# X-Band Deflectors Development at SLAC

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# Outline

1. Introduction of Deflector
2. Deflector Applications
3. Time-resolved electron bunch diagnostics for the LCLS.
4. Super fast RF kicker for the PEP-X Light Source.

# Contributors

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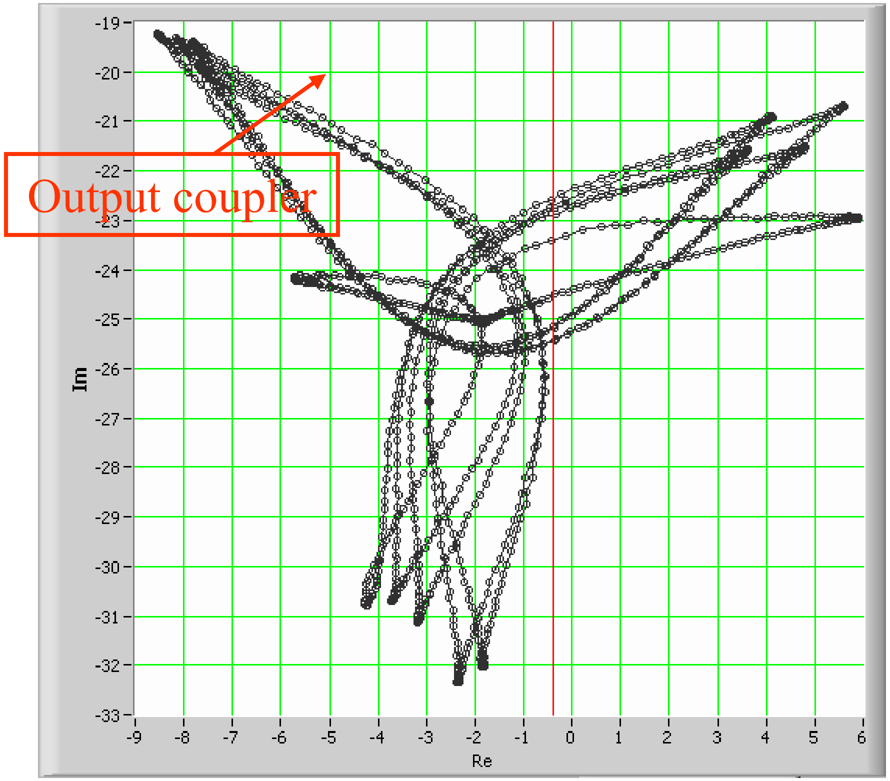
# 1. Introduction

# Early Deflectors

The RF deflectors were developed from 1960's for high energy particles separation using the interaction with a transversely deflecting HEM11 mode.

**Retest of a 13-cell S-Band LOLA structure built in 1960s, which has been installed in LCLS and used for beam diagnostics.**


Complex reflection while a 8mm bead pulling through the deflector with 7.5 mm offset



# Advantages of Traveling Wave X-Band Deflectors

- Simpler RF systems without the requirement of circulators for standing wave structures.
- Higher shunt impedances (proportional to the square root of frequency) than structures working at lower frequencies.
- SLAC is well advanced in the state of art in high power X-Band RF source including klystrons and pulse compression systems.

# Profile of a Structure for Fast Kicker

As a measure of the deflecting efficiency, the transverse shunt impedance $r_\perp$ is defined as:

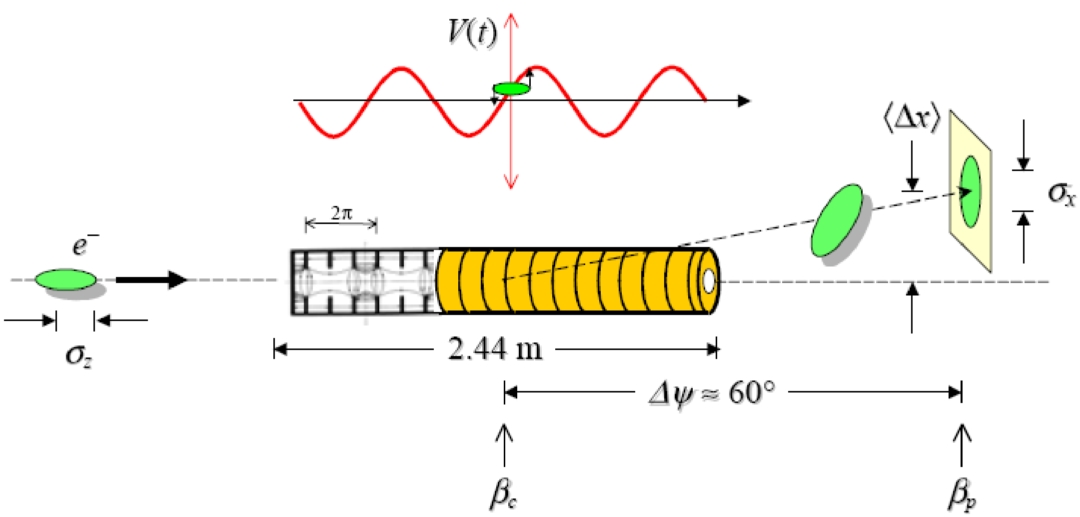
$$r_\perp = \frac{\left(\frac{c}{\omega}\frac{\partial E_z}{\partial r}\right)^2}{\partial P / \partial z}$$

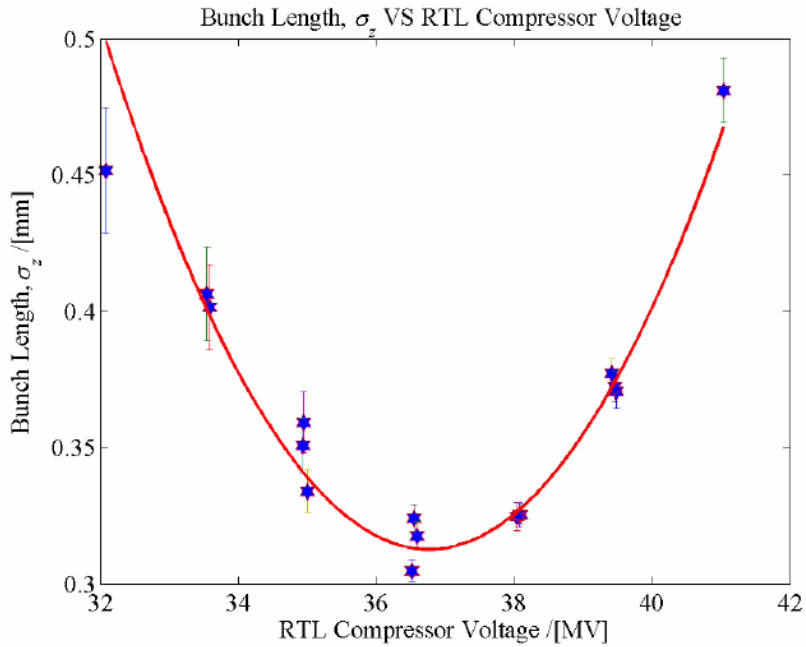
where z and r is structure longitudinal and transverse axis respectively, $E_z$ is the electrical field amplitude for the dipole mode with angular frequency $\omega$ and P is the RF power as function of z.

