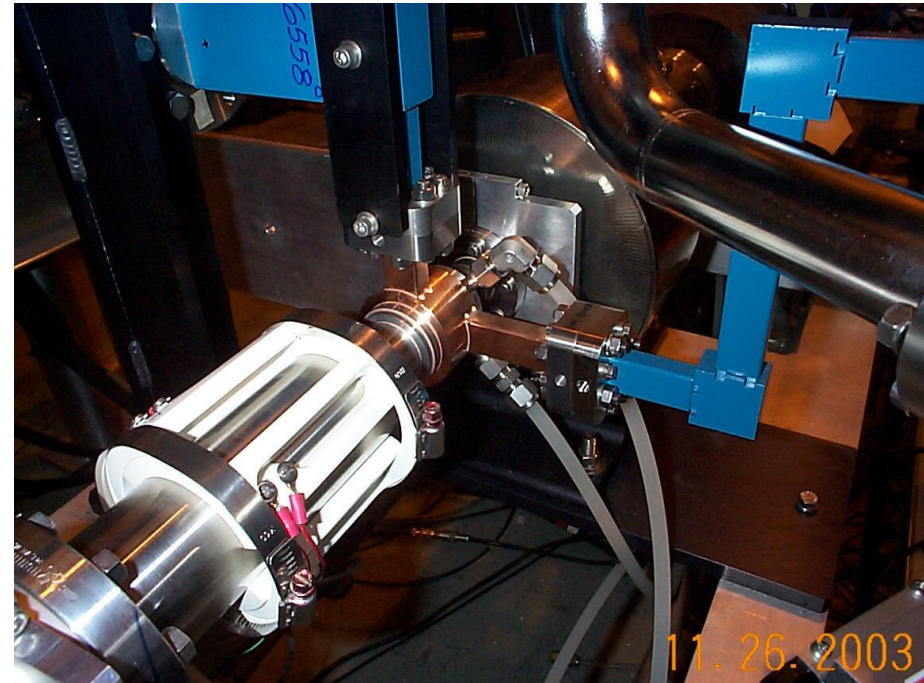
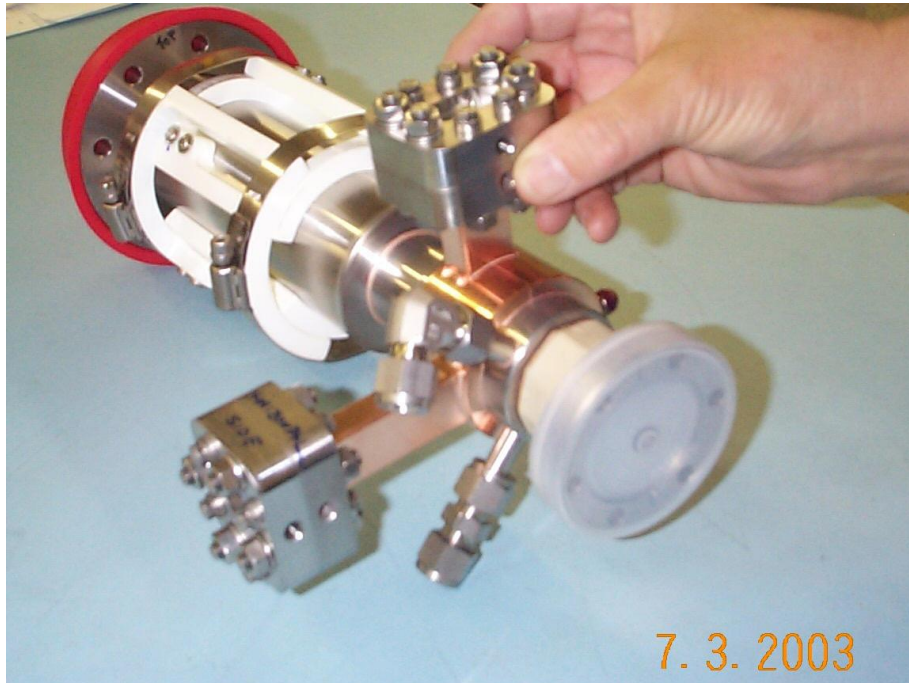


S-Band RF Bunch Measurements Using a Circularly Scanned Beam
(2 x TE102 Rectangular Cavities With Transverse Magnetic Fields)

