Microwave Deflectors: Normal Conducting Crab Cavity for APS and Discussion on Microwave Undulators

Valery Dolgashev
SLAC, Stanford, CA

Talk at Argonne, 17 June 2005

Microwave Deflector

- Requirements
- Design considerations
- Parameters
- Higher Order Modes

Microwave Deflector Requirements

Frequency	2.82 GHz
Deflecting Voltage	6 MV
Available power	5 MW or 2.5 MW
Length	<2.4 m

Michael Borland

Transverse HOM	<2.5 MOhm/m
Longitudinal HOM	< 0.8 MOhm*GHz

Geoff Waldschmidt, "Parameters for the SCRF Deflecting Cavity," APS/CNM 2005 Users Meeting, May 6, 2005

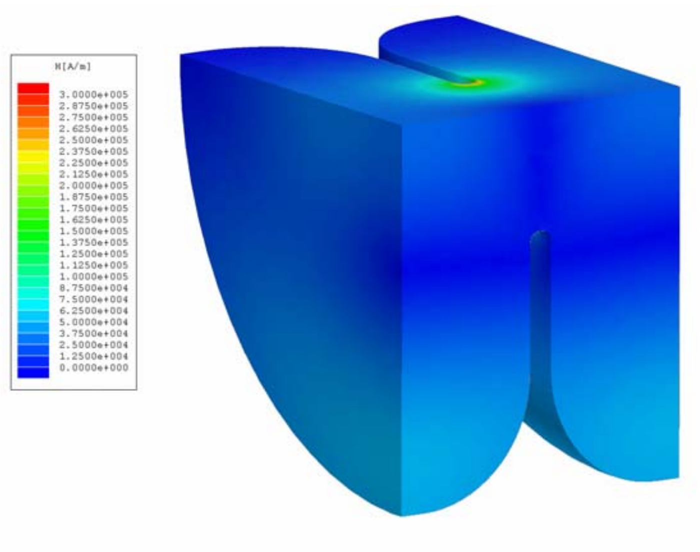
Design consideration

- Limited available power $\leq$ 5 MW
- Large aperture ~2 cm => Low impedance
- Maximum surface electric fields < 100 MV/m
- Pulsed heating < 100 deg. C => maximum surface magnetic field < 200 kA/m for 5 μs pulse
- Deflecting mode degeneracy fixed by wall deformation during tuning
- "Smooth" coupler – no field amplification on edges

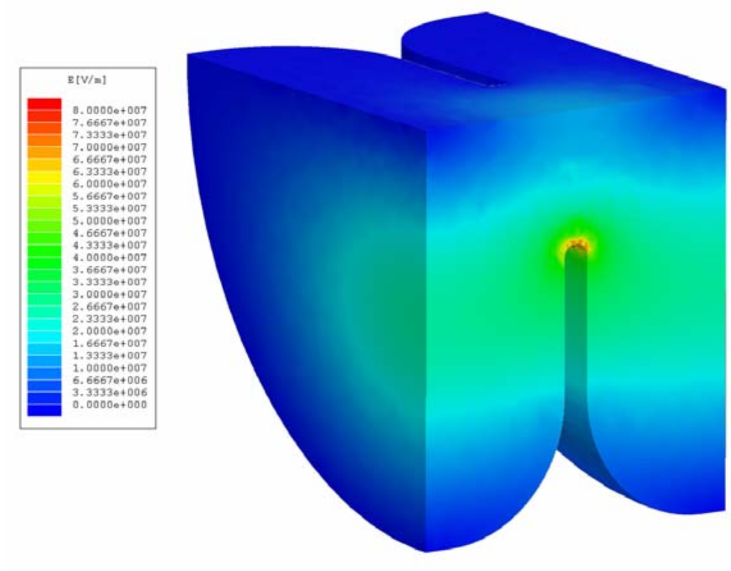
Possible approaches

- Resonant ring traveling wave structure
- Standing wave structure

Regular Cell of Standing Wave Deflector, HFSS Calculations



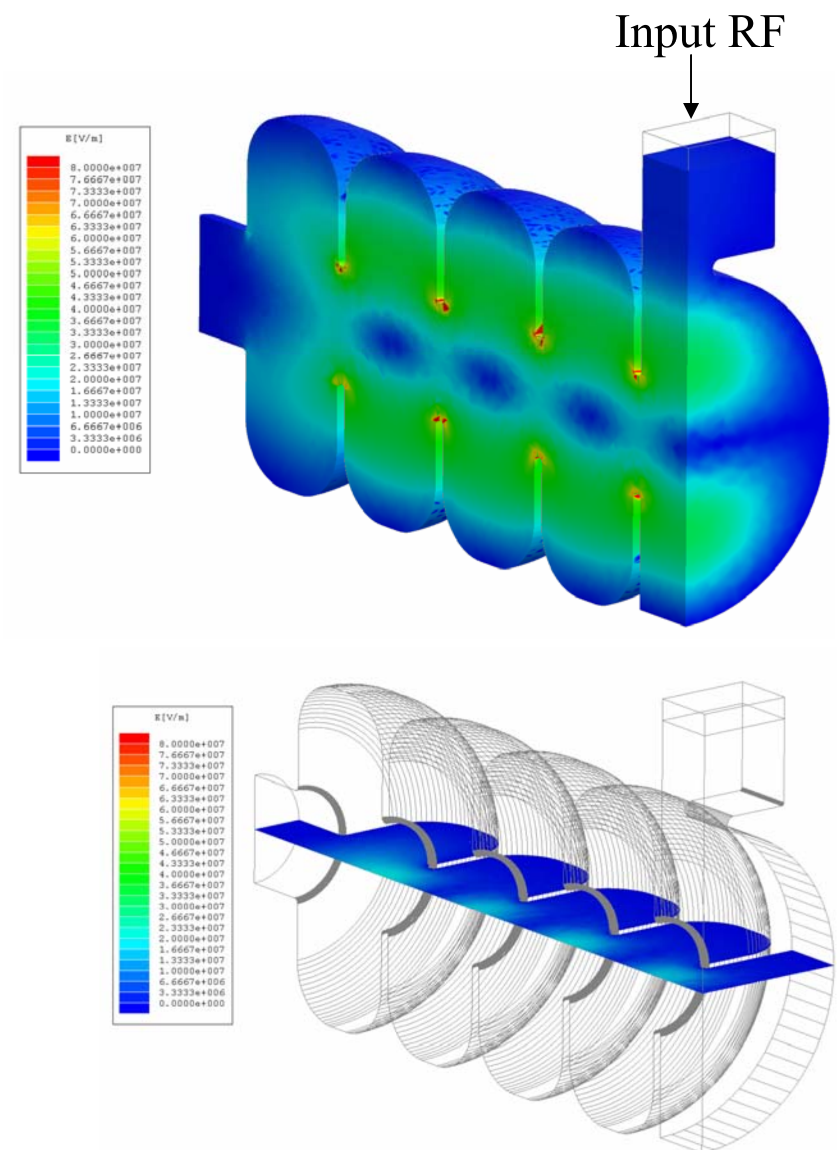
Surface magnetic field for 6/9 MV kick

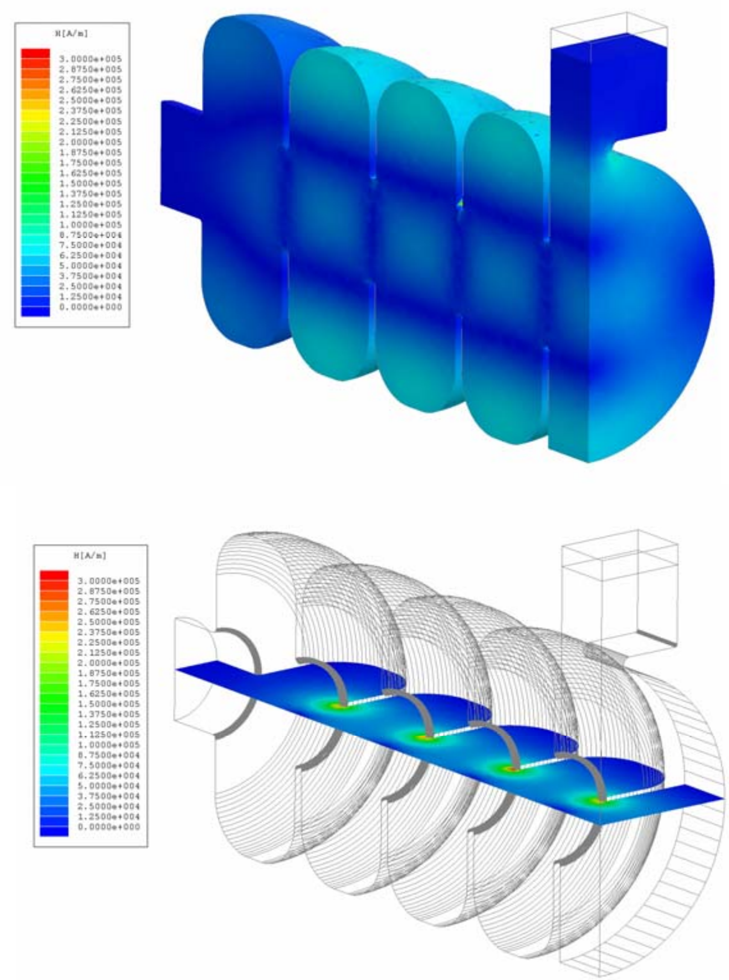


Surface electric field for 6/9 MV kick

Frequency	2.858 GHz
Q	15750
Beam pipe aperture	2 cm
Phase advance per cell	180 deg.
Transv. impedance	0.44 MOhm
Kick / sqrt(Power)	0.95 MV/sqrt (MW)

9 Cell Standing Wave Deflector



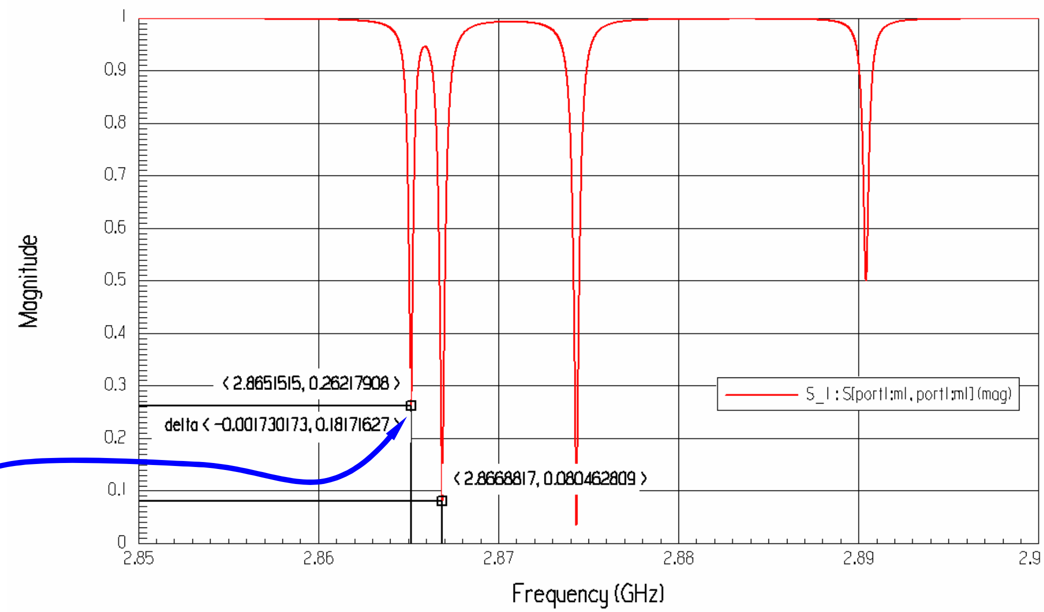


Surface electric field for 5 MW of input power, maximum filed ~70 MV/m

Surface magnetic field for 5 MW of input power, maximum filed ~30 kA/m

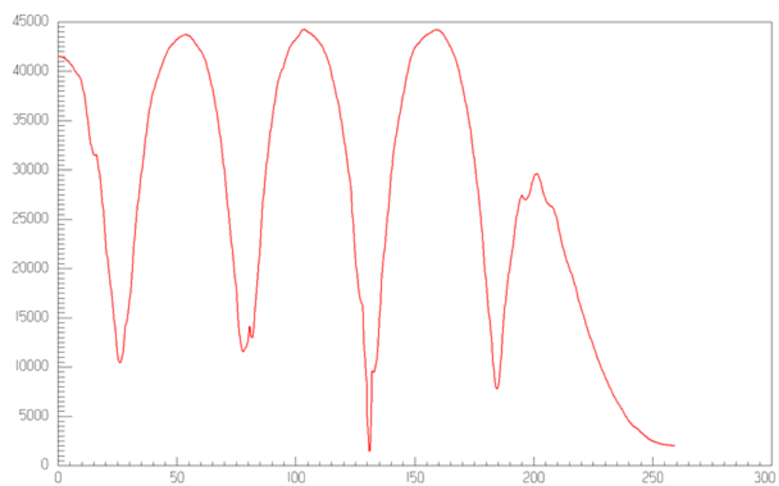
9 Cell Standing Wave Deflector

Reflection *vs.* frequency, mode separation 1.7 MHz



π mode

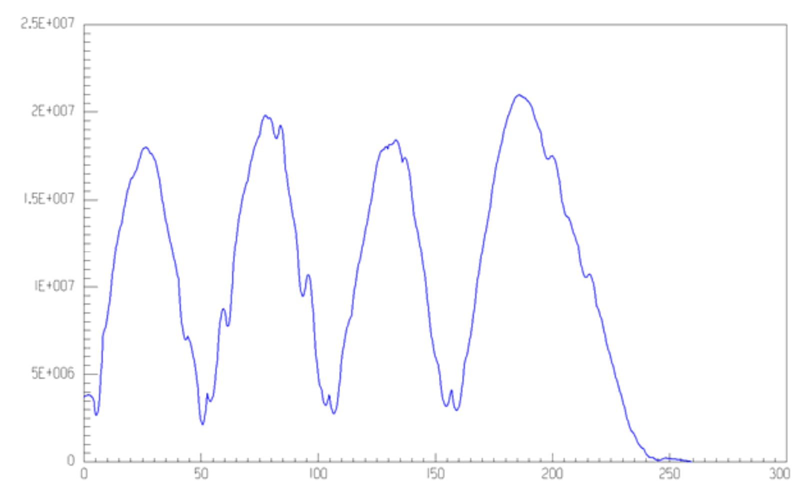
Hx [A/m]



z [mm]

On-axis magnetic field

Hy [V/m]



z [mm]

On-axis electric field

Higher Order Modes for **unloaded** structure First monopole passband, 2D Finite Element calculation (code SLANS)

Must be < 0.8 MOhm*GHz

Frequency [GHz]	Q	Rshunt [MOhm]
1.813	20,000	0.032
1.817	20,000	0.049
1.822	20,000	0.20
1.830	20,000	0.27
1.839	20,000	0.55
1.849	20,000	4.1
1.858	20,000	6.4
1.866	20,000	0.71
1.870	20,000	0.015

Result

- One 9-cell standing wave structure (0.5 m length) will produce 6 MV kick if powered by a 5 MW klystron. The klystron will need circulator for protection from reflected power.
- Two of these structures will produce 6 MV kick if powered by 2.5 MW. In this case a hybrid will protect klystron – no need for circulator. Two structures will occupy about a meter of beam space.

Work to do: HOM suppression

- Unloaded Qs of several monopole modes have to be reduced by an order of magnitude to satisfy beam stability requirements. **Chokes in end cavities are possible solution.**
- π mode of the "wrong polarization" should be damped. **"Damped" coupler is a possible solution**.