Using the simulation codes for electromagnetic field in RF structures, the transverse shunt impedance can be calculated from:

$$r_\perp = \frac{Q V_\perp^{\,2}}{\omega U L} = \frac{c^2 Q V_z^{\,2}}{\omega^3 r_0^2 U L}$$

# Bunch Length Measurement Using a RF Deflector




Principal of operation of the TM11 transverse deflecting RF cavity to crab the electron beam and measure its bunch length on a profile monitor.

Bunch length measured as a function of RTL compressor voltage.

SLAC-PUB-9241 by R. Akre, L. Bentson, P. Emma, P. Krejcik

# 2. Deflector Applications

# Applications of Deflectors

1. Time-resolved electron bunch diagnostics for LCLS and other FEL projects worldwide.
   - > 33 MV vertical deflecting voltage (10-fs temporal resolution)
   - Optimization for high RF efficiency
   - Meet all requirements for beam line tolerances.
2. Super-fast RF kicker for picking single bunch from bunch-train in the FEL insertion elements designed for the PEP-X to use B-Factory bunches.
   - Short RF filling time < 6 ns
   - > 5 MV vertical deflecting voltage
   - Realistic RF power requirement
3. RF kicker for the ILC damping ring.
4. RF separator for ± particles.
5. Crab cavity for linear collider.

# 3. Time-resolved electron bunch diagnostics for the LCLS

# Requirement to the Future Deflector

In order to characterize the extremely short bunch of the LCLS project, we need to extend the time-resolved electron bunch diagnostics to the scale of 10-20 fs. We have to consider a new RF deflector with much powerful deflecting capability. The peak deflecting voltage necessary to produce a temporal bunch resolution of $\Delta t$ is:

$$eV_{\perp} \approx n\frac{\lambda}{2\pi c\Delta t}\sqrt{\frac{\varepsilon_N Emc^2}{\beta_d}}$$

where $E$ is the electron energy and the transverse momentum of the electron at time $\Delta t$ (with respect to the zero-crossing phase of the RF) is $p_y = eV_{\perp}/c$, $n$ is the kick amplitude in the unit of nominal rms beam size, λ is the RF wavelength, $\varepsilon_N$ is the normalized rms vertical emittance, $c$ is the speed of light, and $\beta_d$ is the vertical beta function at the deflector. This is for an RF deflector, which is $\pi/2$ in betatron phase advance from a downstream screen.

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# Deflector Specifications

## 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 | $\Delta t$ | 10 | fs |
| Offset of $\Delta t$-particle on screen, in units of rms beam size | $n$ | 2 | |
| RF wavelength of deflector (X-band) | $\lambda$ | 26 | mm |
| Vertical normalized rms emittance | $\varepsilon_N$ | 1 | $\mu$m |
| Vertical beta function at the center of the RF deflector | $\beta_d$ | 50 | m |
| Peak vertically accelerating voltage seen by beam | $V$ | 33 | MV |

## 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) | $\varphi_{rms}$ | 0.05 | deg-X |
| RF relative amplitude stability (rms) | $\Delta V/V_0$ | 1 | % |

Deflector Location: After Undulator

Paul Emma
Technical Note
Oct. 18, 2006

# Design Examples for a Deflector

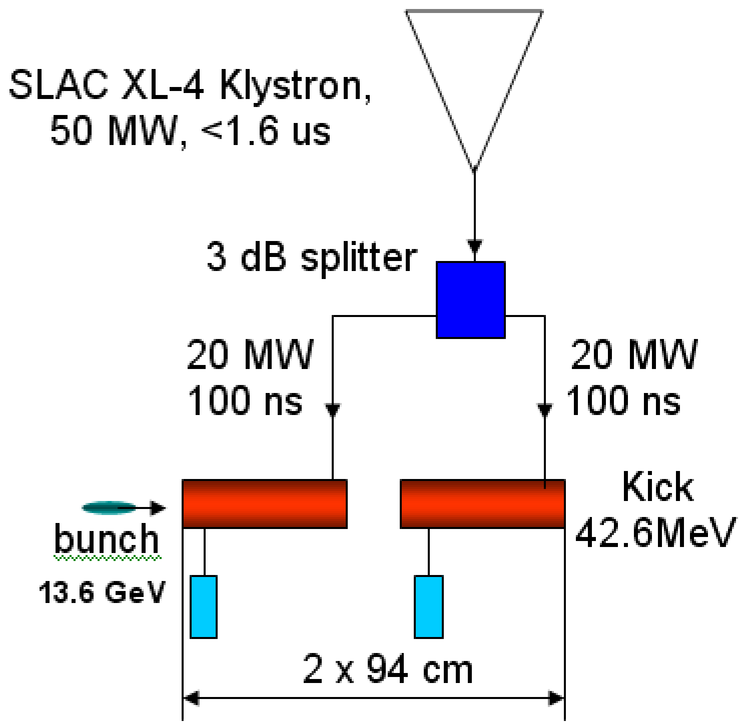
| | |
|---|---|
| Frequency | 11.424 GHz |
| Beam pipe diameter | 10 mm |
| One cell length | 8.747 mm |
| Phase advance per cell | $2\pi/3$ |
| Kick per meter [MeV/Sqrt [MW]] | 31 MeV/m/Sqrt (20 MW) |
| 102 cell structure kick | 21.3 MeV/Sqrt(20 MV) |
| Group velocity/ speed of light | 3.2 % |
| Filling time | 92 ns |
| Structure length (with beam pipes) | ~94 cm |

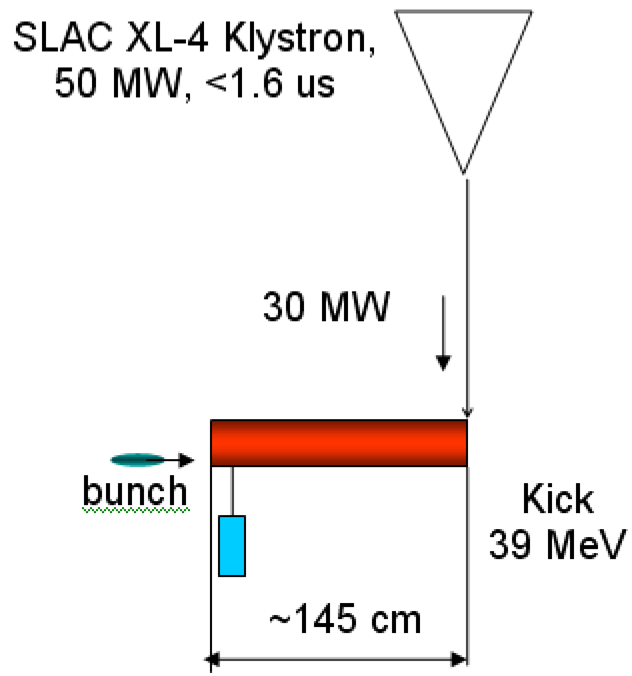
Structure design for a two-section system by Valery (LDRD Proposal)