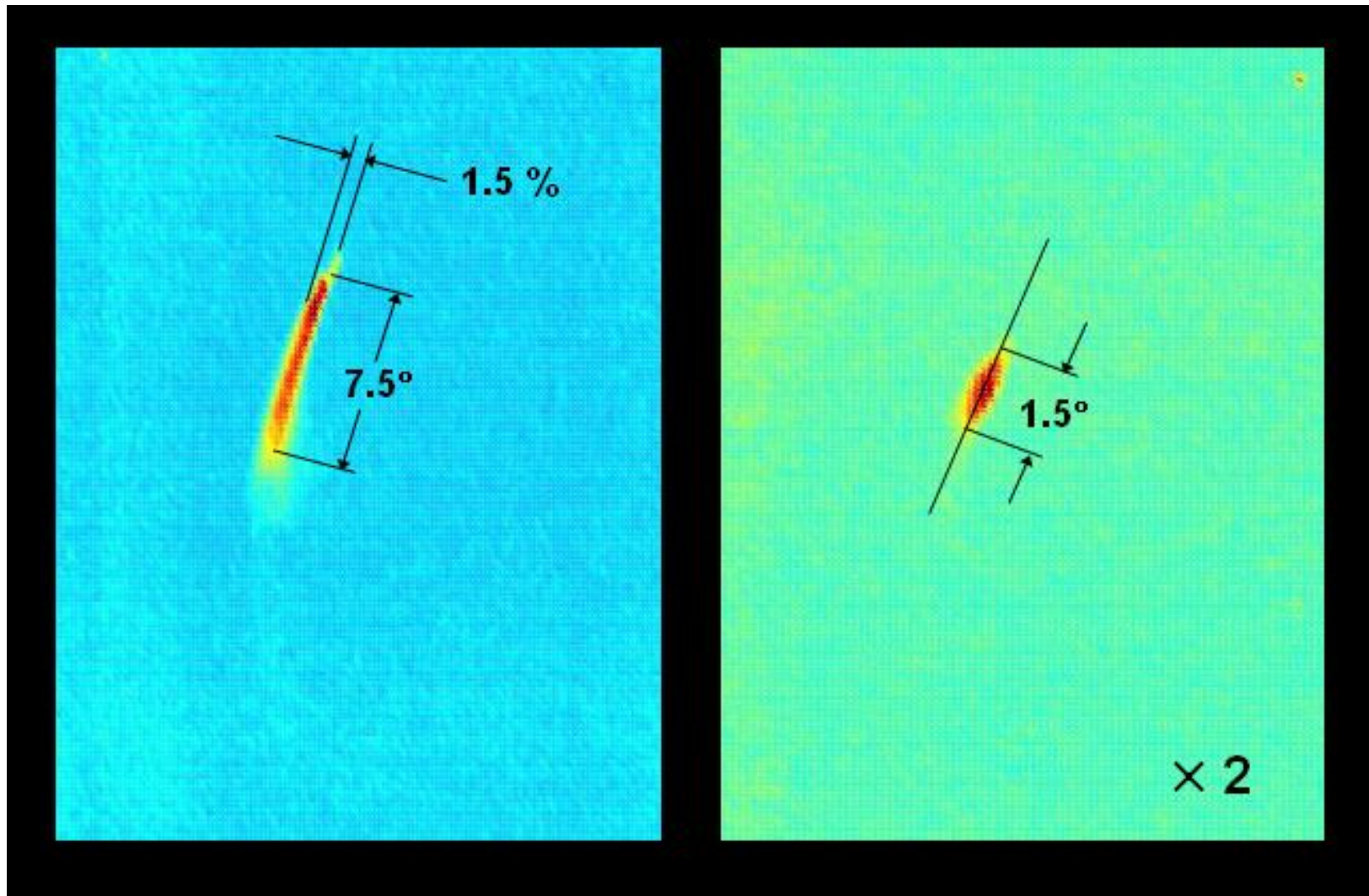
J. Haimson, *High Current Traveling Wave Electron Linear Accelerators*, In *Proc. of PAC 1965*, Washington DC, March 1965, pp. 996-1011

J. Haimson, *Optimization Criteria for Standing Wave Transverse Magnetic Deflection Cavities*, *Proc. of 1966 Linear Accelerator Conference*, LA-3609, Los Alamos, 1966, pp. 303-331.

17 GHz Circularly Polarized RF Deflector Designed for Displaying the Longitudinal Phase Space of 1 Degree Electron Bunches from a 17.136 GHz 15 MeV Linac