RF undulators

- With external power
- Beam powered

Externally powered undulators

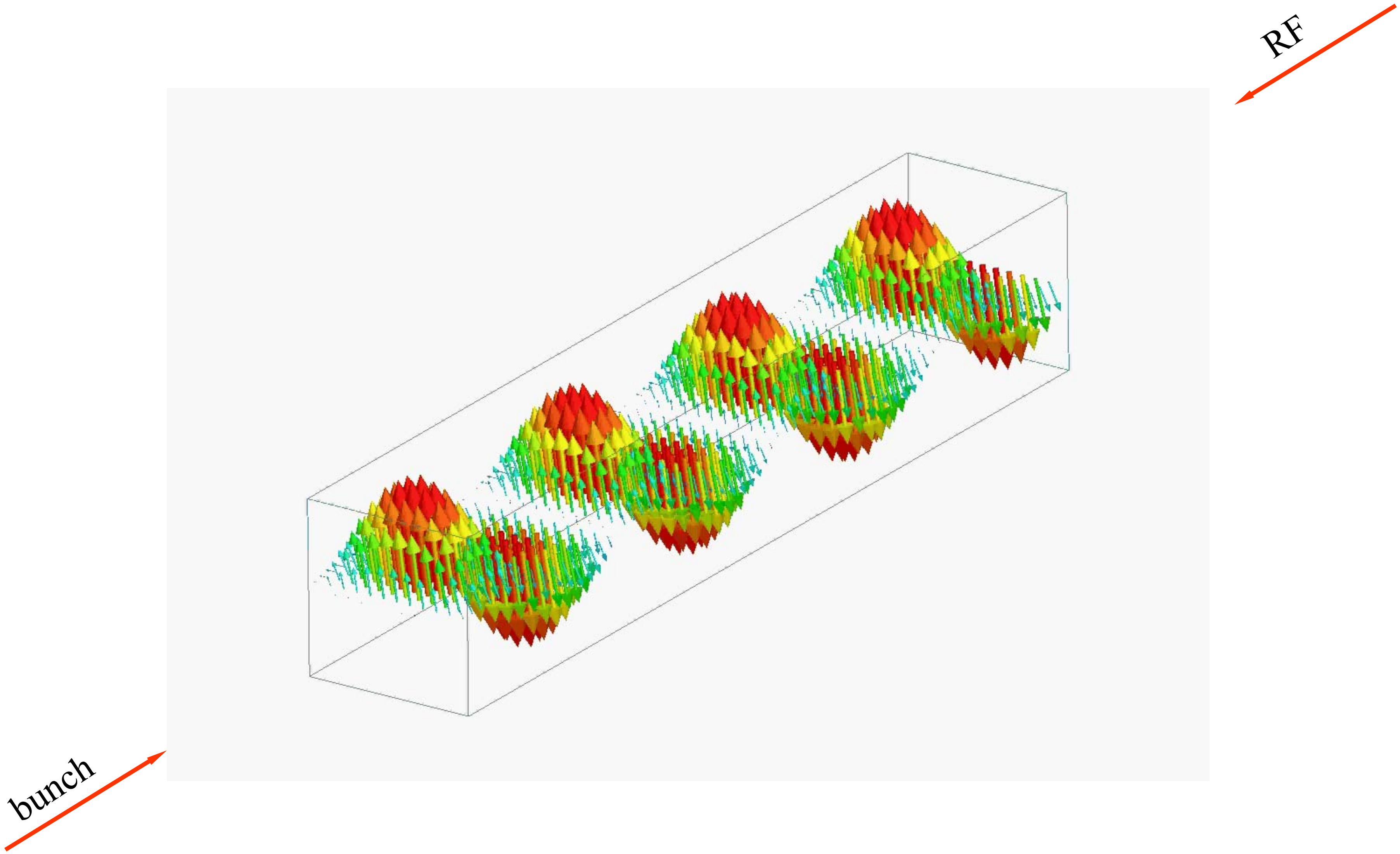
Outline

- Introduction to rf undulators
- Review of the state-of-art in high power Rf generation at X-band.
- Waveguide types suitable for an RF undulator
- RF undulator in an a resonant ring

Main Contributors:

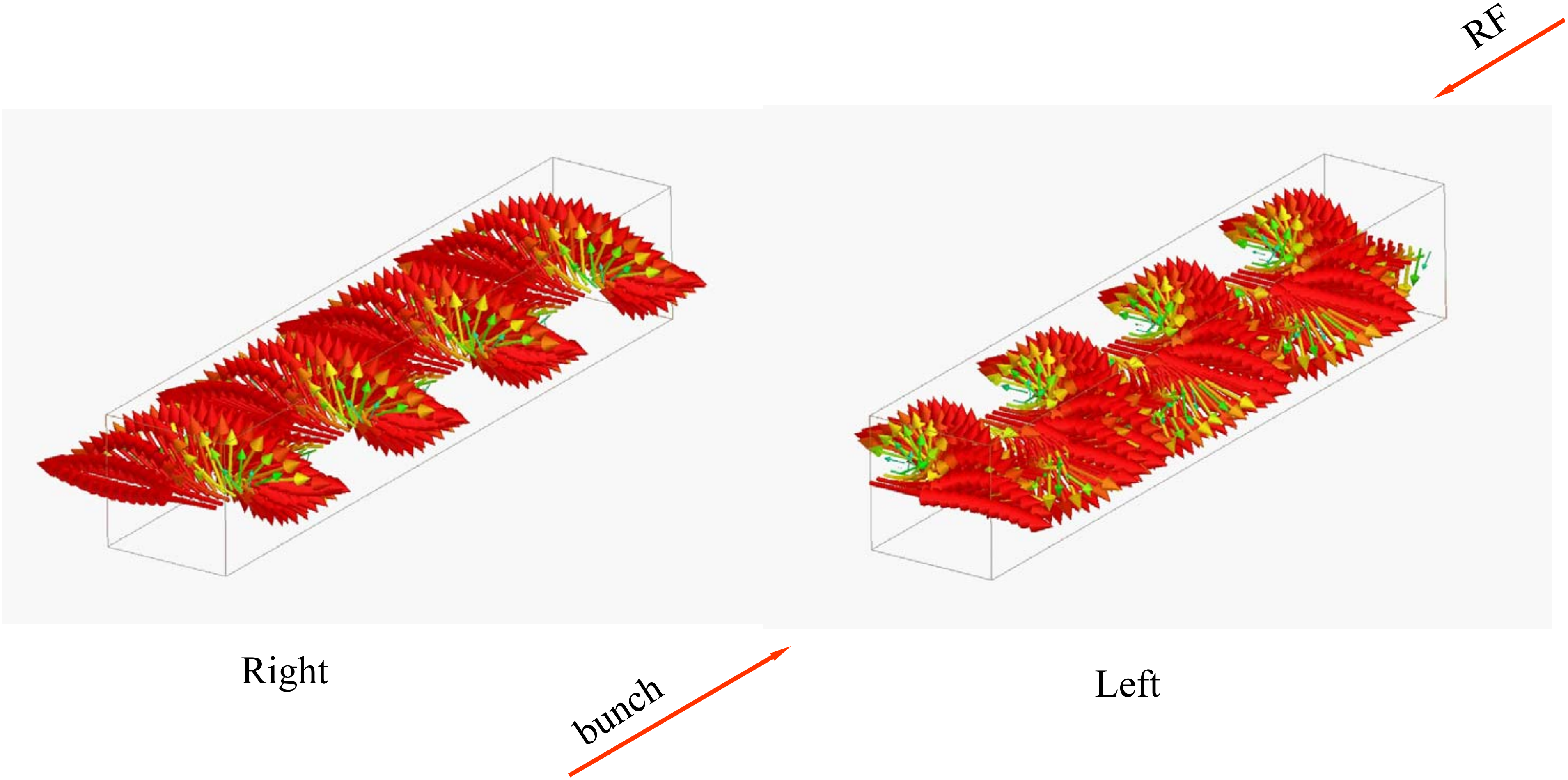
- Sami Tantawi
- Chistopher Nantista

Planar Microwave Undulator



Vector plot of deflecting field in mid-plane of the waveguide

Helical Microwave Undulator



Vector plot of deflecting field in mid-plane of the waveguide

JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 22, NO. 5, MAY, 1983 pp. 844–851

Development of Microwave Undulator

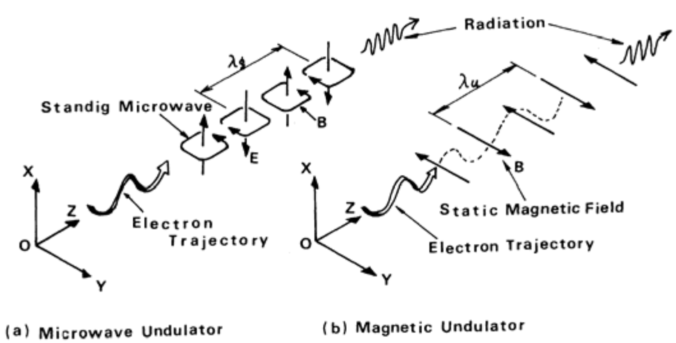
Tsumoru SHINTAKE, Kazuo HUKE [†], Jiro TANAKA [†], Isamu SATO [†] and Isao KUMABE

Department of Nuclear Engineering, Faculty of Engineering, Kyushu University, Fukuoka 812
[†]Photon Factory, National Laboratory for High-Energy Physics, Oho-machi, Tsukuba-gun, Ibaraki 305

(Received November 17, 1982; accepted for publication February 19, 1983)

f = 2856 MHz
λu = 5.5 cm
Bu = 0.043 T

A microwave undulator which uses transverse fields of standing microwaves the been operated successfully at the Photon Factory electron linac. The undulator consists of a long rectangular cavity with two ridges. Using a pulsed S-band microwave of 300 kW and a pulsed electron beam, the undulator radiation was observed in the visible region, and the spectral intensities were measured. The equivalent magnetic field and the period are 430 Gauss and 5.5 cm, respectively.



Development of Microwave Undulator

Fig. 1. Coordinates of microwave undulator and magnetic undulator. Electrons undulate in *xz*-plane.

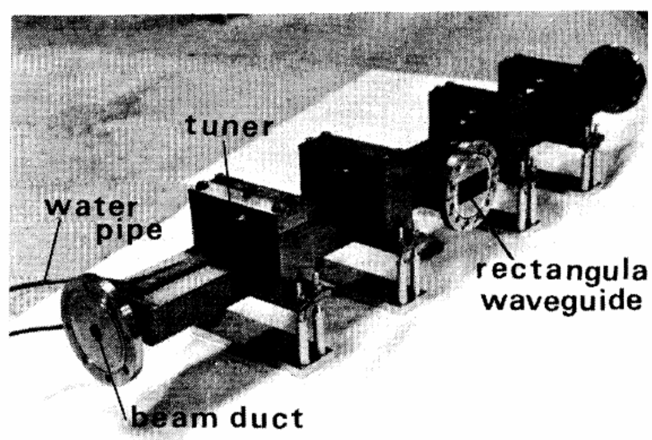


Fig. 5. Photographs of undulator cavity. (a) Completed cavity. (b) Cross-sectional view, before welding beam duct. (c) Coupling hole. Front is rectangular waveguide WRJ-3.

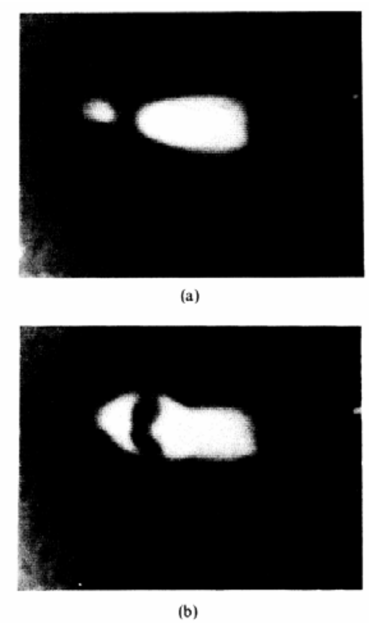


Fig. 10. Photographs of normal synchrotron light and undulator light, taken on TV screen. (a) When undulator is switched off; there are two normal synchrotron light spots produced at the two bending magnets. (b) When microwave power is fed into cavity; ring-shaped undulator light emerges.

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

A MICROWAVE BEAM WAVEGUIDE UNDULATOR FOR A BRILLIANT ABOVE 100 KEV PHOTON SOURCE*

Y. Kang, J. Song, and R. Kustom, Argonne National Laboratory, Argonne, IL

f = 34 GHz

λu = 4.5 mm

Bu = 0.25 T

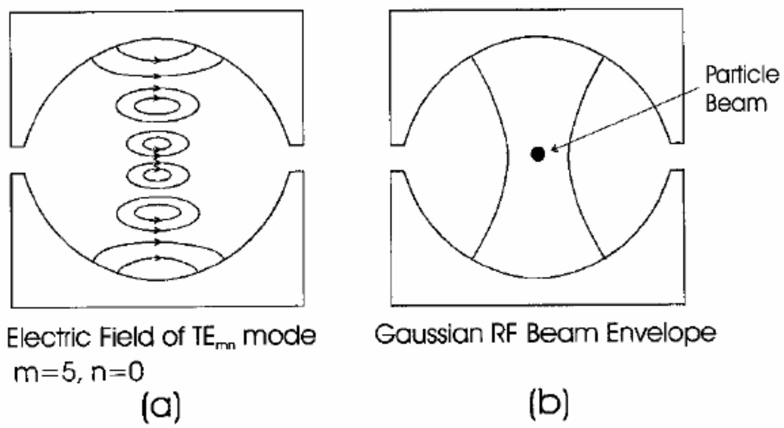


Figure 2: Cross section of a parallel reflector beam waveguide. (a) Electric field of the TE_{50} mode, (b) particle beam with respect to the microwave beam.

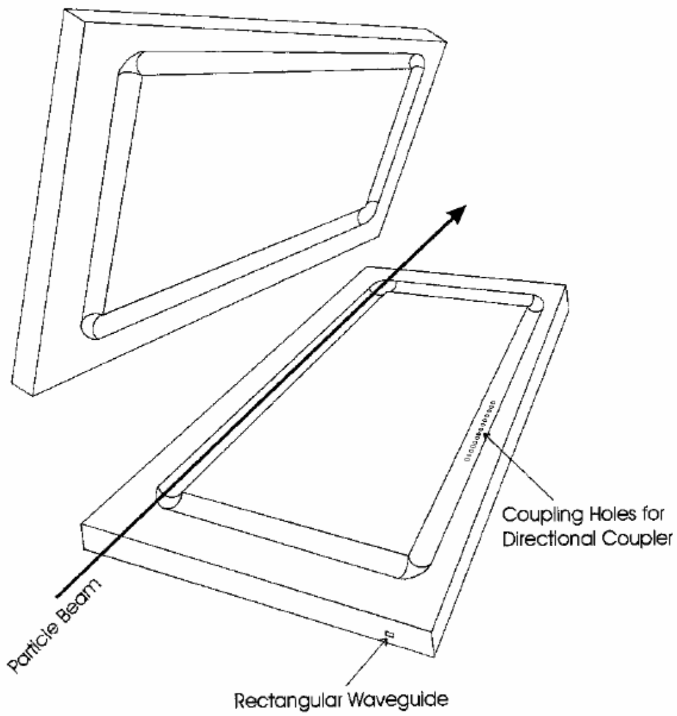


Figure 6: A proposed design of a beam waveguide microwave undulator.

Why rf for beam deflection?

- RF makes possible small period and large aperture undulators
- Helical undulators are relatively easy with rf
- No magnets to damage by radiation
- Dynamic: **Could change properties from pulse to pulse,** for example flip polarization of helical undulator

Why such devices are difficult to make?

•High power (100s of MW) rf sources with **precision amplitude and phase** are expensive
•Handling of ~100 MW rf power at 10s of GHz is difficult and required expensive R&D efforts

More information on X-band traveling wave undulator, Claudio Pellegrini, UCLA: http://pbpl.physics.ucla.edu/Literature/_library/pellegrini_2005_624.pdf