| Structure type | TW DLWG |
|---|---|
| Mode | $2\pi/3$ Backward wave |
| Aperture 2a | 10.00 mm |
| Cavity diameter 2b | 29.74 m |
| Cell length d | 8.7475 mm |
| Disk thickness | 1.45 mm |
| Quality factor Q | 6400 |
| Kick factor k | $2.986\times10^{16}$ V/C/m/m |
| Transverse shunt impedance $r_\perp$ | 43.17 M$\Omega$/m |
| Group velocity Vg/c | - 3.165 % |
| Total length L | 1.5 m |
| Filling time $T_f$ | 158 ns |
| Attenuation factor $\tau$ | 0.885 |
| Input peak RF power | 30 MW |
| Maximum electric field | 129 MV/m |
| Maximum magnetic field | 0.45 MA/m |
| Deflecting voltage | 38.9 MV |

Structure design for a one-section system by Juwen & Sami (LINAC2008, SLAC-PUB-13444)

# System Layout

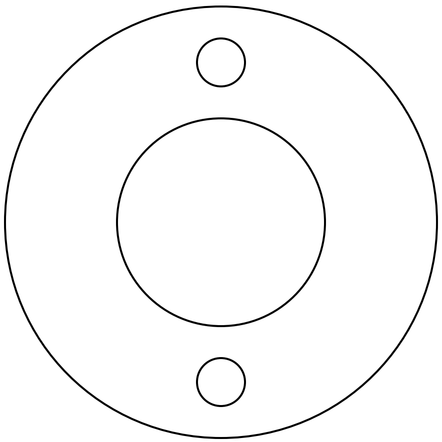


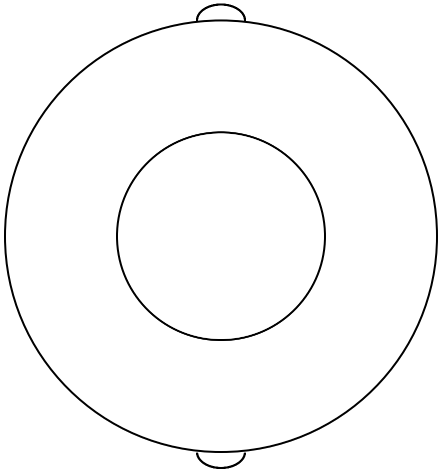

**Two-section system**

**One-section system**

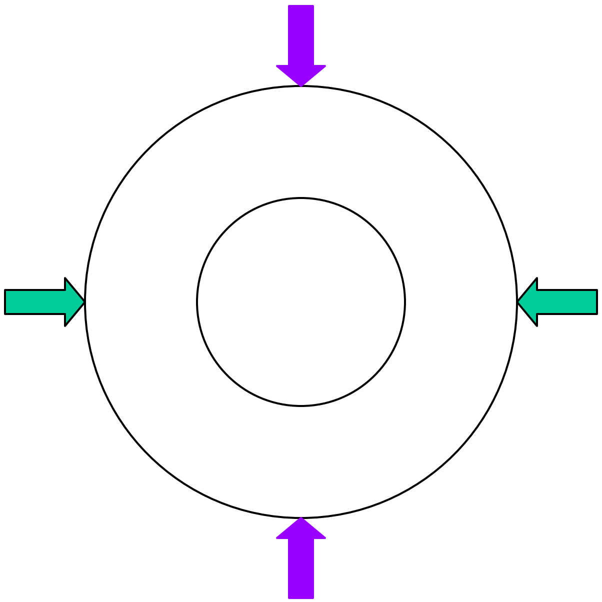
# Cup Shapes for Stabilization of Desired Polarized Dipole Modes



Two holes
(LOLA Structures)