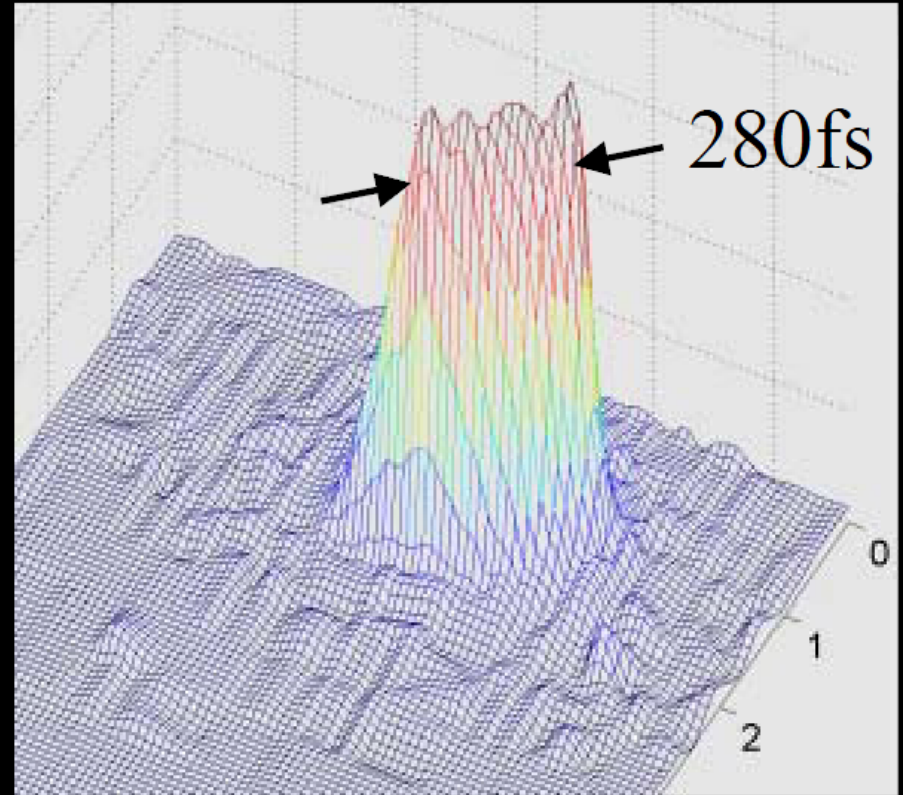
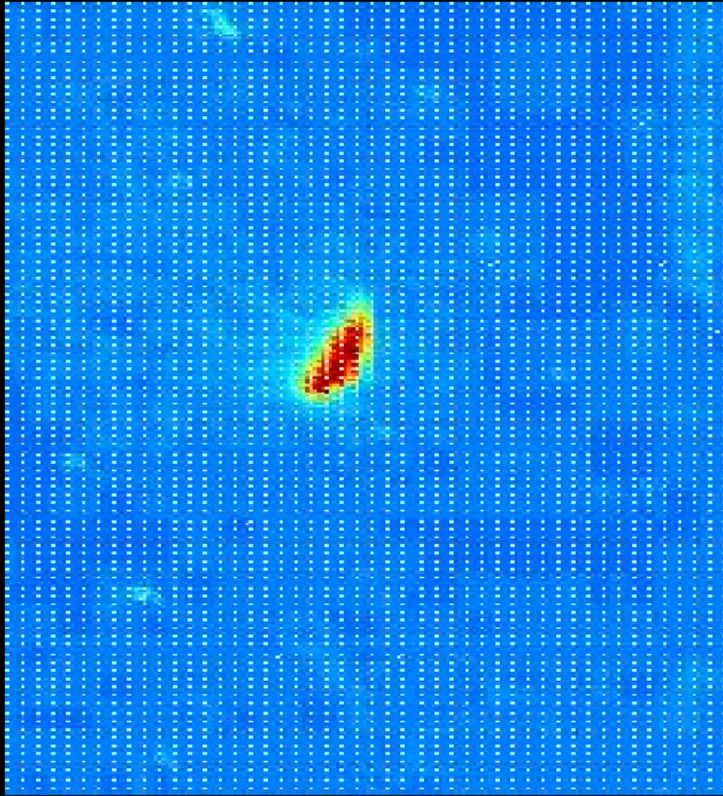
Application: Measurement of Longitudinal Phase Space



Typical electron bunch longitudinal phase space displays obtained with near optimum chopper-prebuncher operation of the 17 GHz linac, showing the energy and phase charge distributions as the injector controls were adjusted to reduce the bunch length by a factor of 5.

J. Haimson, Haimson Research Corporation

Application: Measurement of Longitudinal Phase Space



15 MeV, 1.7° Linac Bunch After Circularly Polarized Deflection and Transmission Through a Matrix of Precision Collimators

New X-band RF Sources

Recently advertised commercial 9.3 GHz klystrons

Parameter	Units	CPI-VKX-7993	L3-L-6145
Focusing		PPM	Solenoid
Frequency	GHz	9.3	9.3
Peak Power	MW	2.7	5
Average Power	kW	5.4	20
Efficiency	%	43	47
Saturated Gain	dB	53	47
Bandwidth (-1 dB)	MHz	65	>40MHz
Beam Voltage	kV	120	130
Duty factor	%	0.2	0.4
Beam Current	A	52	83



CPI-VKX-7993



L3-L-6145

A. Balkcum et al., *Design and Operation of a 2.5 MW, PPM Focused X-Band klystron*, In Proc. of IEEE International Vacuum Electronics Conference, Rome, Italy, April 28-30, 2009

Mark Kirshner et al., *High Power X-Band Klystron*, In Proc. of IEEE International Vacuum Electronics Conference, Rome, Italy, April 28-30, 2009

Summary

- X-band deflectors are used for beam manipulations, fs beam diagnostics, and novel methods in ultrafast physics
- Development of new rf deflectors utilizes mature high gradient X-band technology
- Introduction of commercial X-band klystrons opens new possibilities for practical applications of the rf deflectors