8-Pack Phase 1

coherent power source

Frequency 11.424 GHz

Output power 500 MW

Pulse length 400 ns pulse

Rep. rate 60 Hz

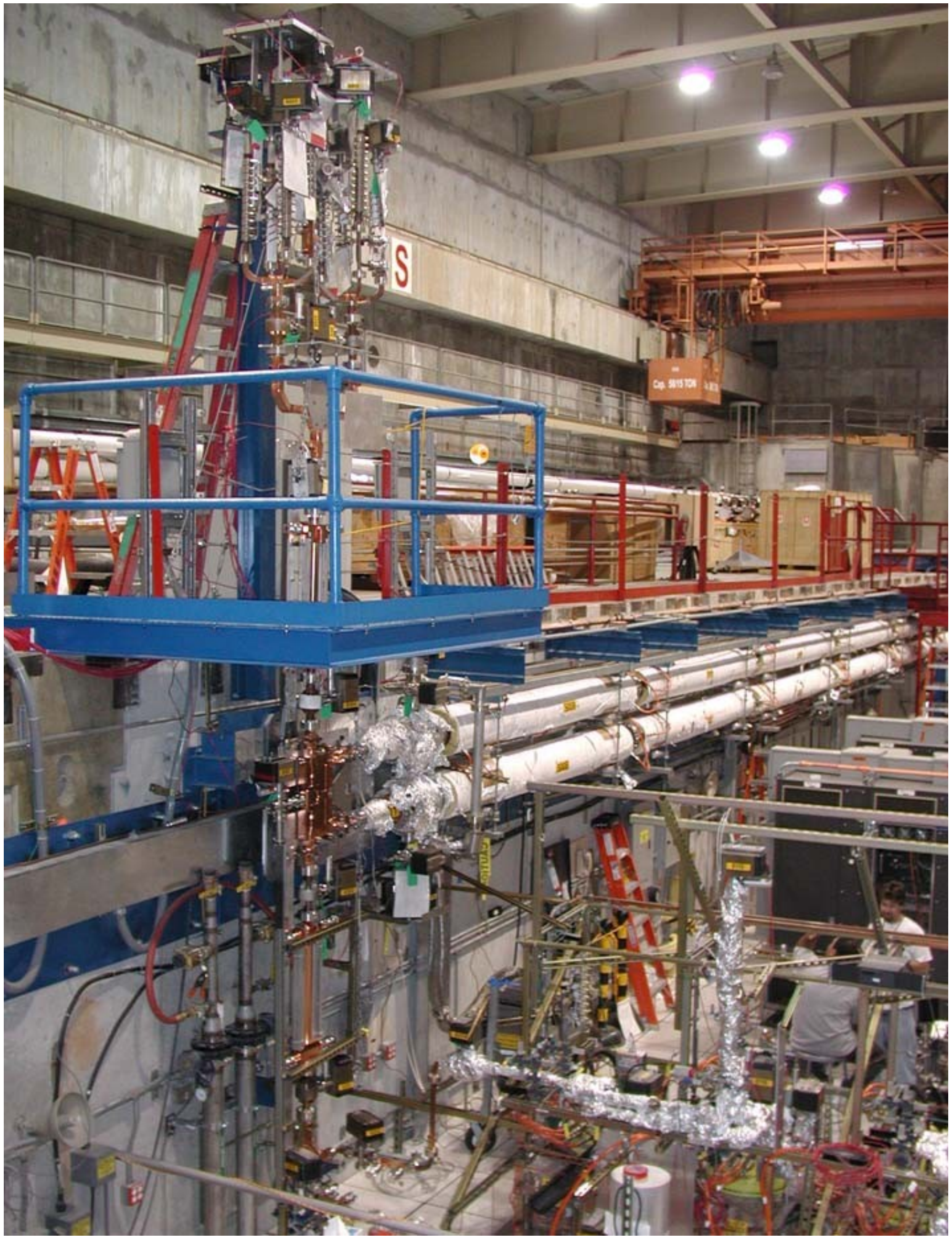
can power

60 m of rf undulator

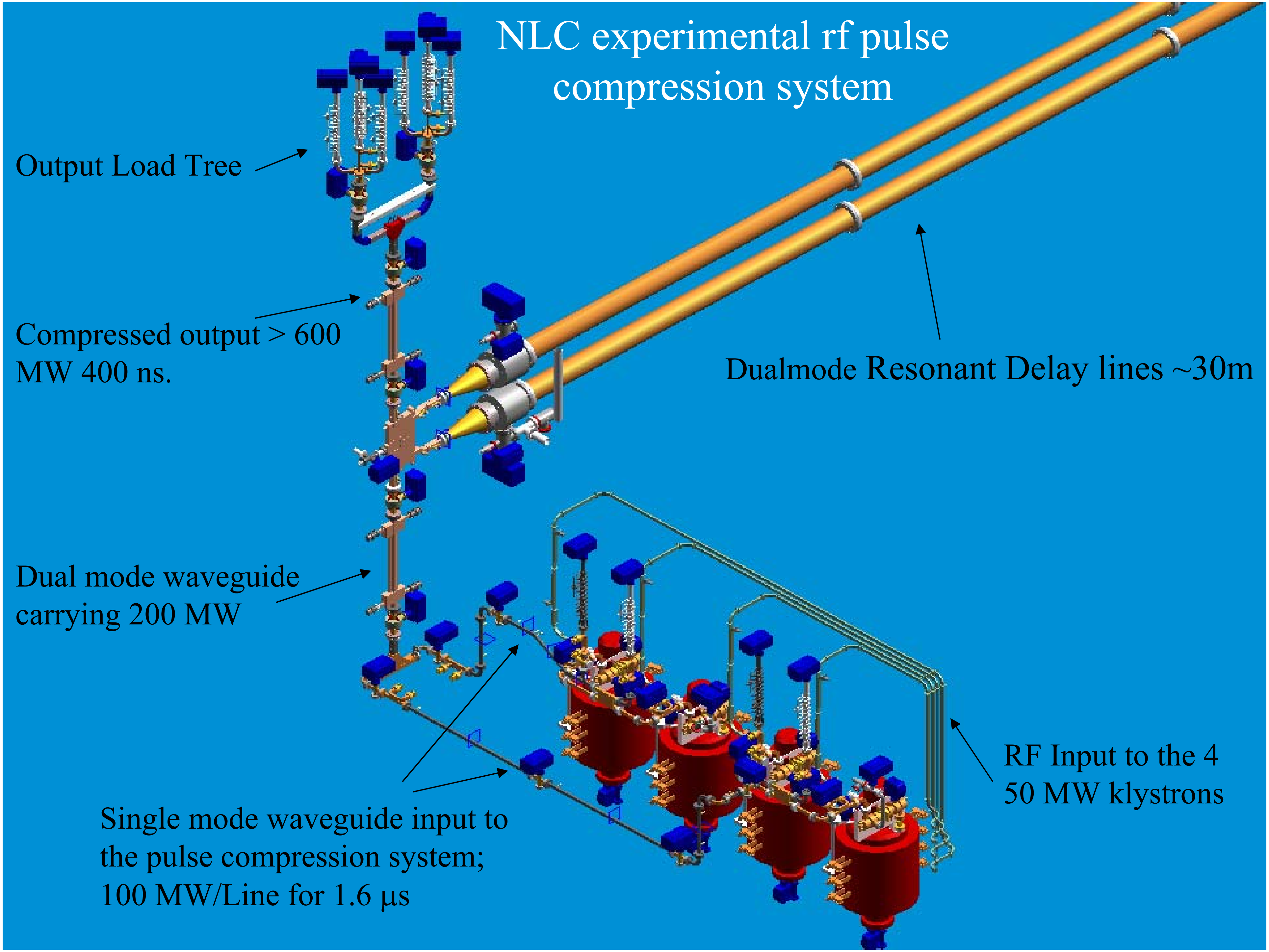
with

period~**1.6 cm** and

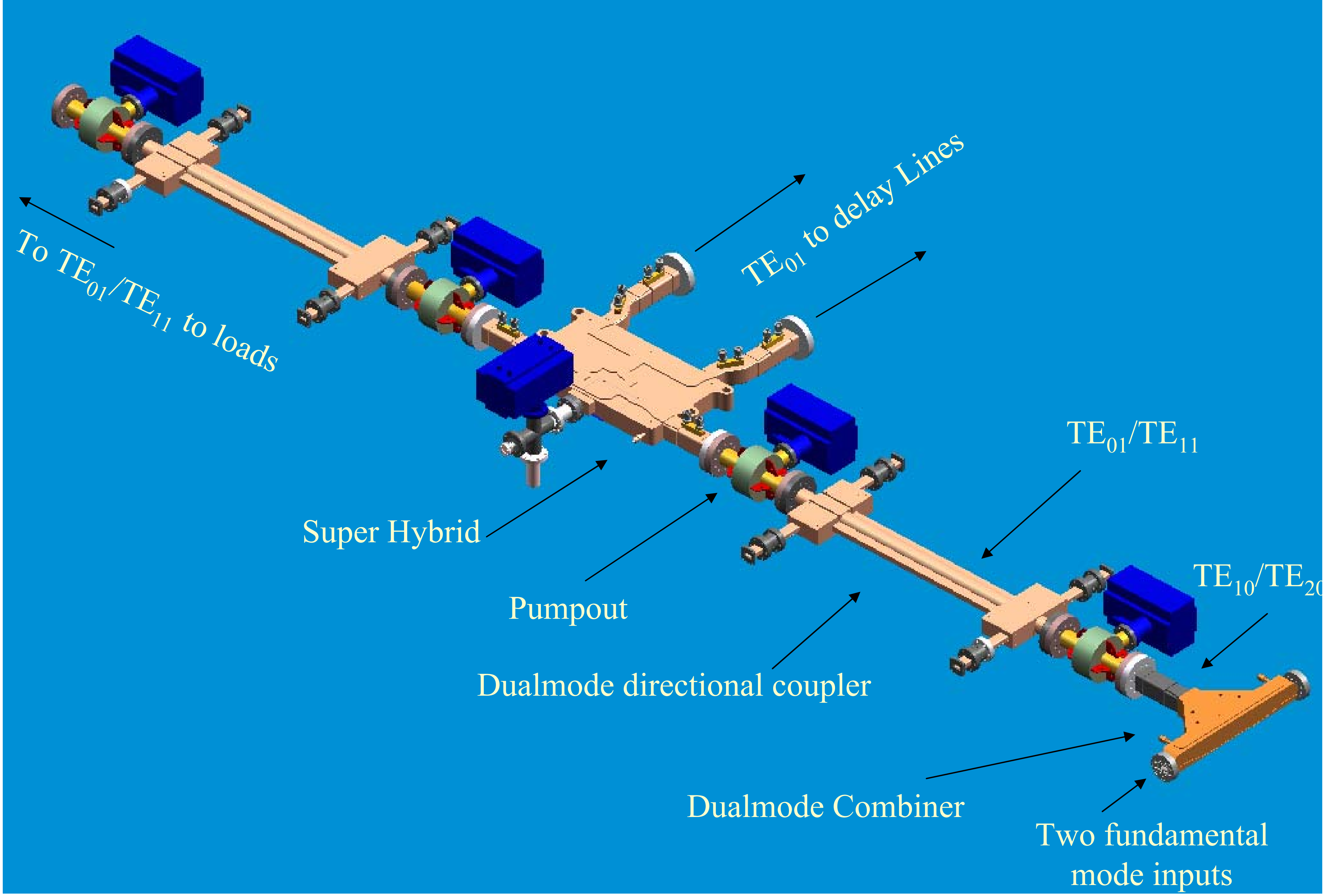
K ~0.4

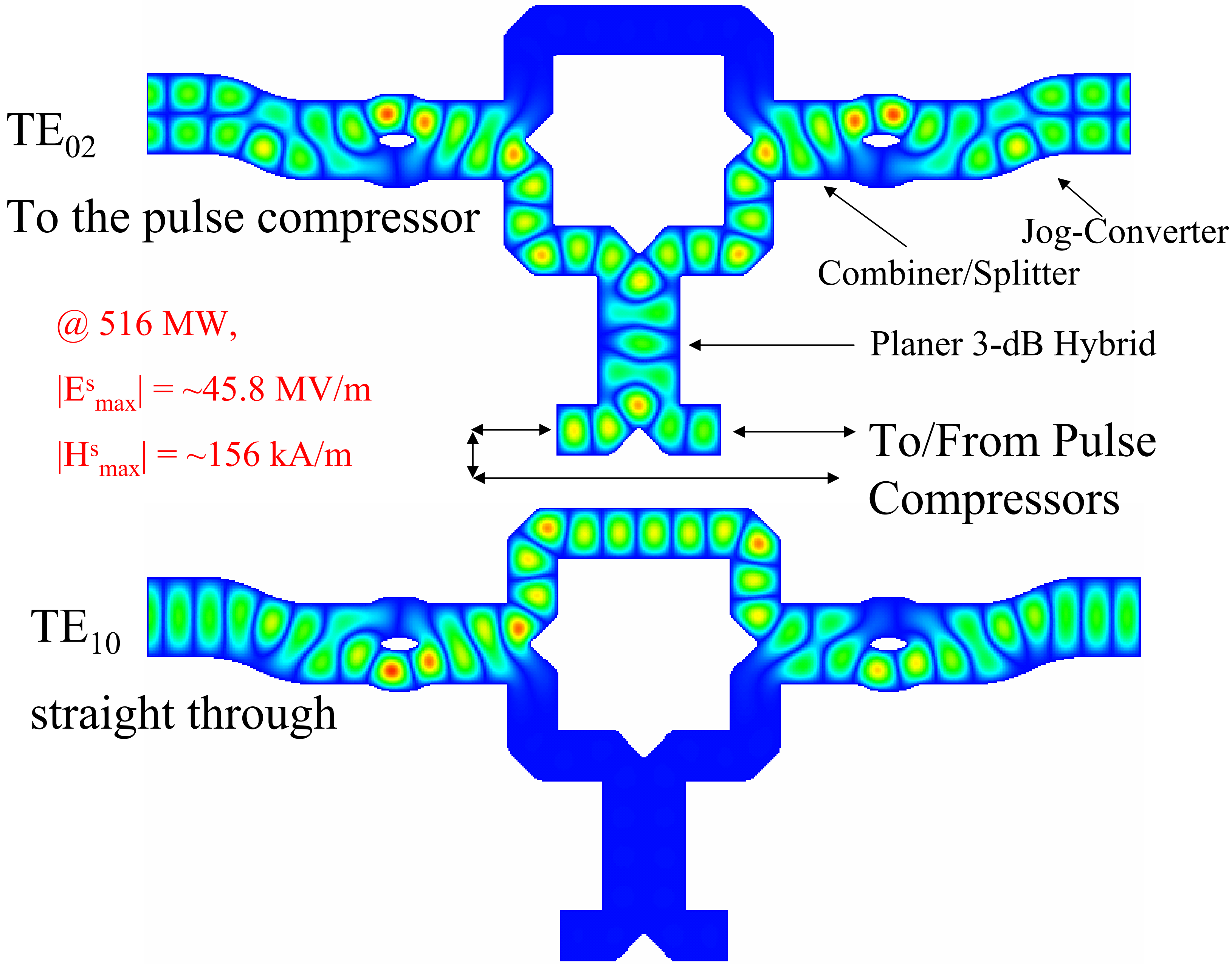


NLCTA team

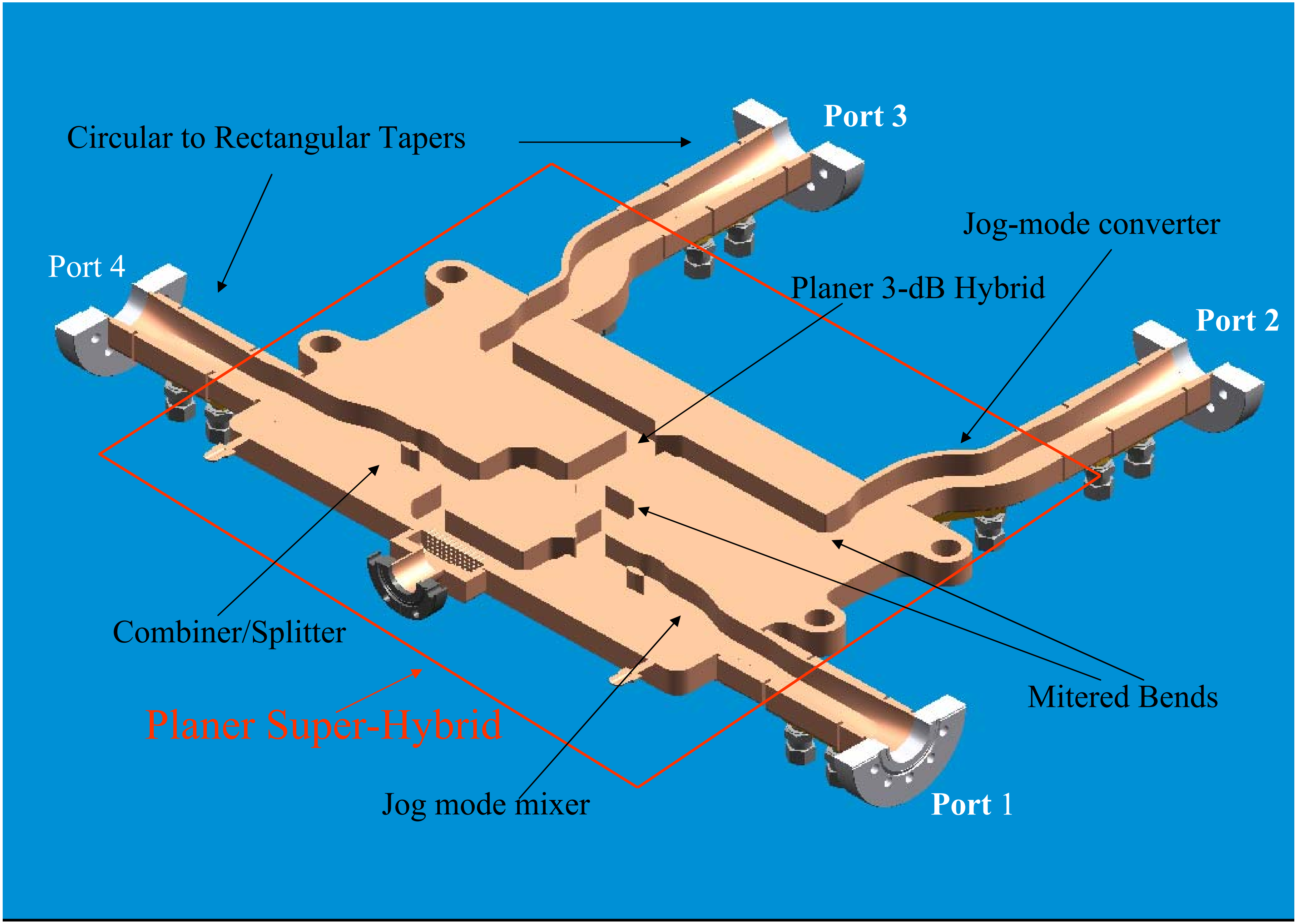

NLC experimental rf pulse compression system
Output Load Tree
Compressed output > 600 MW 400 ns.
Dual mode waveguide carrying 200 MW
Dualmode Resonant Delay lines ~30m
RF Input to the 4 50 MW klystrons
Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 µs

The Head of the pulse compression system





TE02
To the pulse compressor
@ 516 MW,
|Es max| = ~45.8 MV/m
|Hs max| = ~156 kA/m
TE10
straight through
Jog-Converter
Combiner/Splitter
Planer 3-dB Hybrid
To/From Pulse Compressors