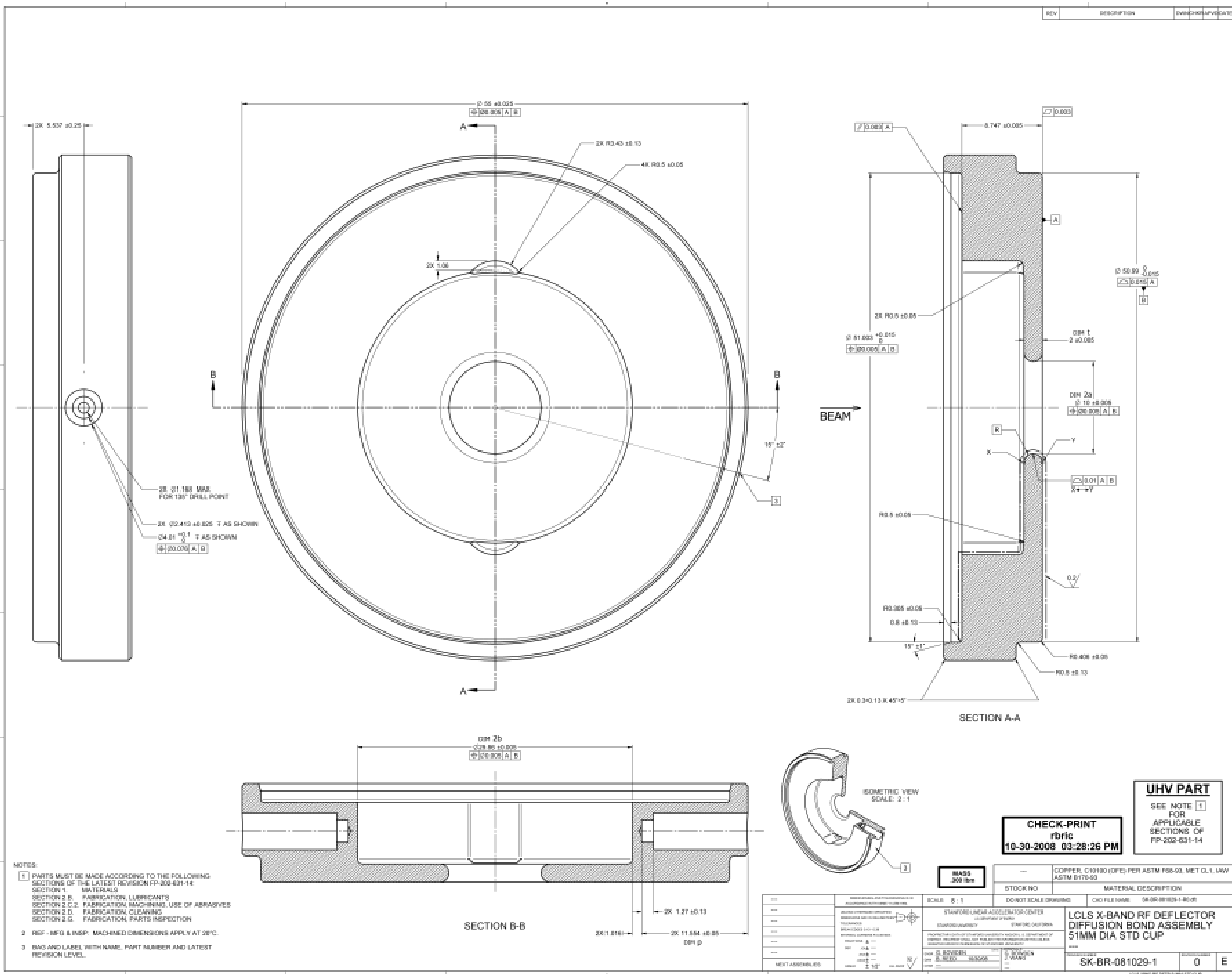


Two caved-ins
on cell ID surfaces

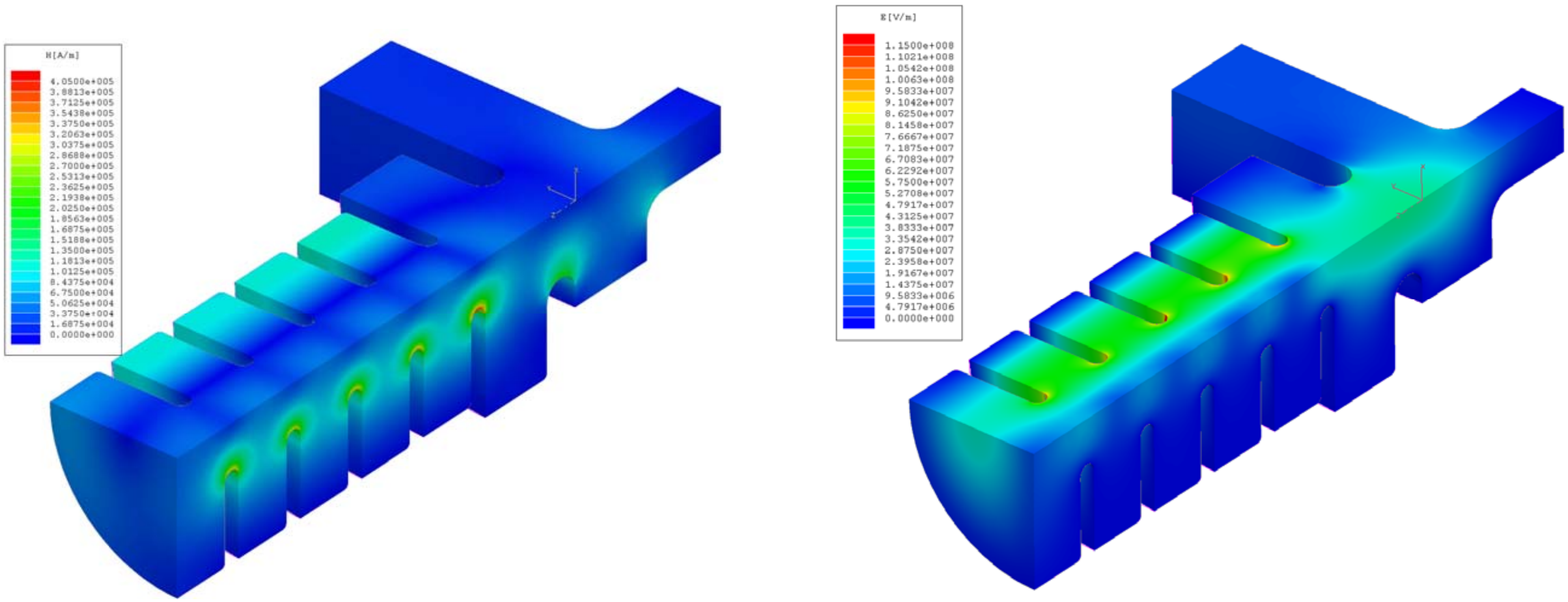


Deforming using
two more tuning holes

# Preliminary Design for Deflector Cups



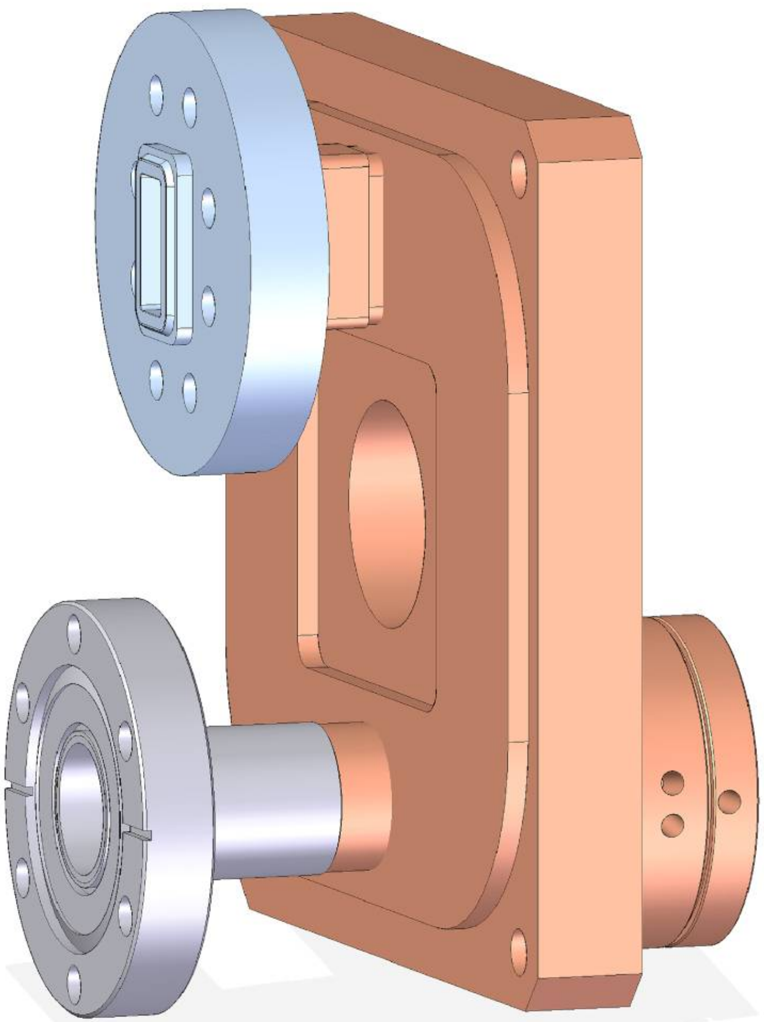
# Coupler Design Simulation

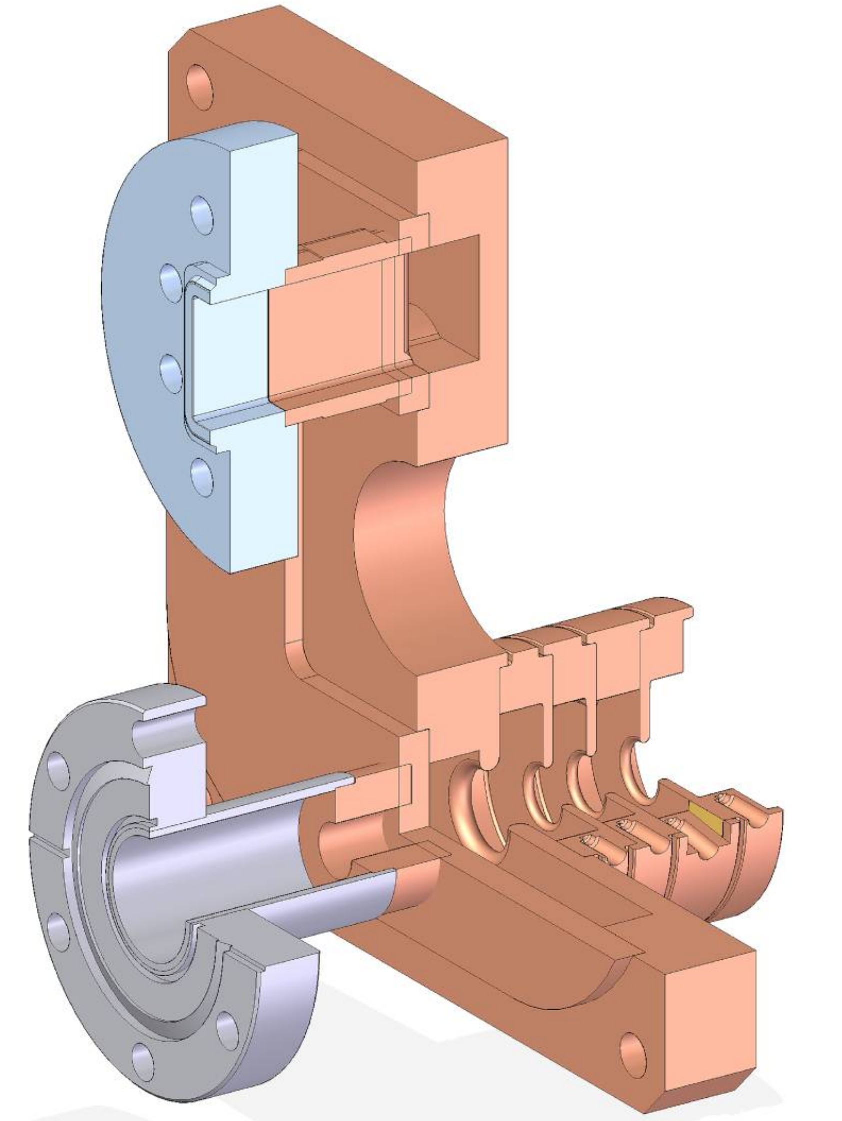



Finite-element electromagnetic simulation of one quarter of traveling wave x-band deflector input: *a)* surface electric fields; *b)* surface magnetic fields. The fields are calculated for 20 MW of transmitted power, or 21.3 MeV kick for 89 cm structure.

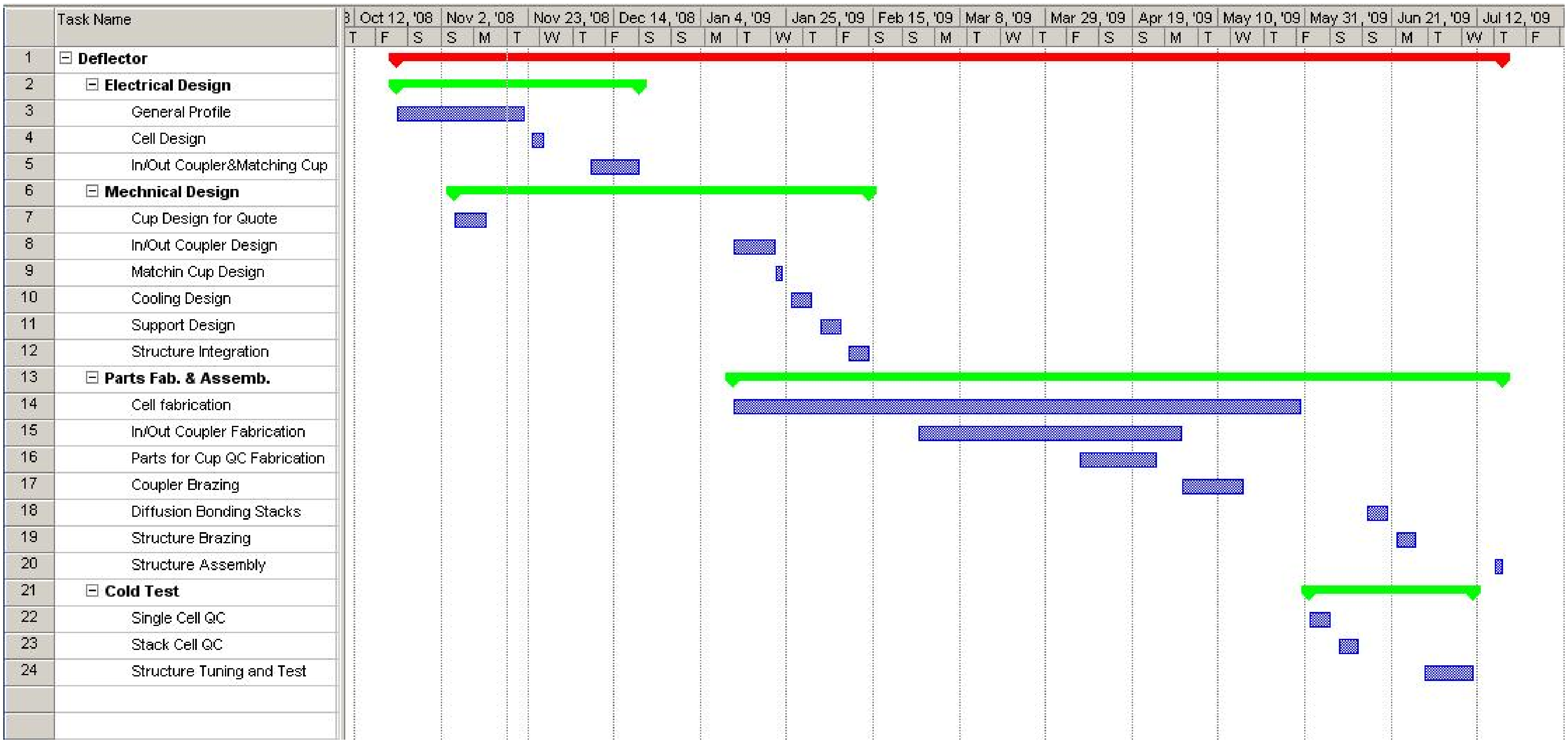
Valery Dolgashev

# Coupler Design





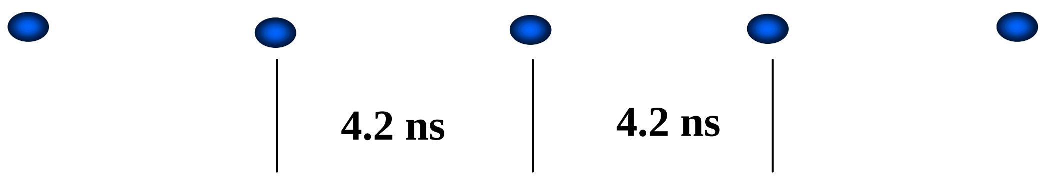
# Preliminary Schedule of the Deflector Project



# 4. Super fast RF kicker for the PEP-X Light Source

# Challenge – Super Fast Kicker

It has been proposed to convert the SLAC B-factory to a very strong FEL light source called PEP-X. In order to pick up single bunches from the bunch-trains, we need to have an ultra-fast RF kicker.