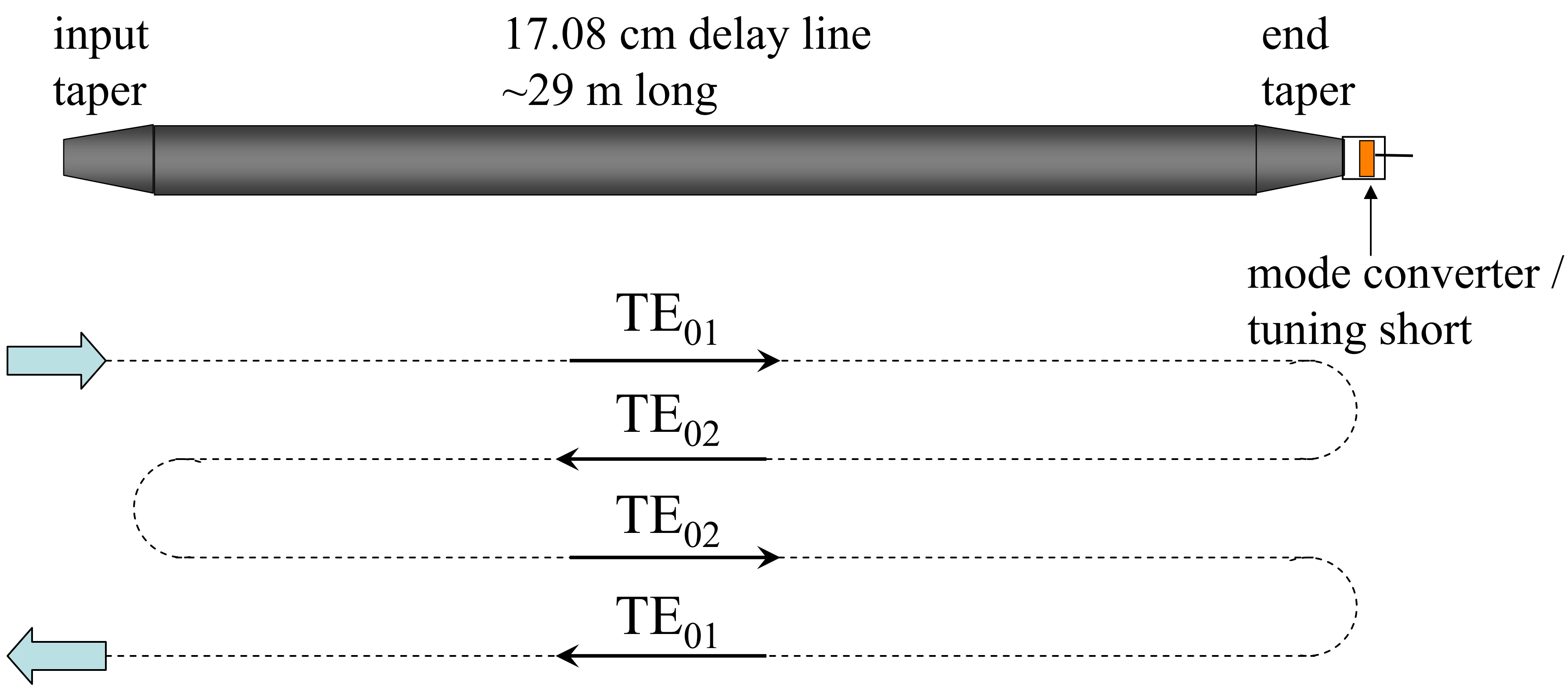

Circular to Rectangular Tapers
Port 3
Port 4
Jog-mode converter
Planer 3-dB Hybrid
Port 2
Combiner/Splitter
Planer Super-Hybrid
Mitered Bends
Jog mode mixer
Port 1

Dual-Moded Delay Line

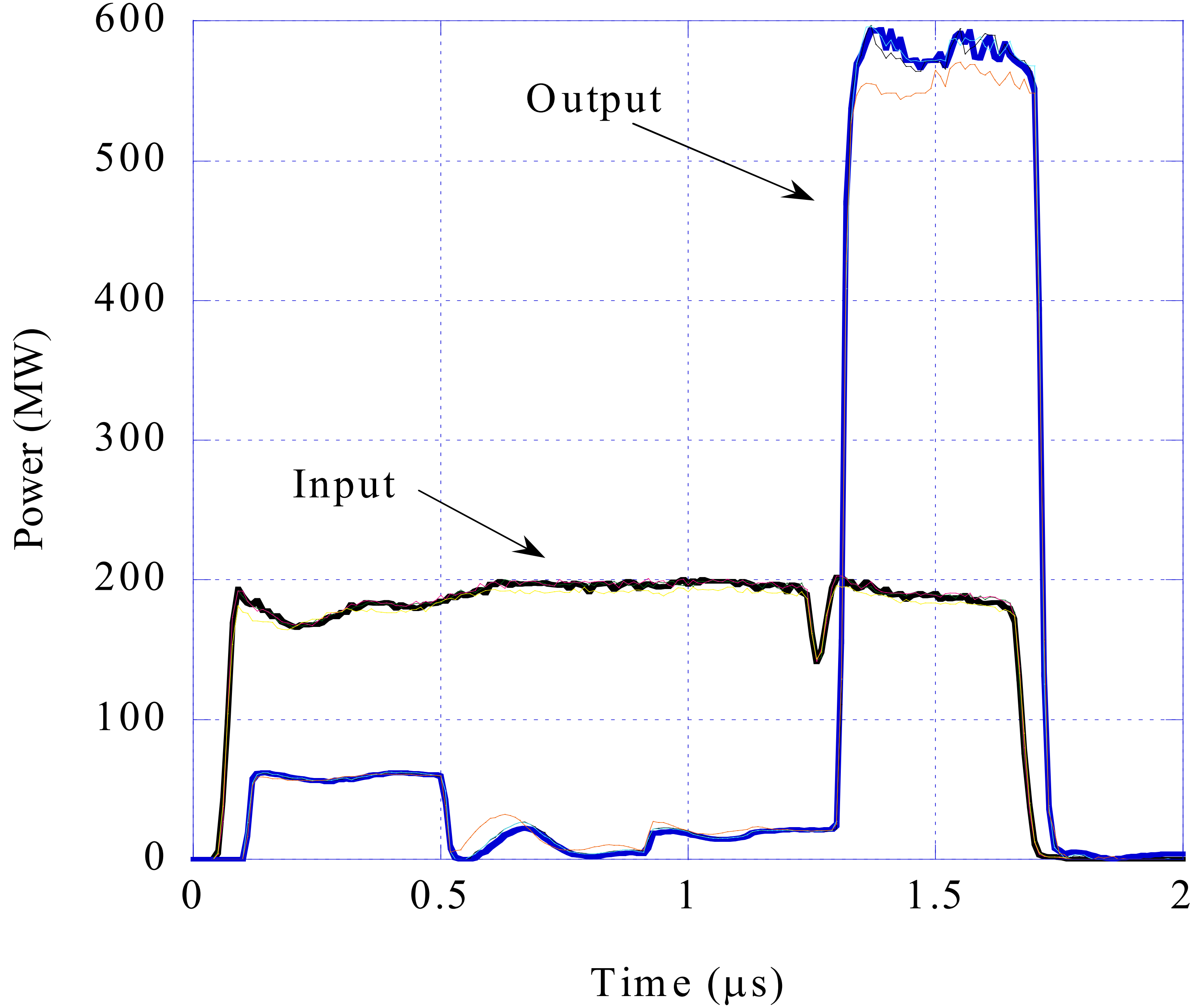
Dual-moding the delay lines cuts their required length approximately in half.

$$L = \frac{T}{2} \frac{v_{g1} v_{g2}}{v_{g1} + v_{g2}}$$

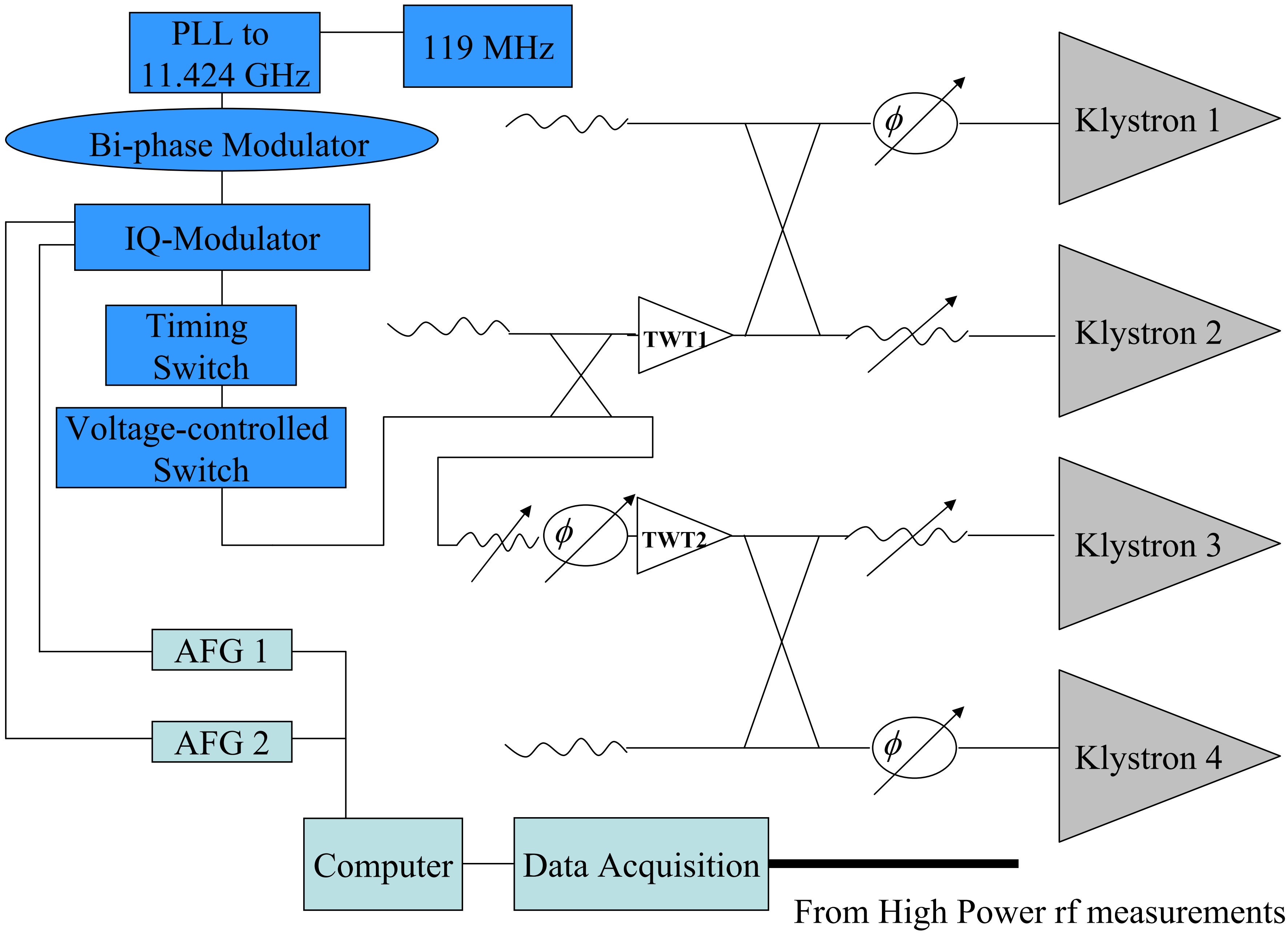
Where L is the required length of the line, T is the compressed pulse width, and v_{g1} and v_{g2} are the group velocities of the two modes used.



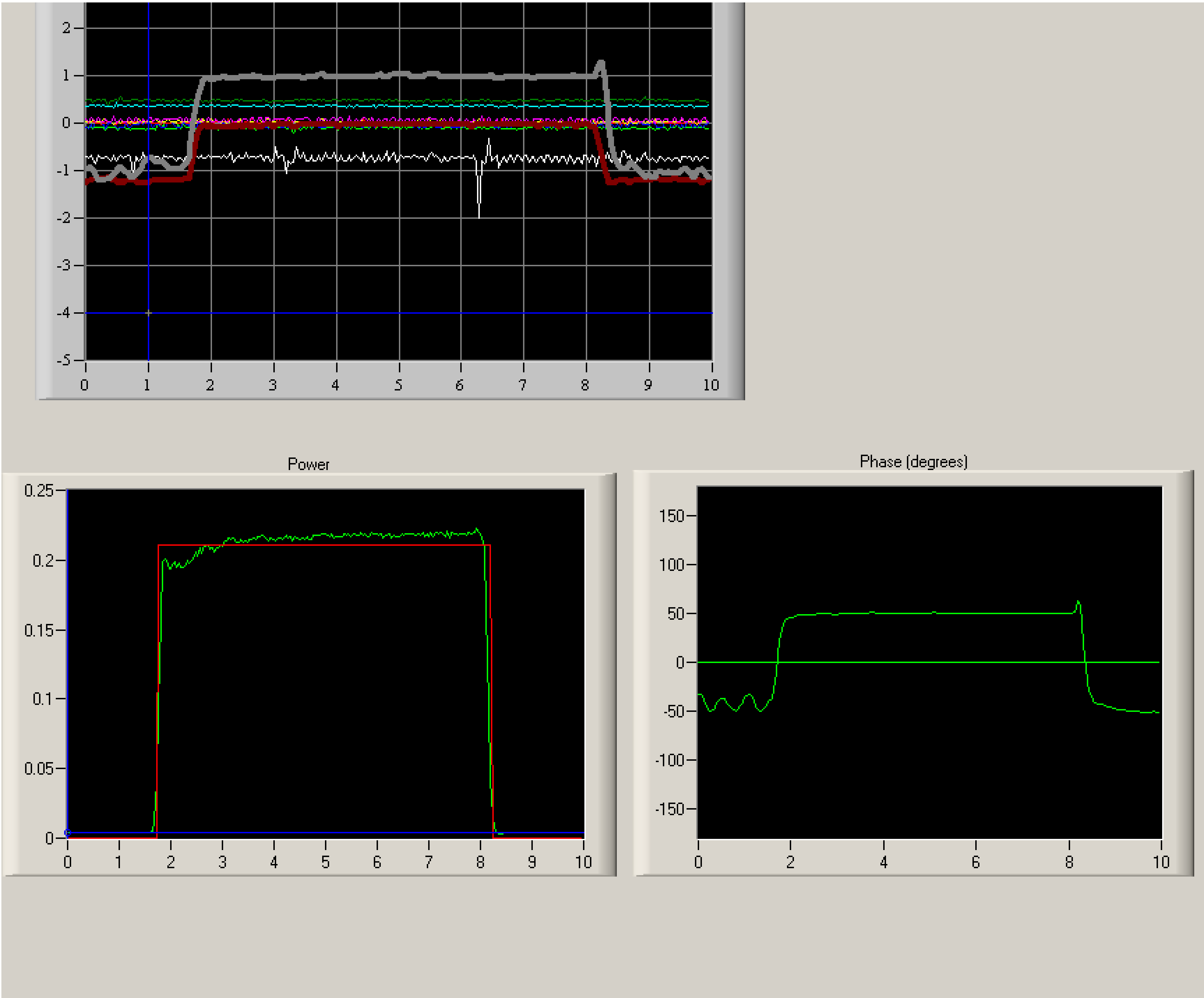

PEP II SW WINDOW TRAVELLER

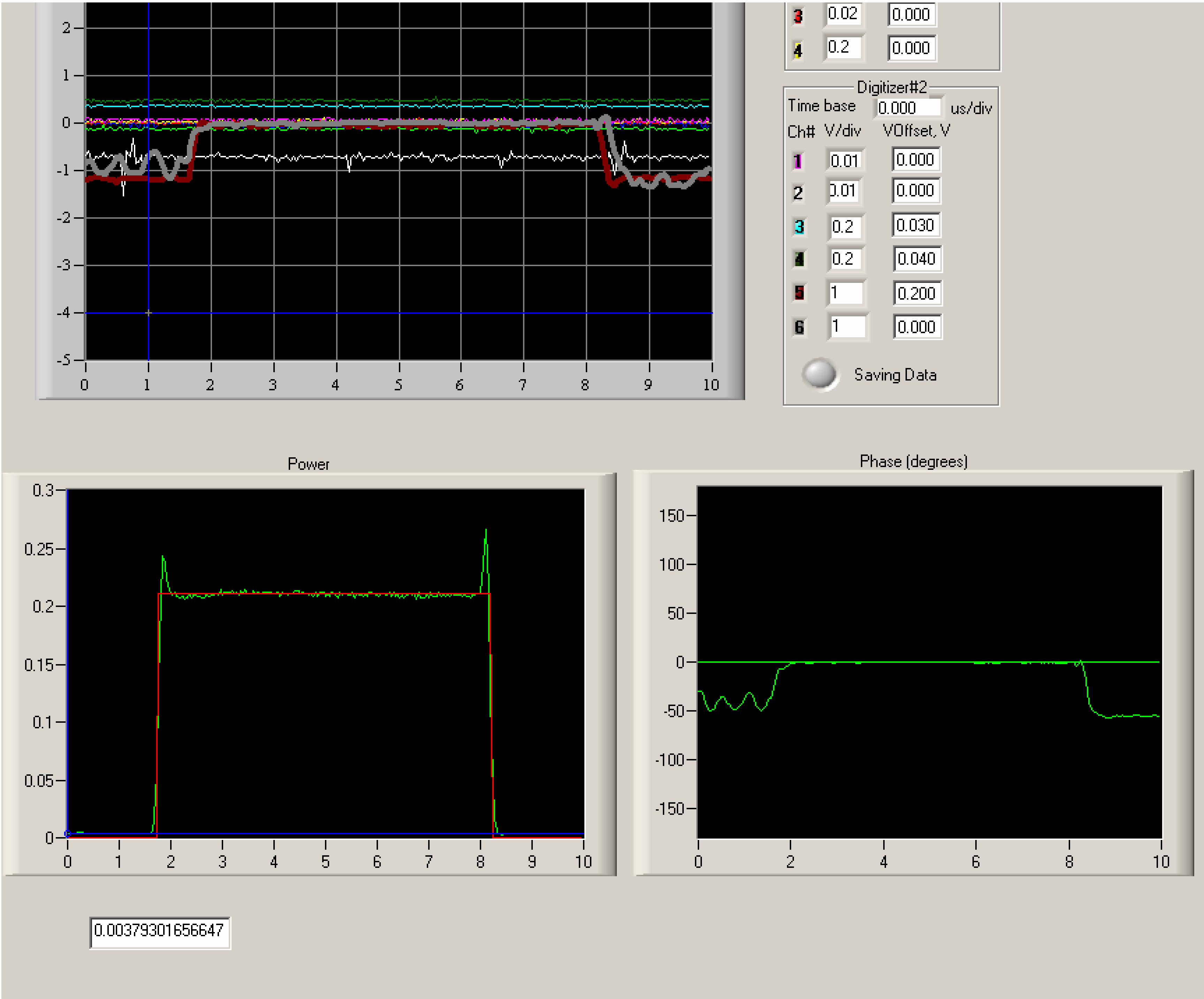


Output
Input
600
500
400
300
200
100
0
0
0.5
1
1.5
2
Power (MW)
Time (μs)