There are 1746 bunches circulating in an orbit with 2200 meters circumference in the B-factory. The bunch spacing is two RF periods with 1.26 m in space or 4.2 ns in time. Therefore, the most challenging design issues are to obtain less than 6 ns RF filling time and more than 5 MV vertical deflecting voltage.

# “HEM-11 modes revisited”

J.W. Wang and G.A. Loew (SLAC). SLAC-PUB-5321, Sep. 1990.

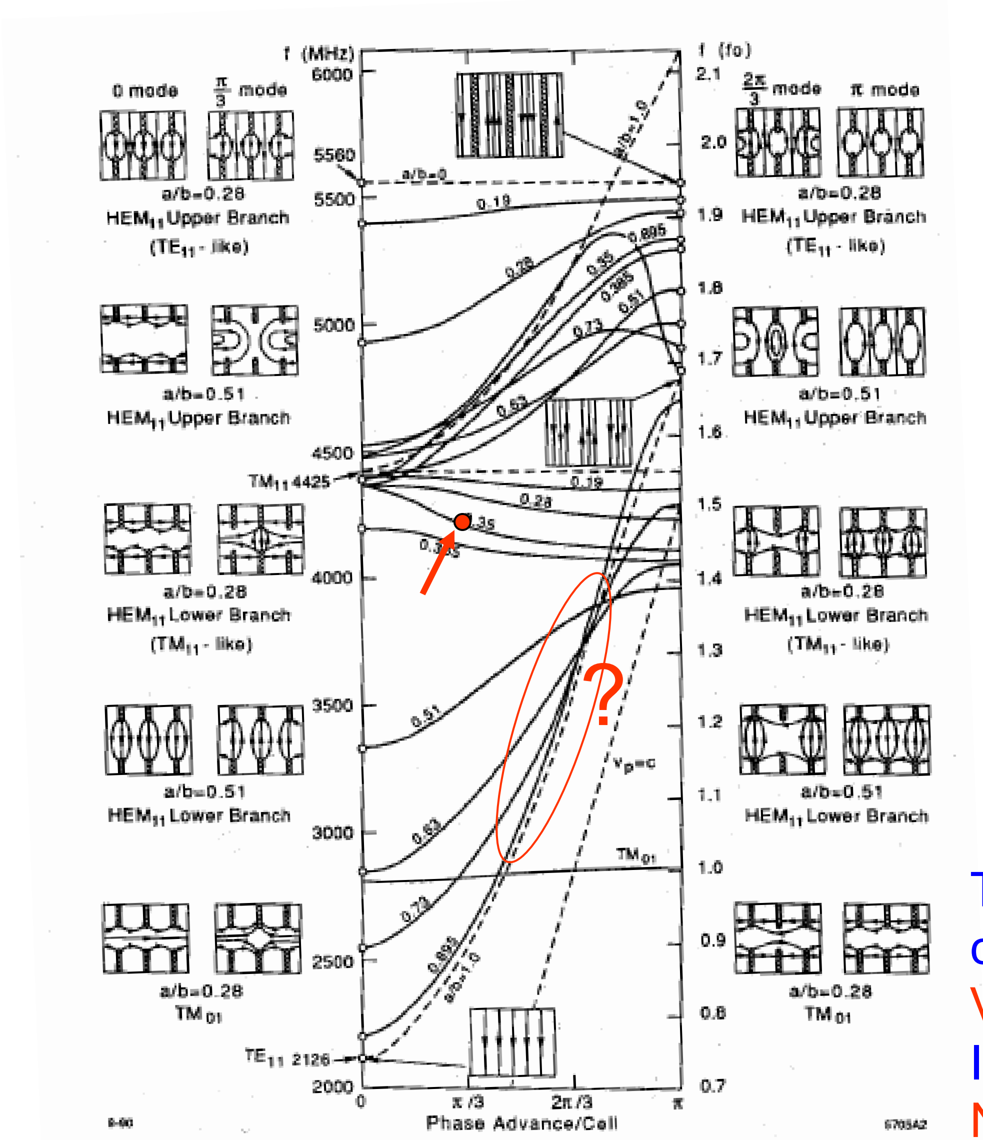
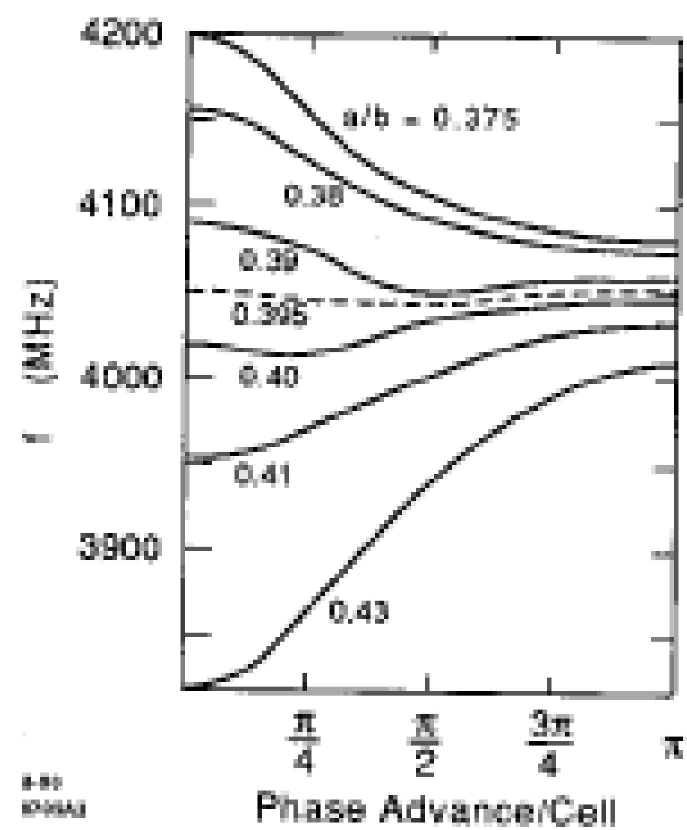
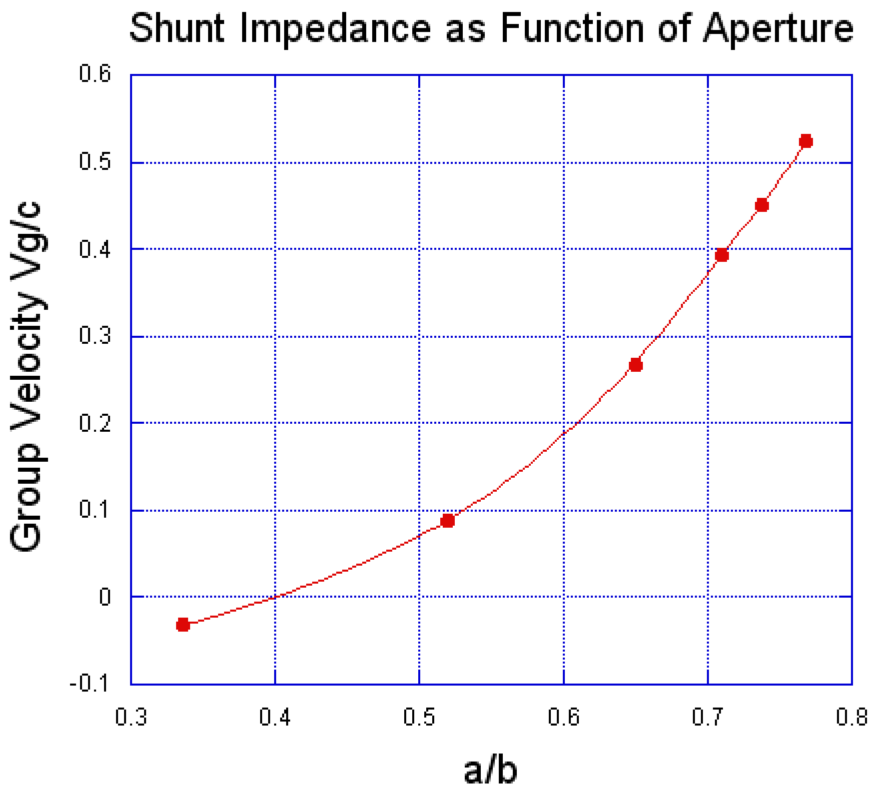


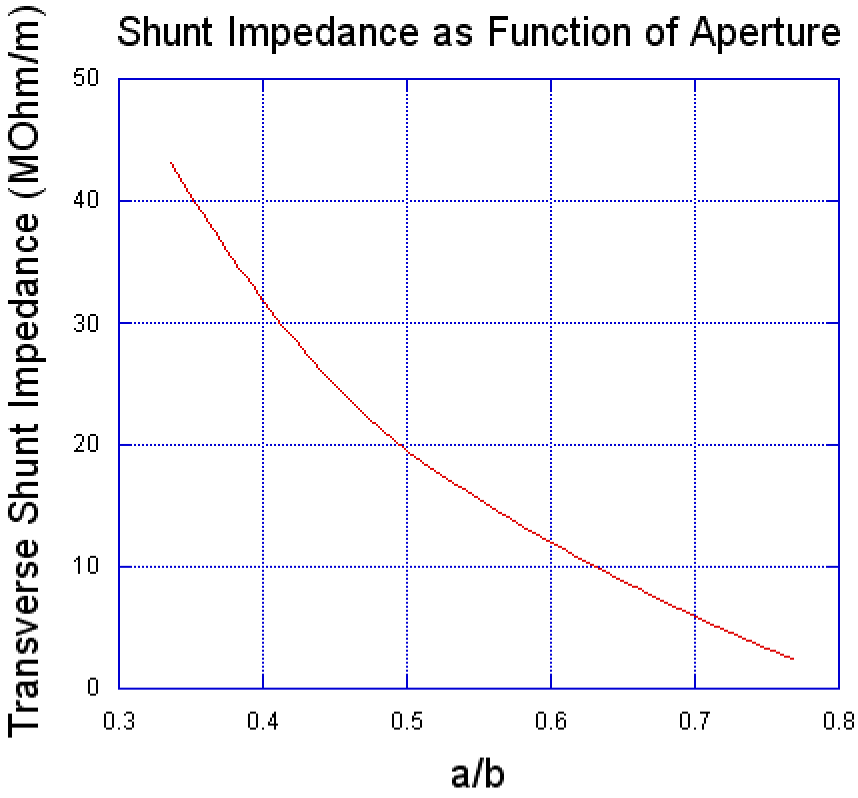

Figure 2. Dispersion diagrams and E-field configurations of $TM_{01}$ and $HEM_{11}$ modes as the b-dimension is kept fixed (4.13 cm) and the ratio a/b varies between 0 and 1.