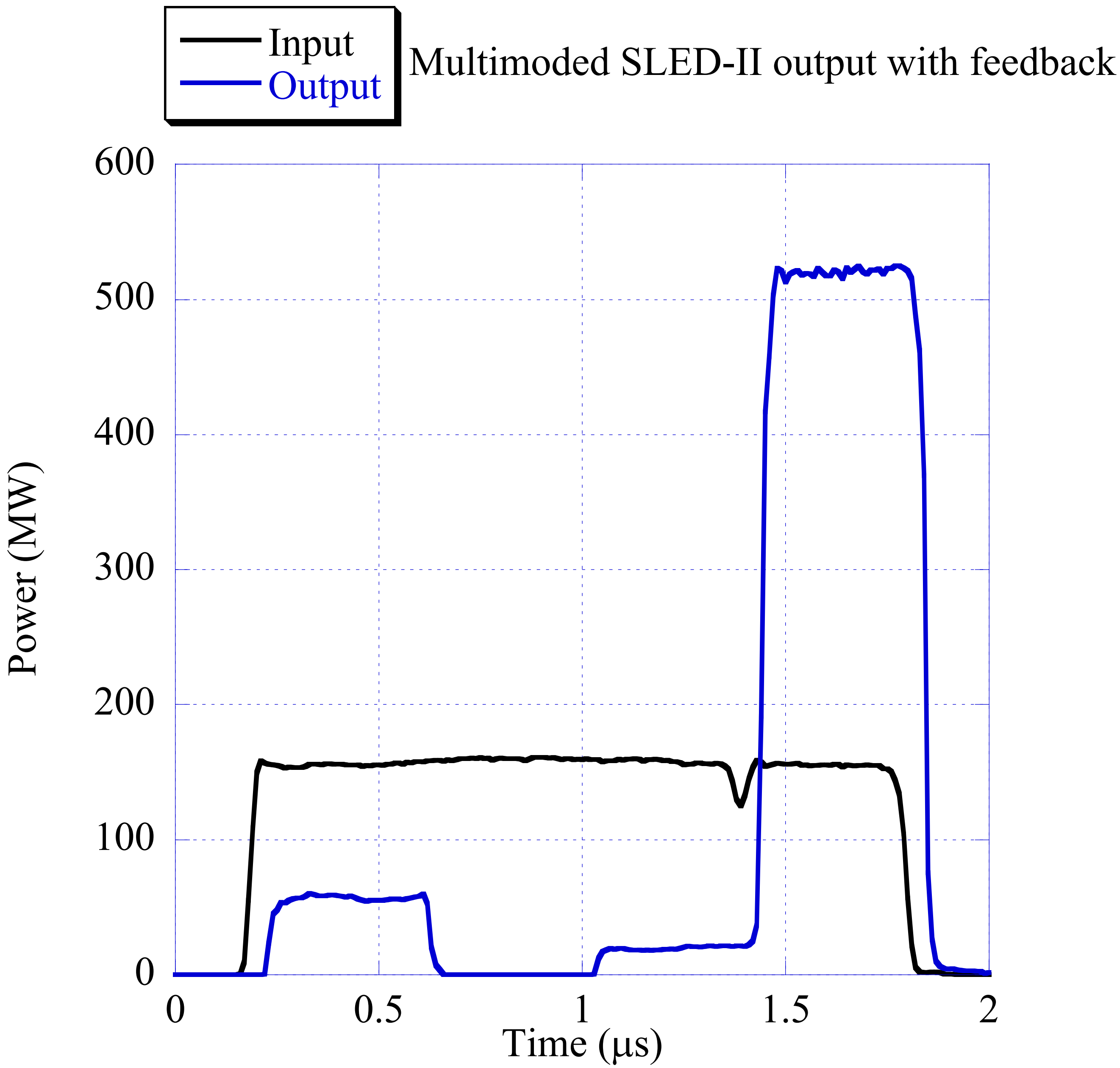


Low-Level RF Architecture

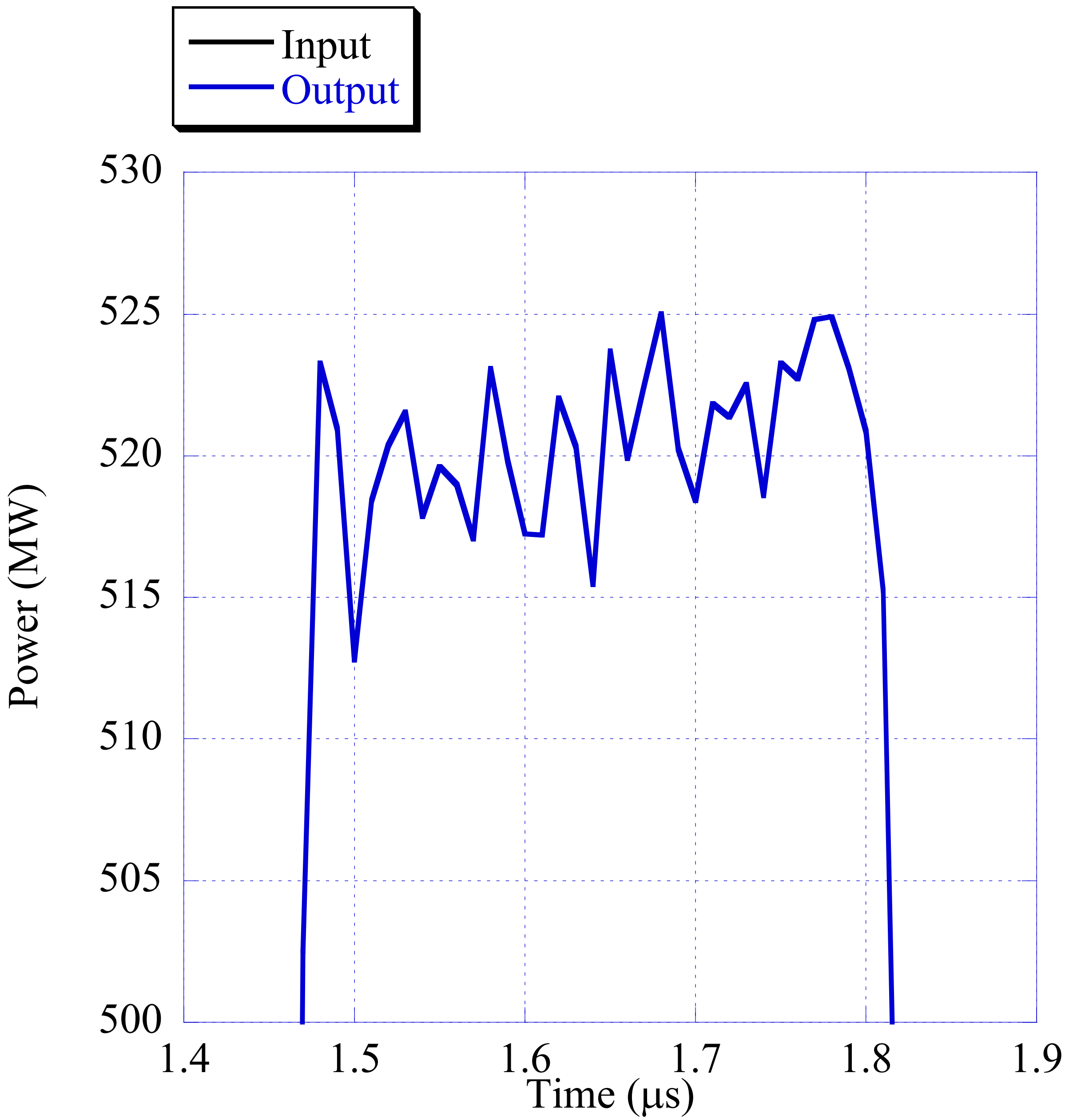

Power
Phase (degrees)



3 0.02 0.000
4 0.2 0.000
Digitizer#2
Time base 0.000 us/div
Ch# V/div VOffset, V
1 0.01 0.000
2 0.01 0.000
3 0.2 0.030
4 0.2 0.040
5 1 0.200
6 1 0.000
Saving Data
Power
Phase (degrees)
0.00379301656647

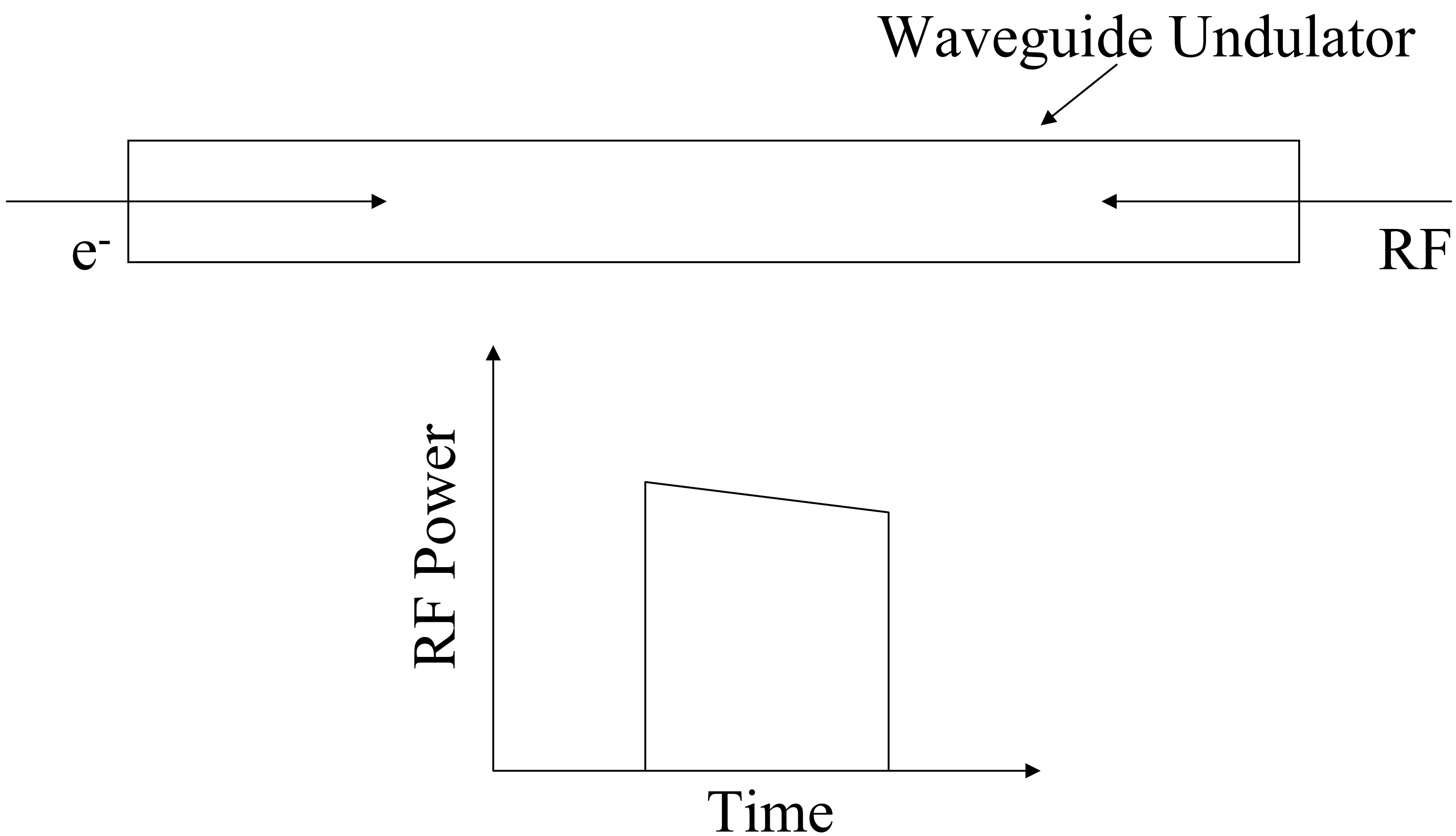


Sami Tantawi (1/27/2004)



Sami Tantawi (1/27/2004)

In a “single pass” undultor we have to tailor the rf pulse to compensate for losses and errors in the waveguide



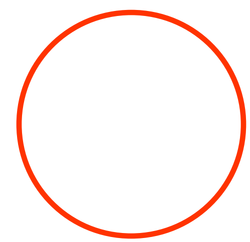
RF Undulator Realization

- Waveguide need to be precisely machined. Tolerances in the order of 10 microns is desirable.
- High power handling capabilities of the undulator waveguide have to be maximized and losses in the waveguide minimized.

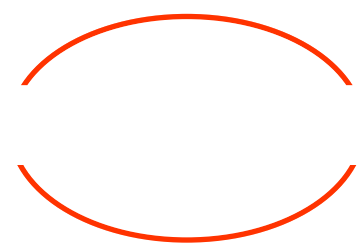
Possible Waveguide Types

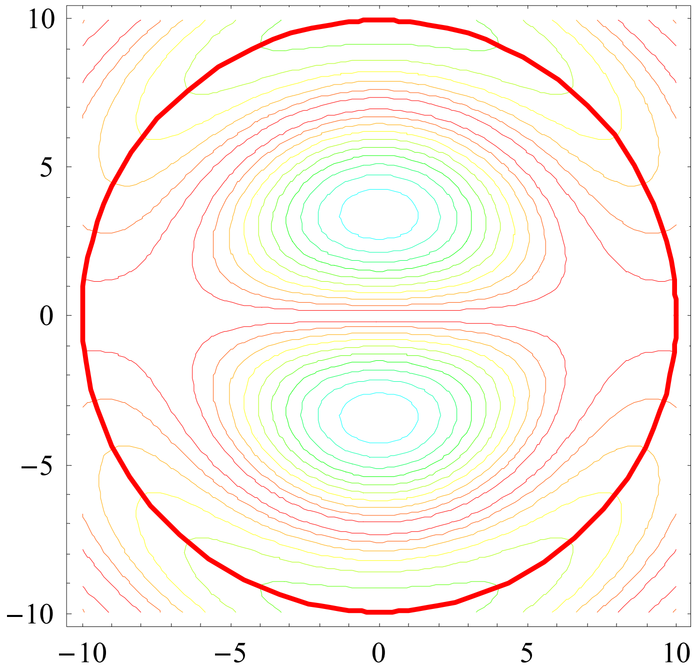
- Rectangular (Square)
  - High Attenuation

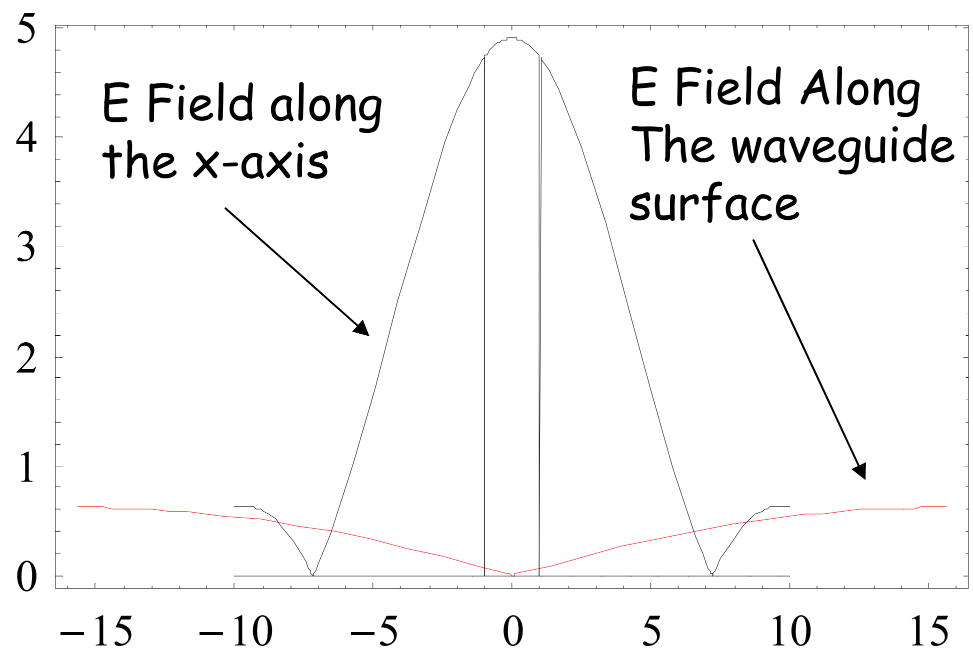
- Circular
  - Lower Attenuation



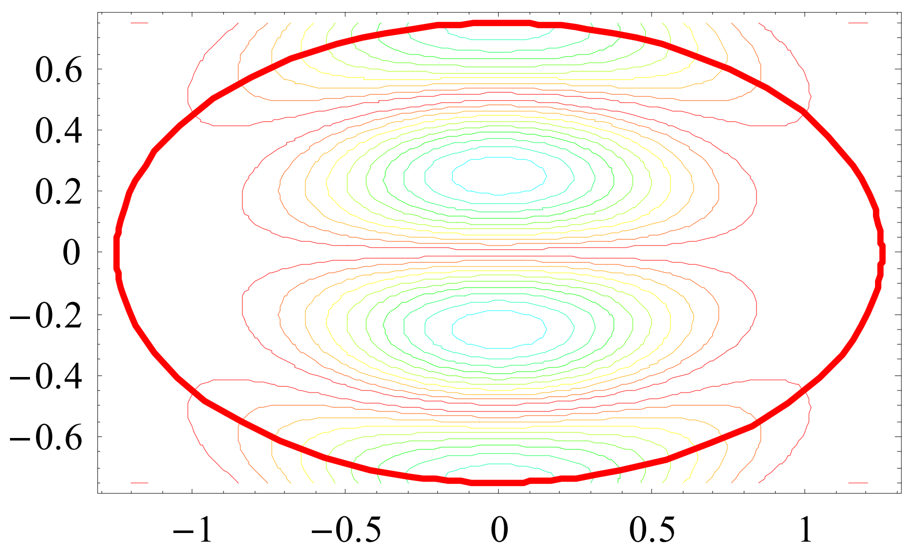
- Open Waveguides
  - Low Attenuation
  - Low transverse impedance

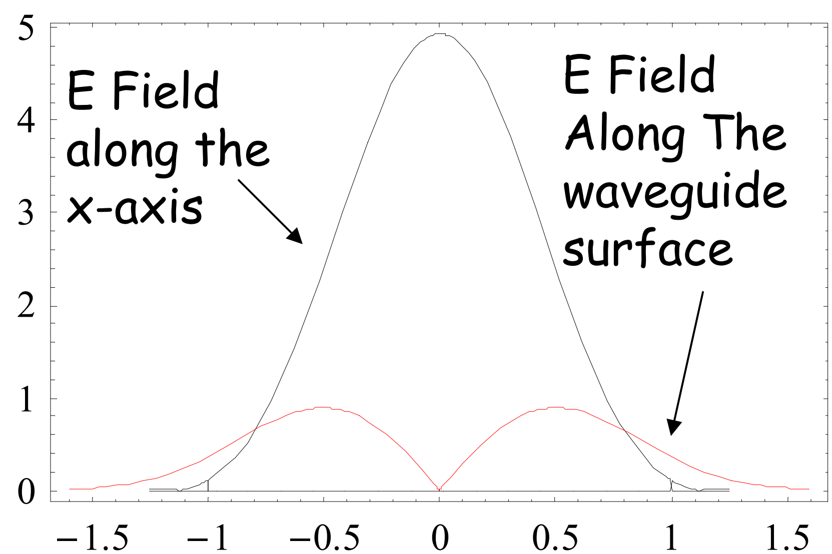






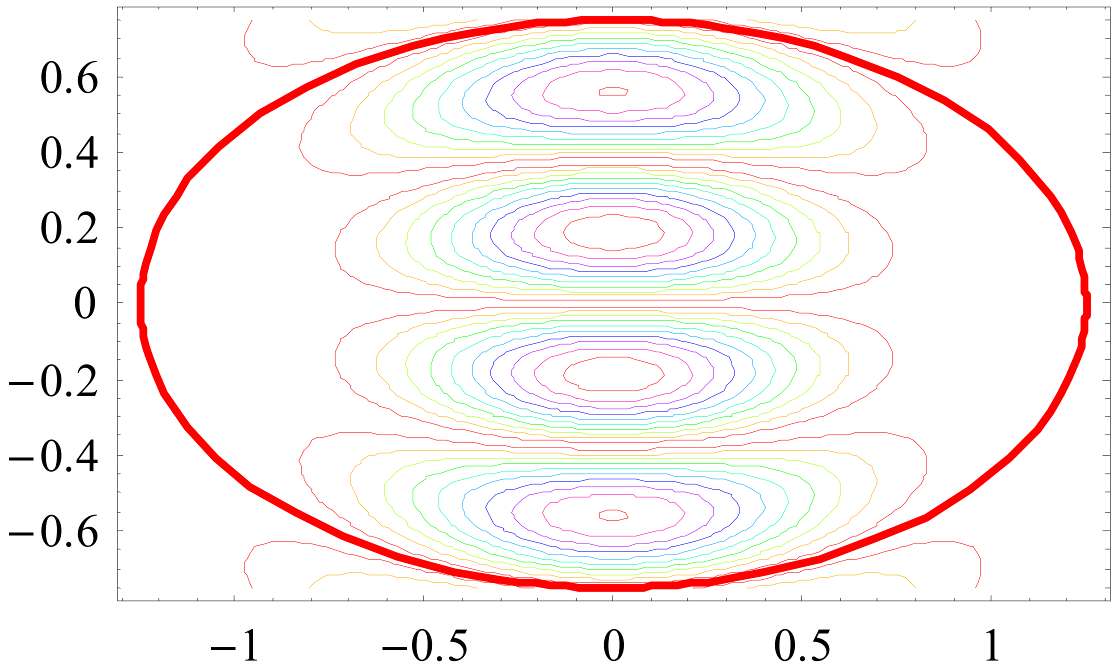
TE$_{12}$ in circular guide (E field Lines)



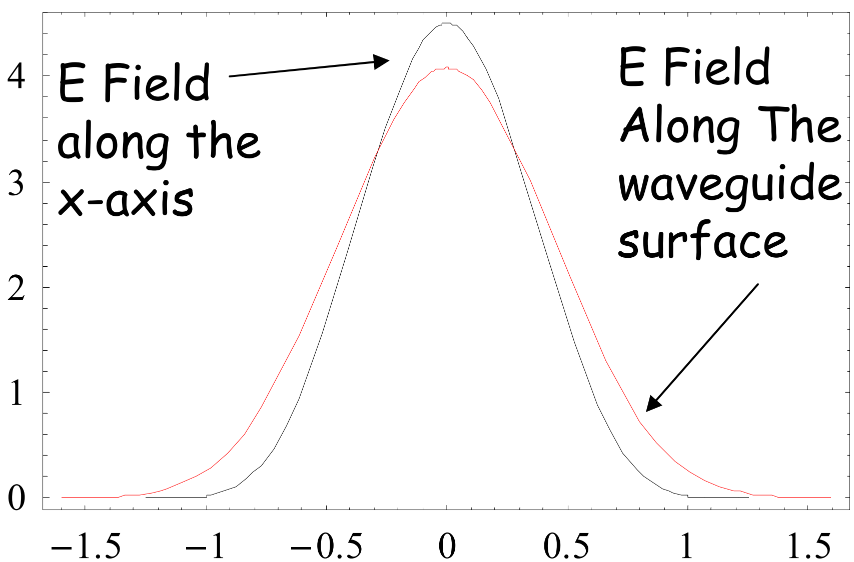


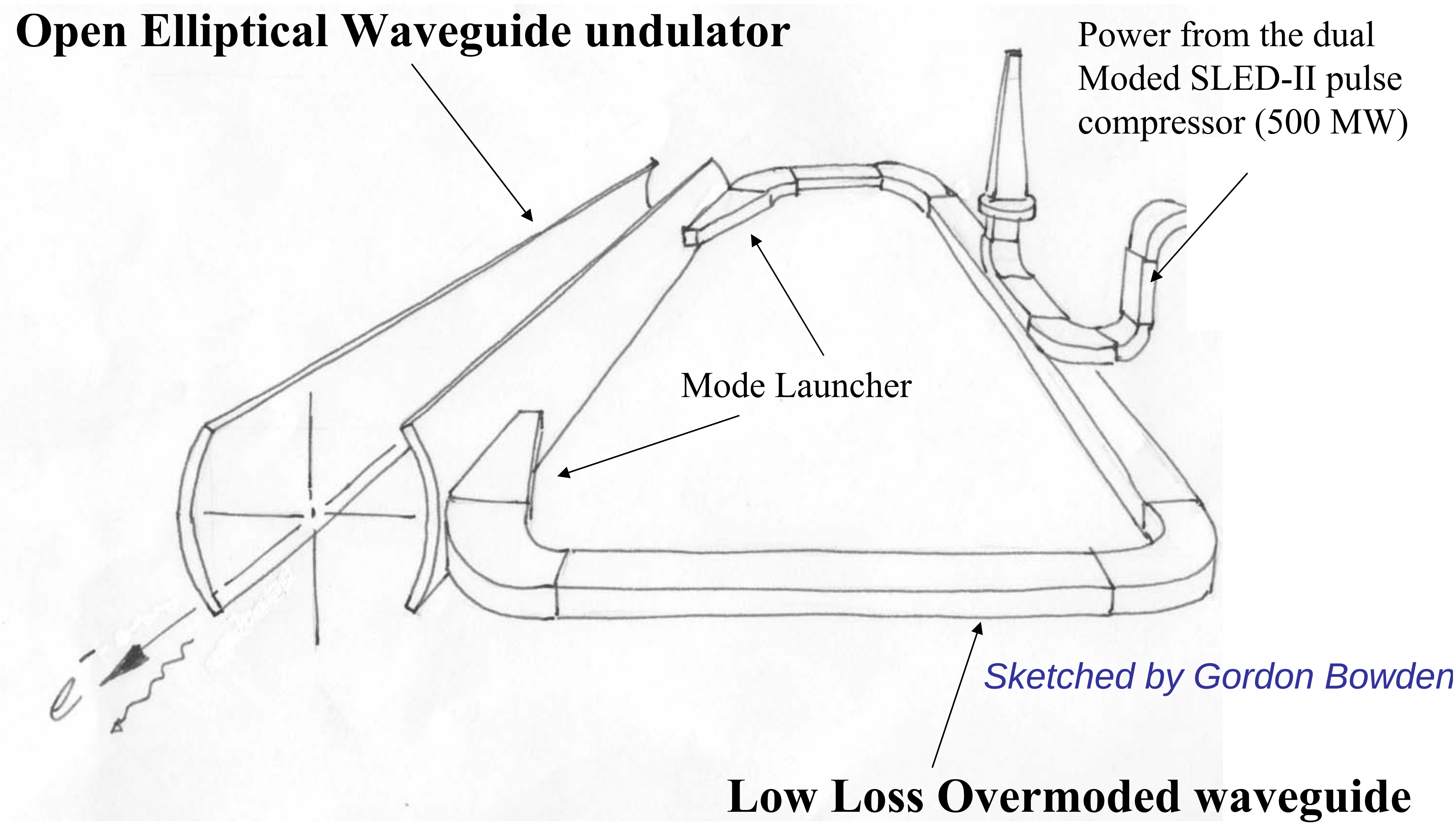
sTE$_{12}$ in elliptical guide (E field Lines)

Sami Tantawi

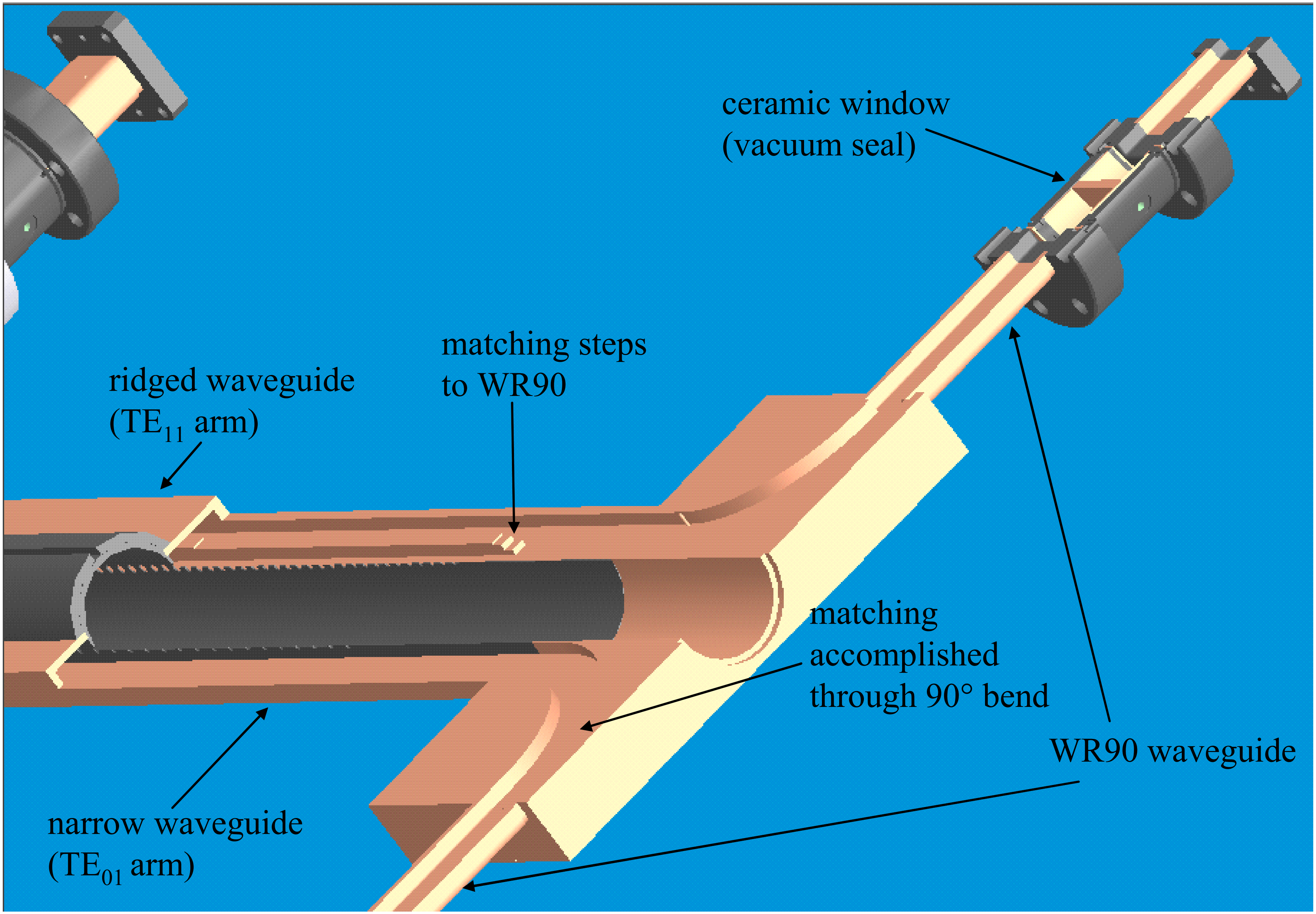


sTM_{12} in elliptical guide (H field Lines)