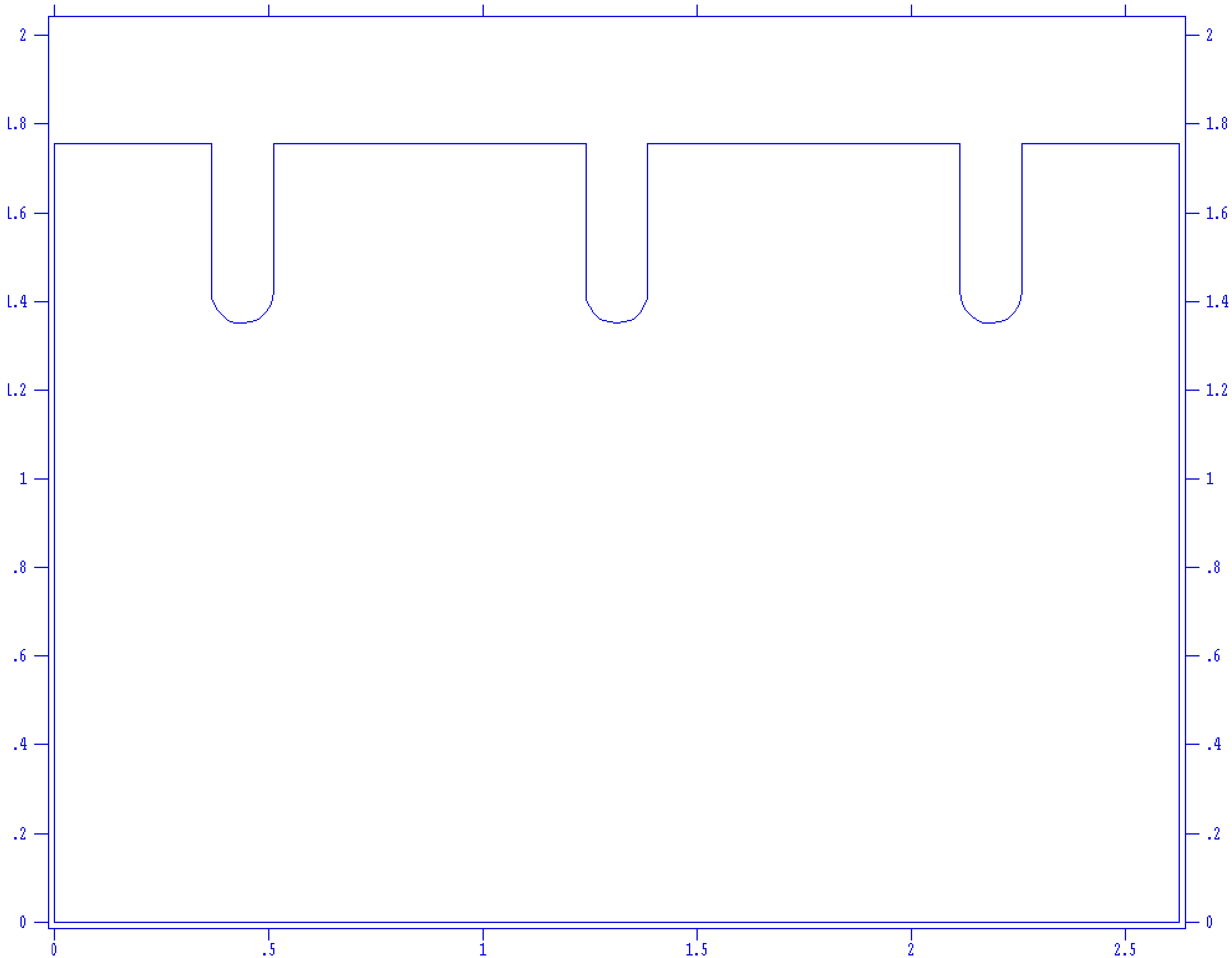

The red dot shows a calculated π/3 mode case for a=5 mm, b=14.9546, (a/b=0.334). Vg/c=4.2% , Tf~40 ns for a 0.5m structure. It is hard to increase Vg by factor of 5. Need to explore the forward wave region.

# Parameter Studies

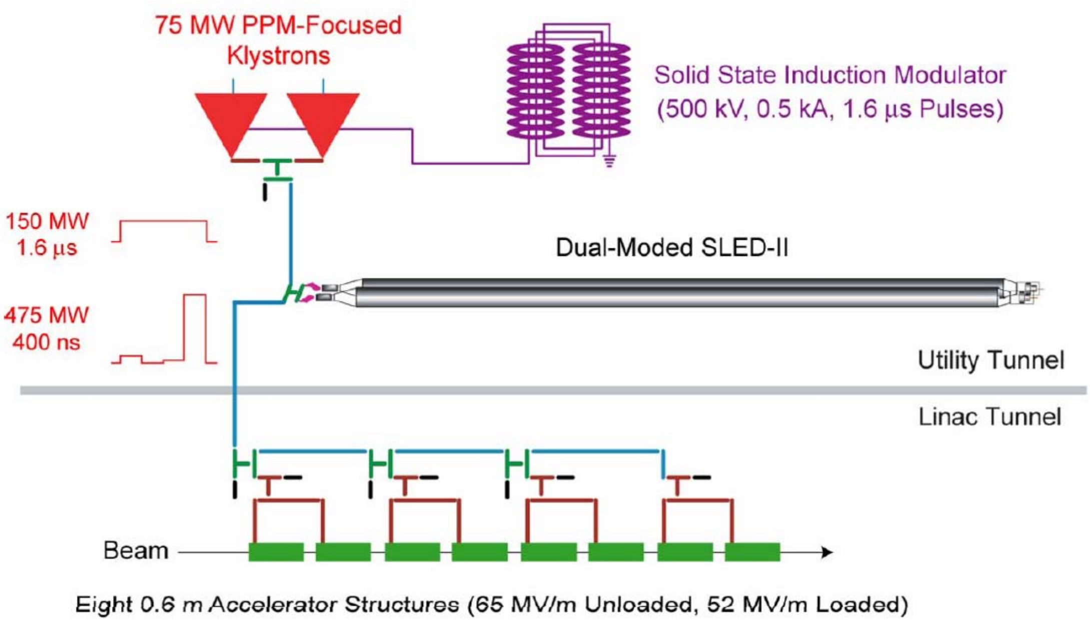


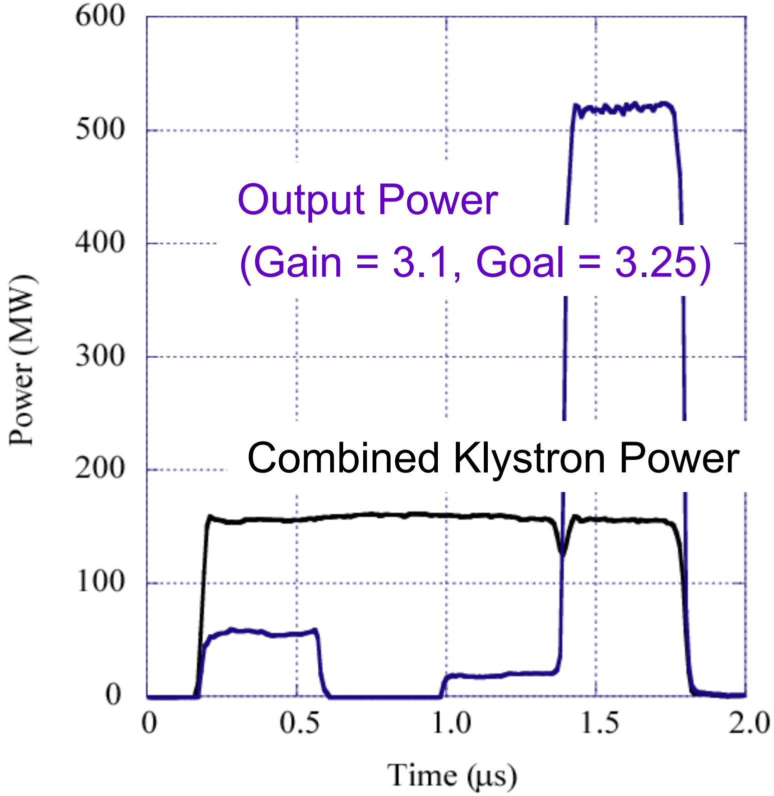
# Profile of a Structure for Fast Kicker



# High Power X-Band RF System for the Fast Kicker




Schematic Diagram of the SLED-II System




Waveforms of the input and output power for a SLED-II system.

# Design Example for a Fast Kicker

| | |
|---|---|
| Structure type | TW DLWG |
| Mode | 2 π /3 Forward wave |
| Aperture 2a | 27.0 mm |
| Cavity diameter 2b | 35.33 mm |
| Cell length d | 8.7475 mm |
| Disk thickness | 1.45 mm |
| Quality factor Q | 9763 |
| Kick factor k | $1.052\text{x}10^{16}$ V/C/m/m |
| Transverse shunt impedance $r_{\perp}$ | 2.39 MΩ/m |
| Group velocity Vg/c | 52.4 % |
| Total length L | 0.75 m |
| Filling time $T_f$ | 4.77 ns |
| Attenuation factor τ | 0.0176 |
| Input peak RF power | 400 MW |
| Maximum electric field | 121 MV/m |
| Maximum magnetic field | 0.19 MA/m |
| Deflecting voltage | 5 MV |