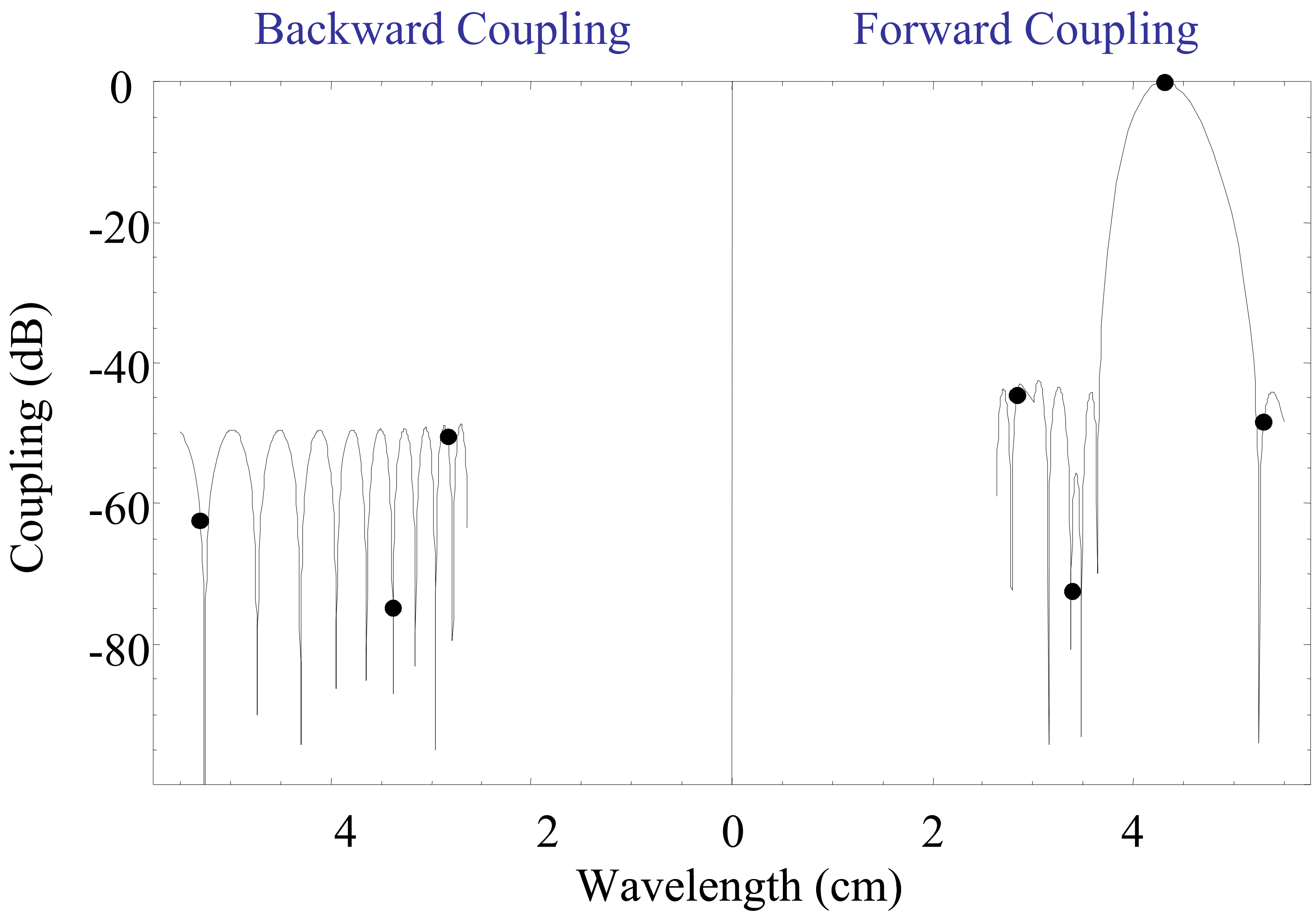




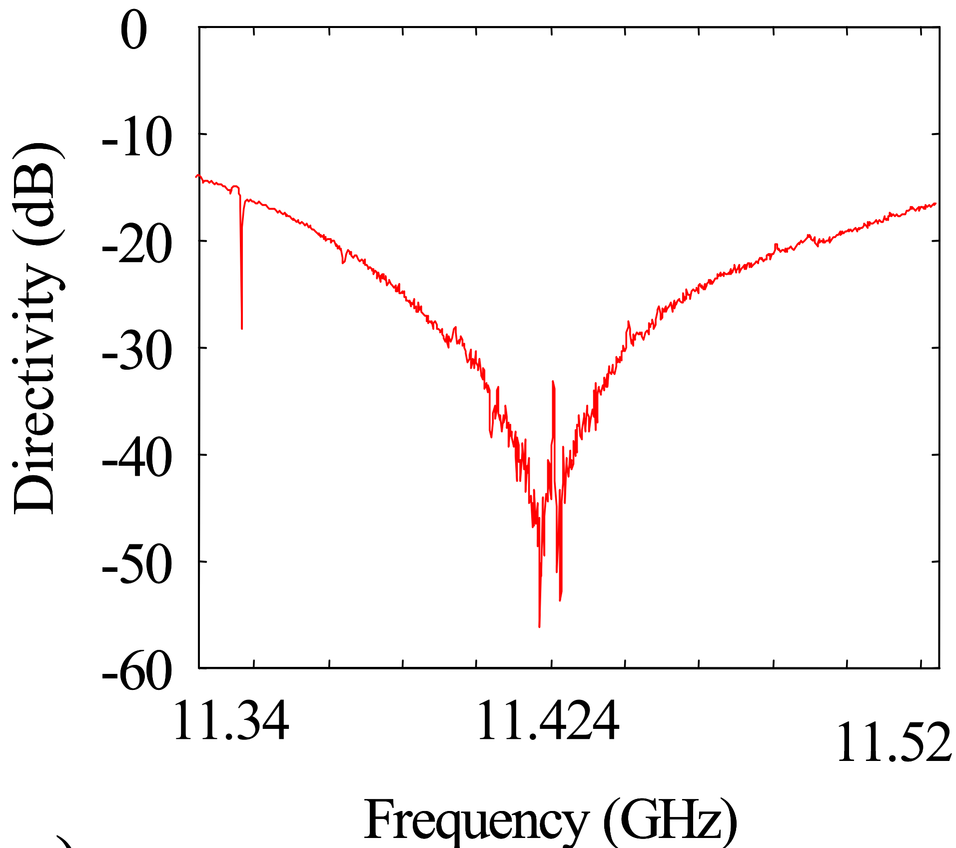
Because of the integration of RF pulses in a resonant ring the rf pulse in the undulator can be smoothed. Further, the ring can have a multiplication factor of more than 10, resulting in 5 GW of RF power through the undulator waveguide.



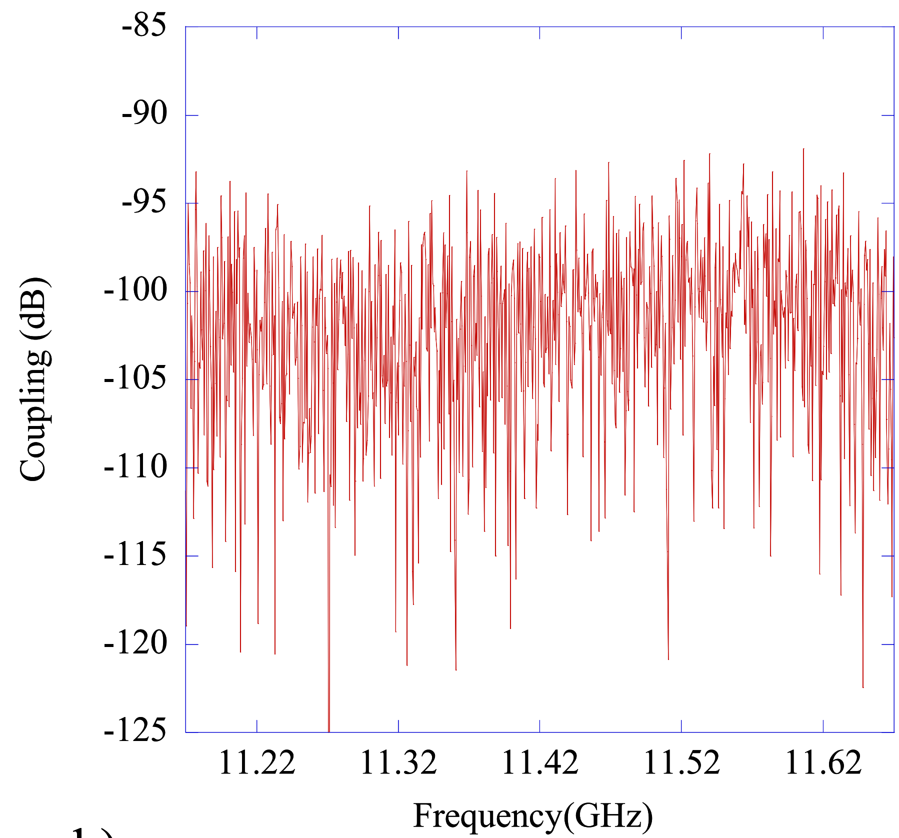
Inner structure of the dual-mode directional coupler



Coupling *vs*. guided wavelength. TE01 directional coupler response (normalized to forward coupling of the TE01 mode). Coupler length =50.6 cm. Number of coupling holes=44. Points represent : TE11, TE21, TE01, TE31. The TE01 mode is not shown in the backward coupling because it is theoretically zero because of the choice of coupling holes spacing.



a)



b)

Directivity

Coupling between TE01 and TE11 mode
Measurements Limited by available dynamic range

Conclusion on powered rf undulators

- High power microwave technologies developed for NLC make rf undulators practical: **we have a system that reliably manipulates hundreds of MW in highly overmoded waveguide**
- Open elliptical waveguide might provide an attractive design for an rf undulator
- Making the undulator a part of an RF resonant ring will help smooth the RF power and will provide an extra flexibility for the RF system by introducing high compression gain

Beam-powered rf undulators

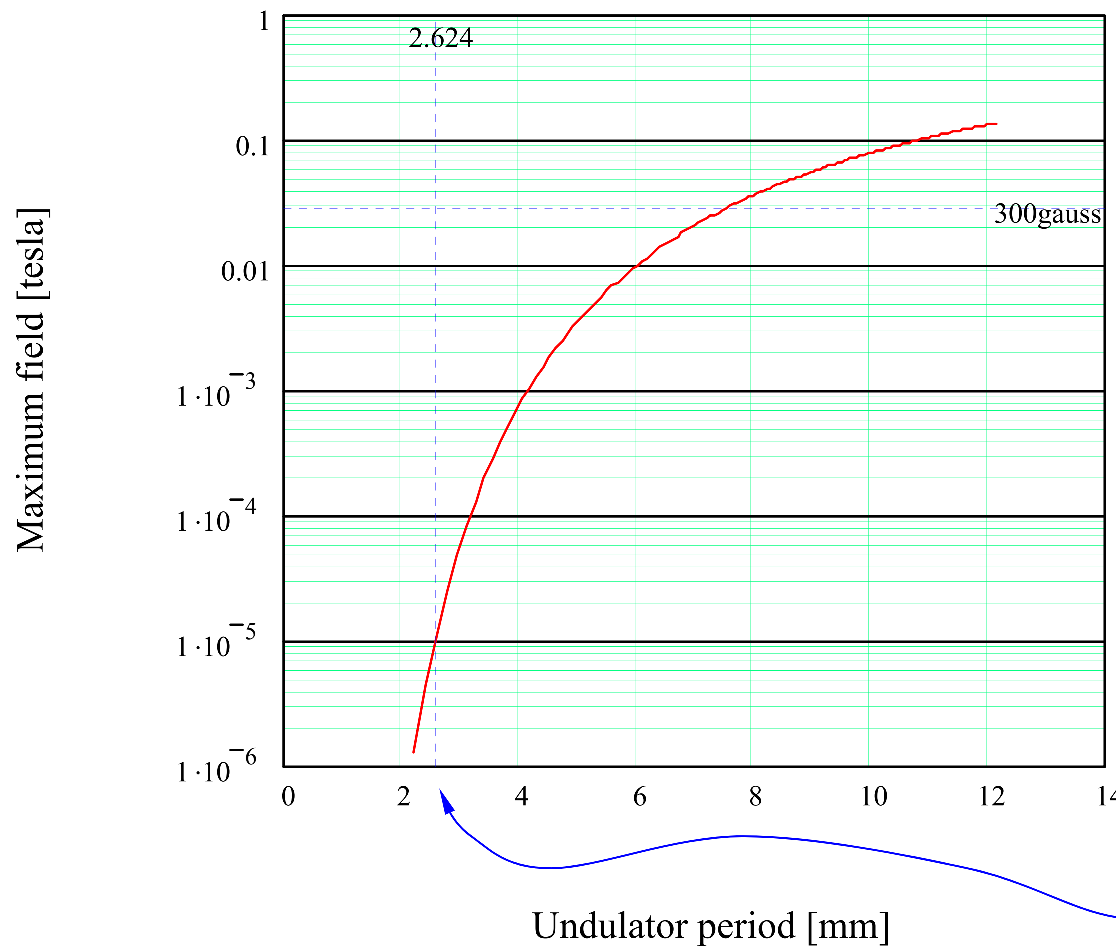
Idea:

Synchrotron radiation sources require **high charge, high current beams**. Small portion of the energy in the beam could be used to generate deflecting fields in rf undulator.

Use of beam power to generate rf allows **"practical"** undulators with ~1 cm aperture, ~1 mm period, and K ~ 0.01.

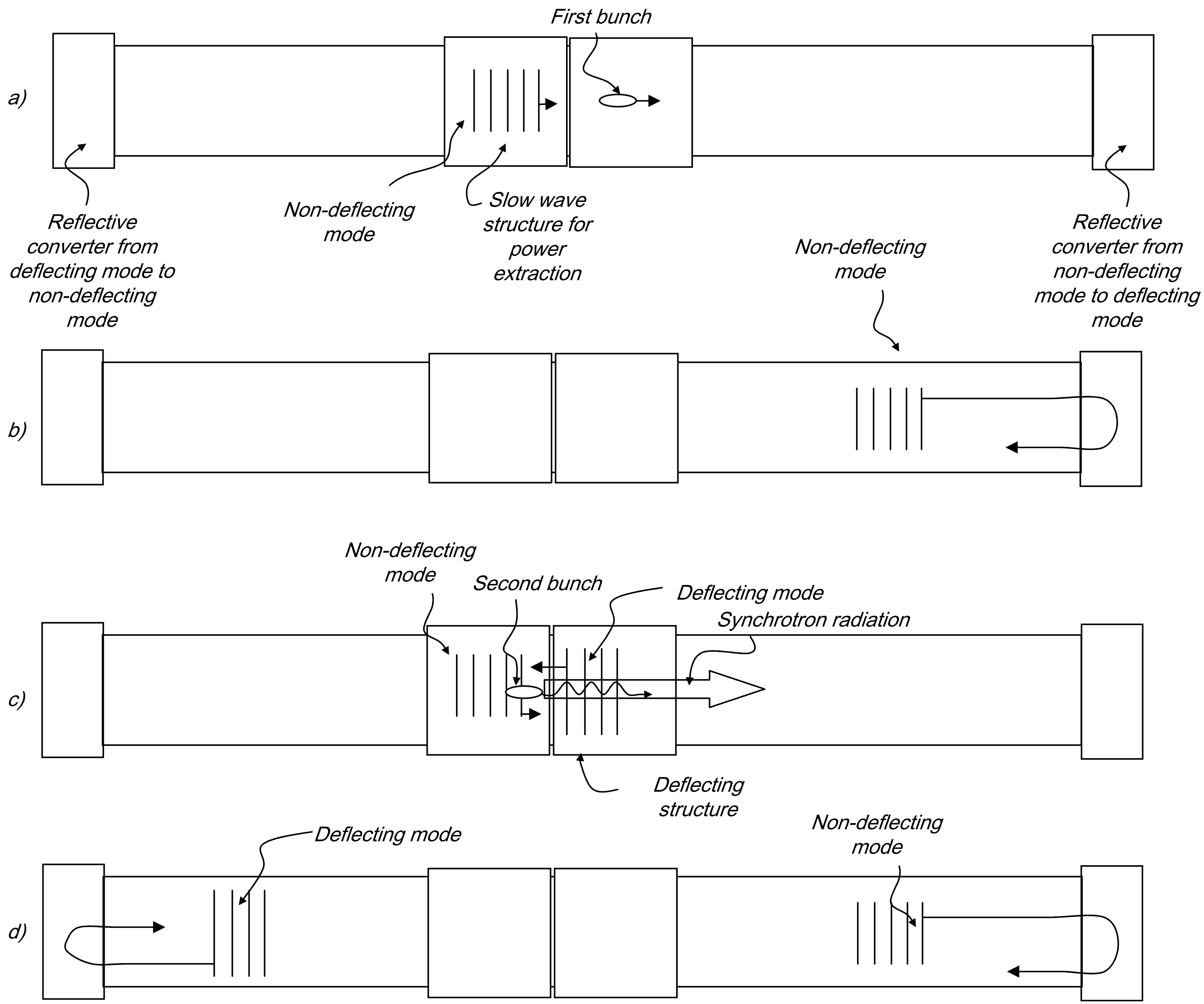
To make such an undulator with an external source one will need ~MW, 50-90 GHz, **coherent** power source.

Maximum magnetic field for permanent magnets undulator *vs.* its period. Undulator gap is 1 cm, and permanent magnet Br = 0.9 Tesla.

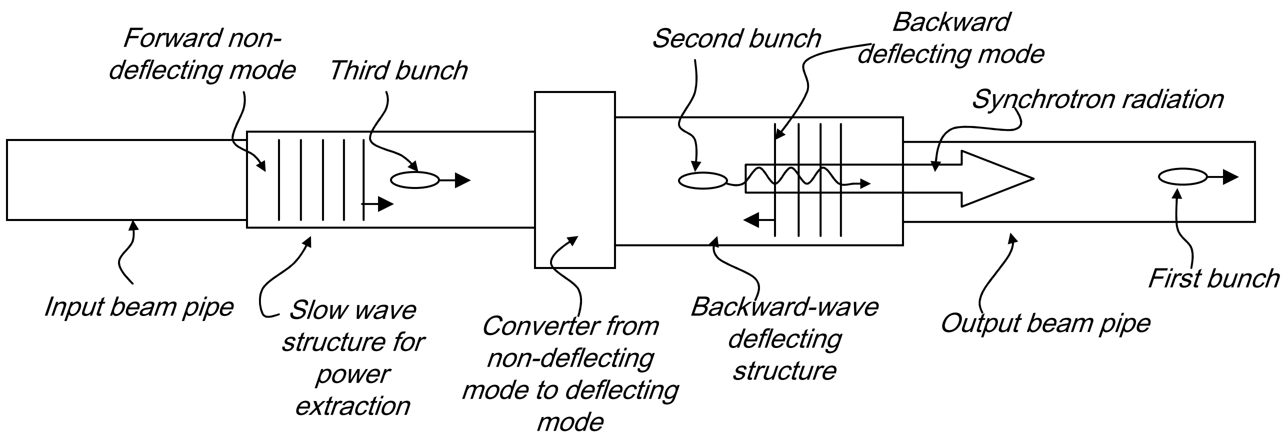


57 GHz
RF undulator,
period 2.6 mm,
K= 0.007

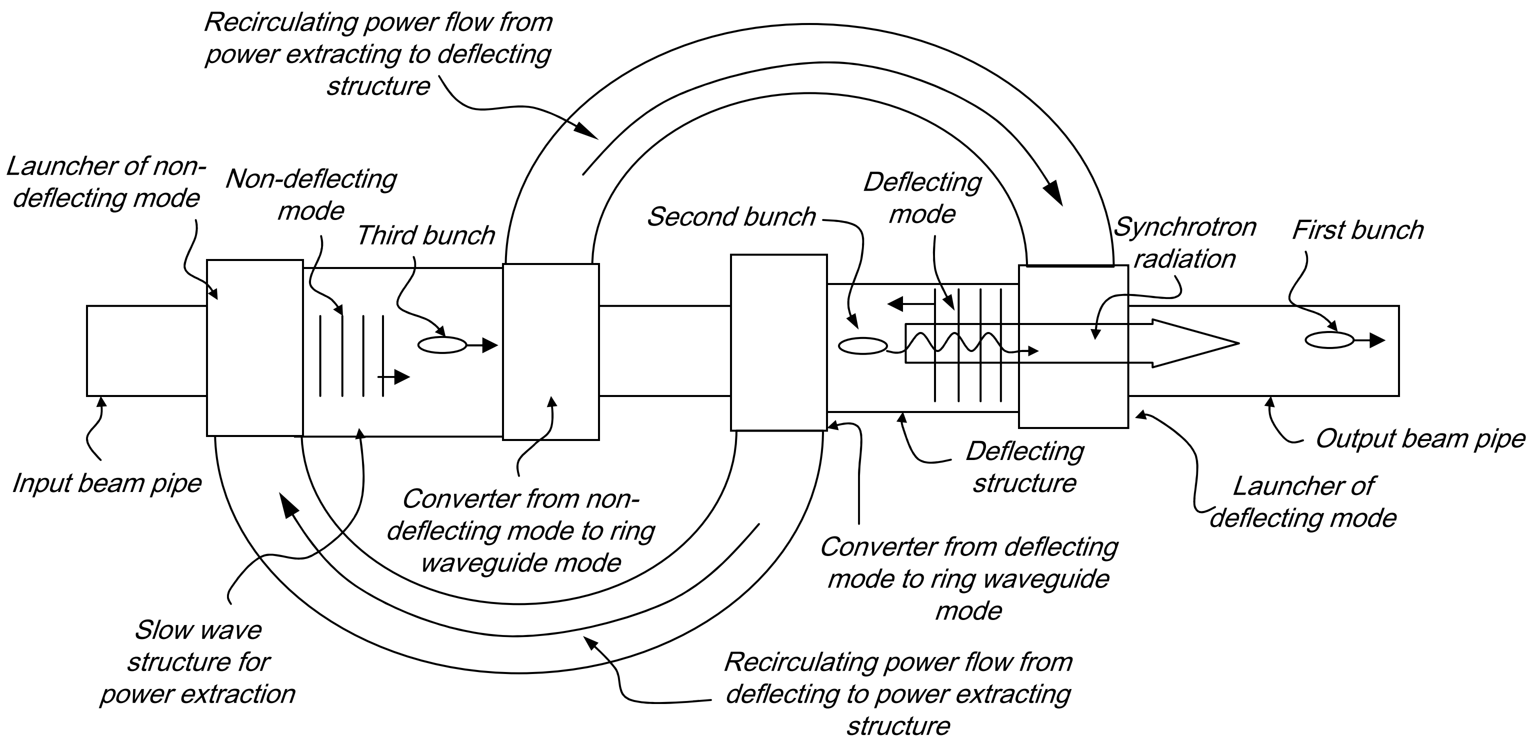
RF undulator with reflective mode converters



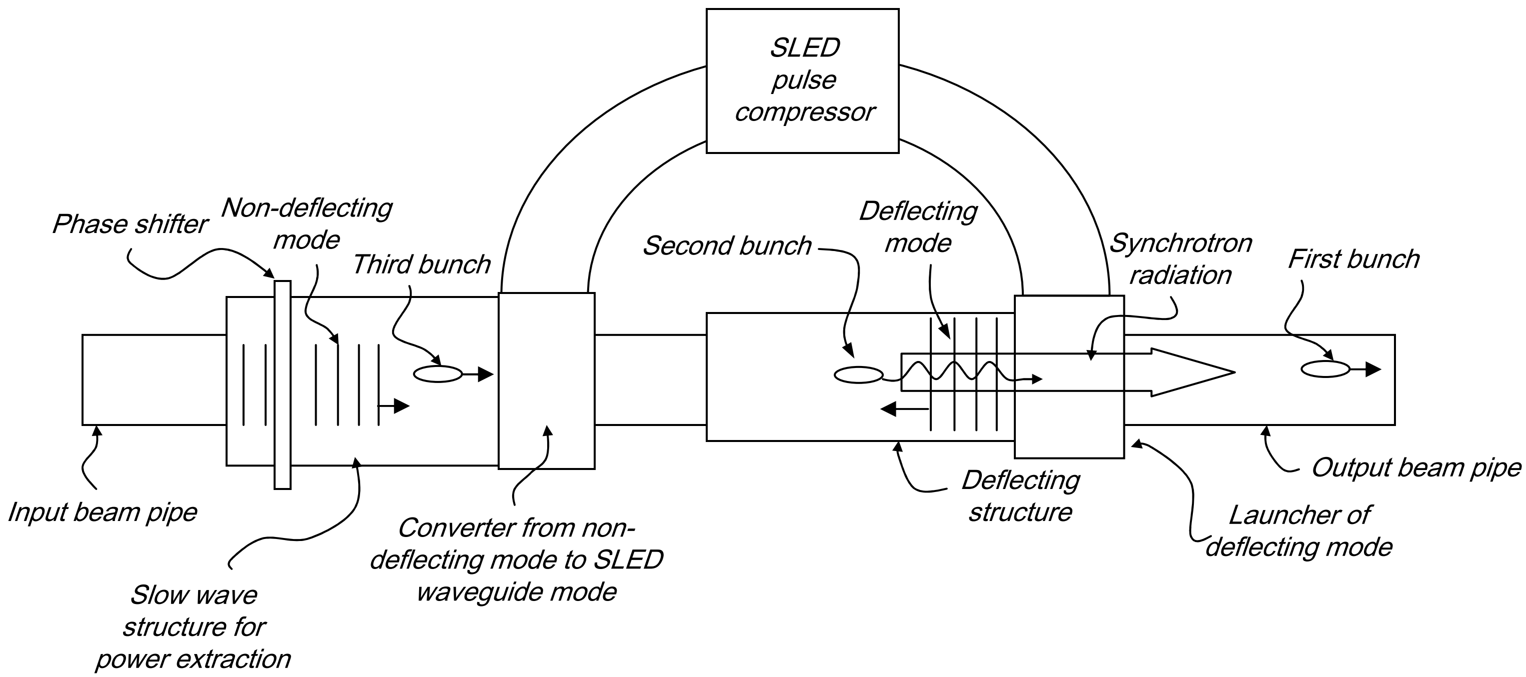
Inline rf undulator



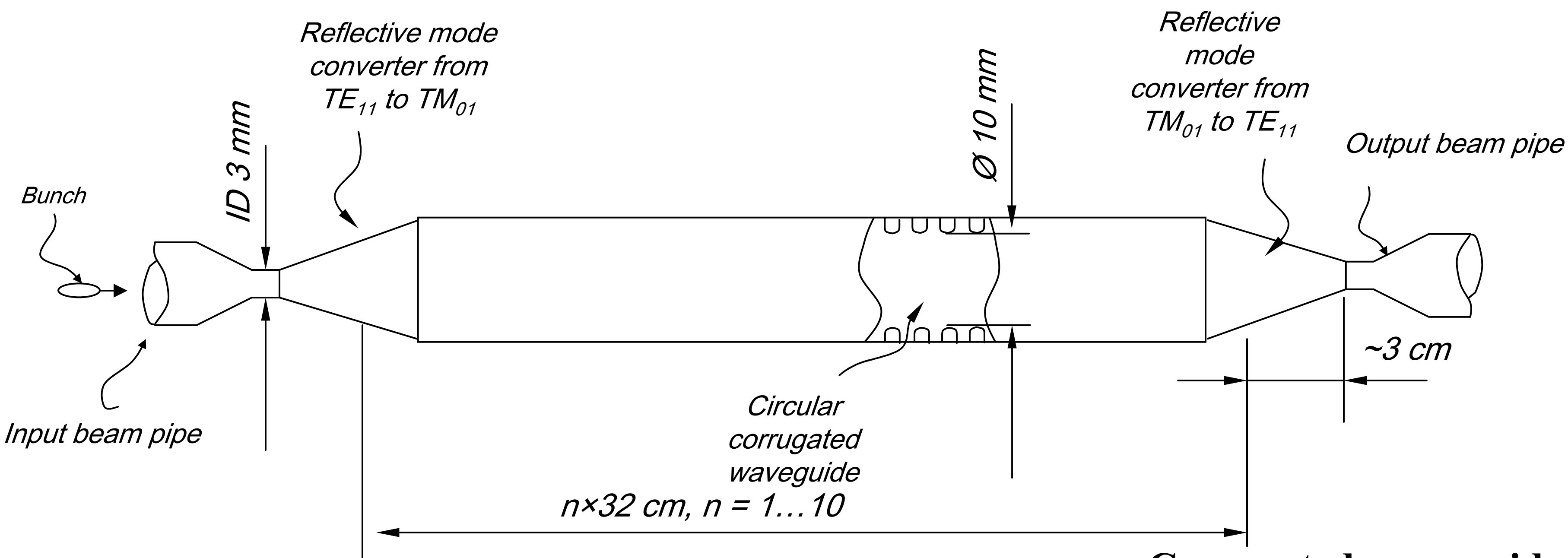
RF undulator with resonant ring



RF undulator with SLED pulse compressor



Example of rf undulator with reflective mode converters



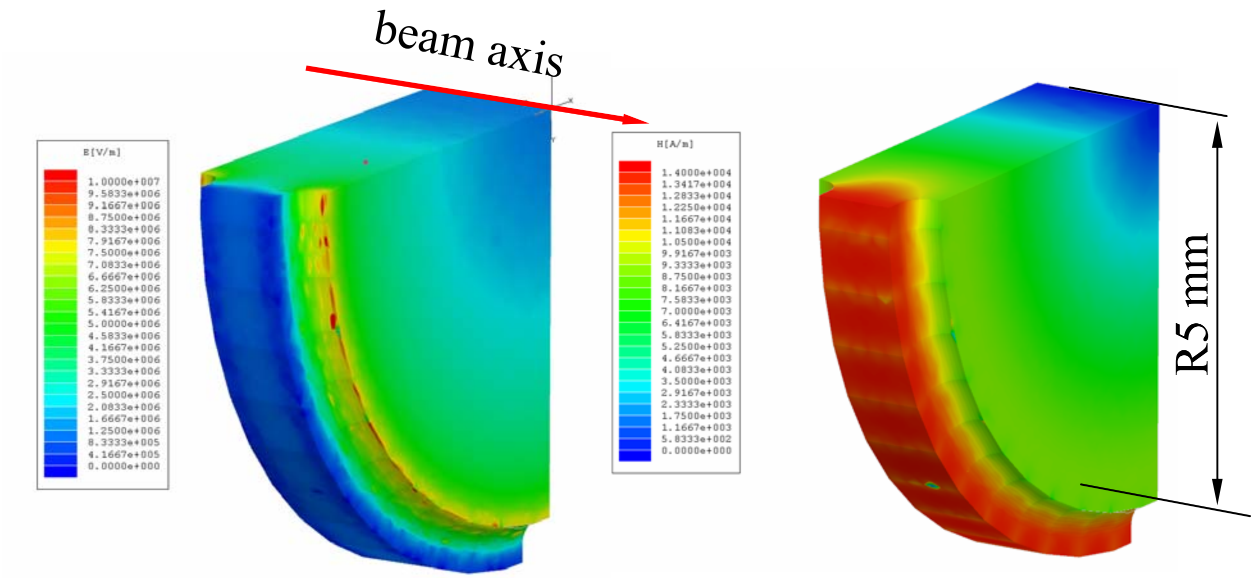
Properties of rf undulator for 10^{10} electrons in each bunch, and 1.4 ns bunch spacing:

- Frequency 57 GHz
- Period 2.6 mm
- Equivalent static field 0.028 … 0.036 T
- K = 0.0068 …0.0087
- Length of “deflection” 2.9 cm×*n*

Corrugated waveguide

Parameter	Value
Aperture radius (a)	5 mm
Large radius (b)	5.6012 mm
Period (D)	1.7495 mm
Iris thickness (t)	0.7495 mm
Iris radius (r)	$t/2$

Corrugated waveguide, monopole mode



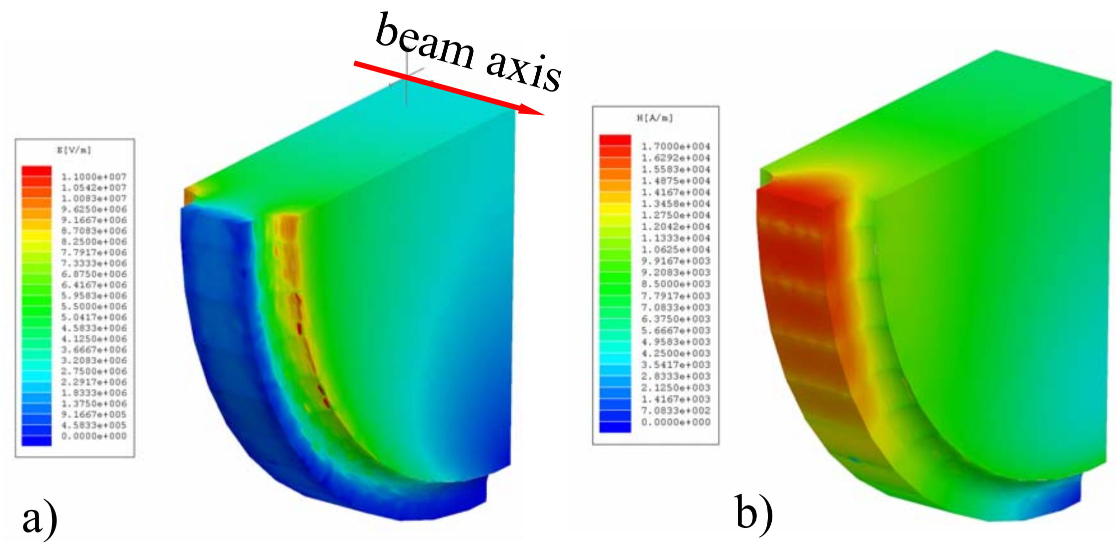
a) b)

Parameter	Value
Frequency	57.12 GHz
Q value	6217
Effective impedance	1.221 kOhm/m
Shunt impedance	7.59180 MOhm/m
Phase advance per cell	120 degrees
Loss factor	461 V/pC/m
Group velocity	.762*c*
Dissipation length	396 cm

Field amplitudes of first monopole in the corrugated waveguide for 1 MW of transmitted power:
a) amplitude of electric fiel
b) amplitude of magnetic field

Parameters of corrugated waveguide as power extractor calculated by 2D Finite Element Code SLANS. Here *c* is the speed of light.

Corrugated waveguide, deflecting mode



Field amplitudes for the first dipole mode in the corrugated waveguide for 1 MW of transmitted power:

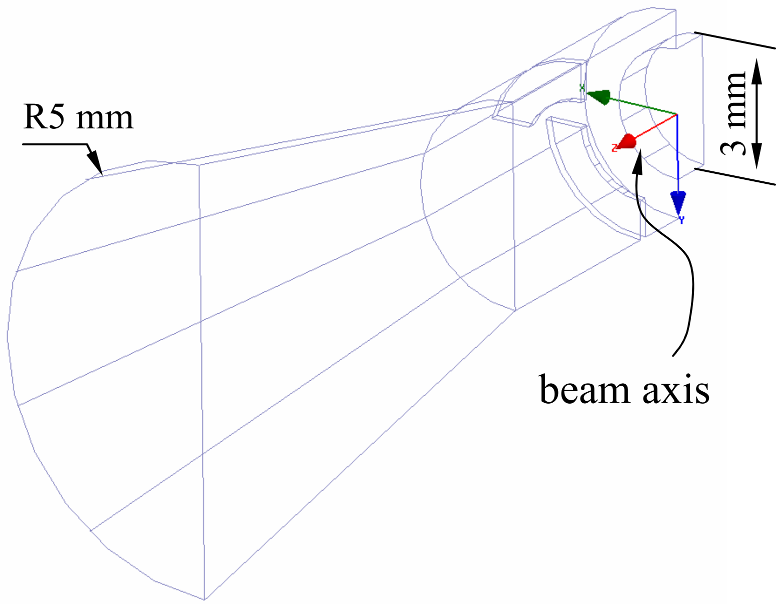
a) amplitude of electric field;

b) amplitude of magnetic field

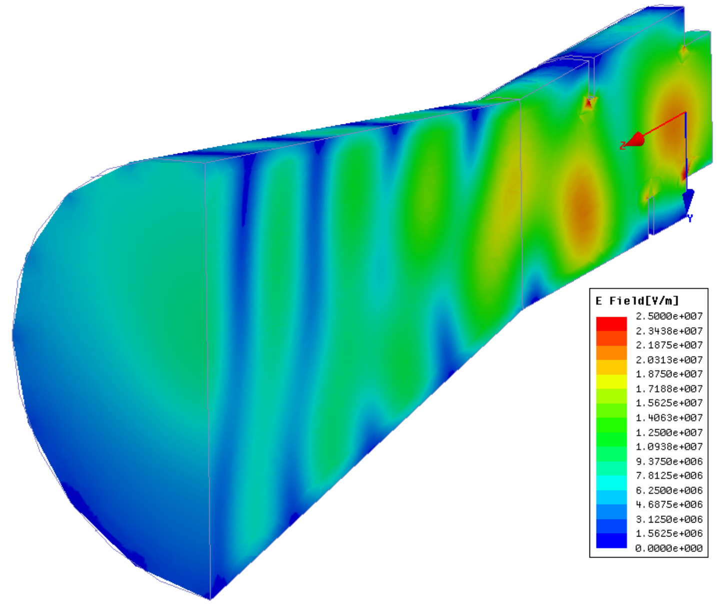
Parameter	**Value**
Frequency	57.23 GHz
Q value	7724
Maximum deflection	0.02 Tesla/sqrt(MW)
Phase advance per cell	120 degrees
Group velocity	.813*c*
Dissipation length	524 cm

Parameters of corrugated waveguide as a deflector calculated by 3D Finite Element Code HFSS.

Example of TM_{01} to TE_{11} mode converter

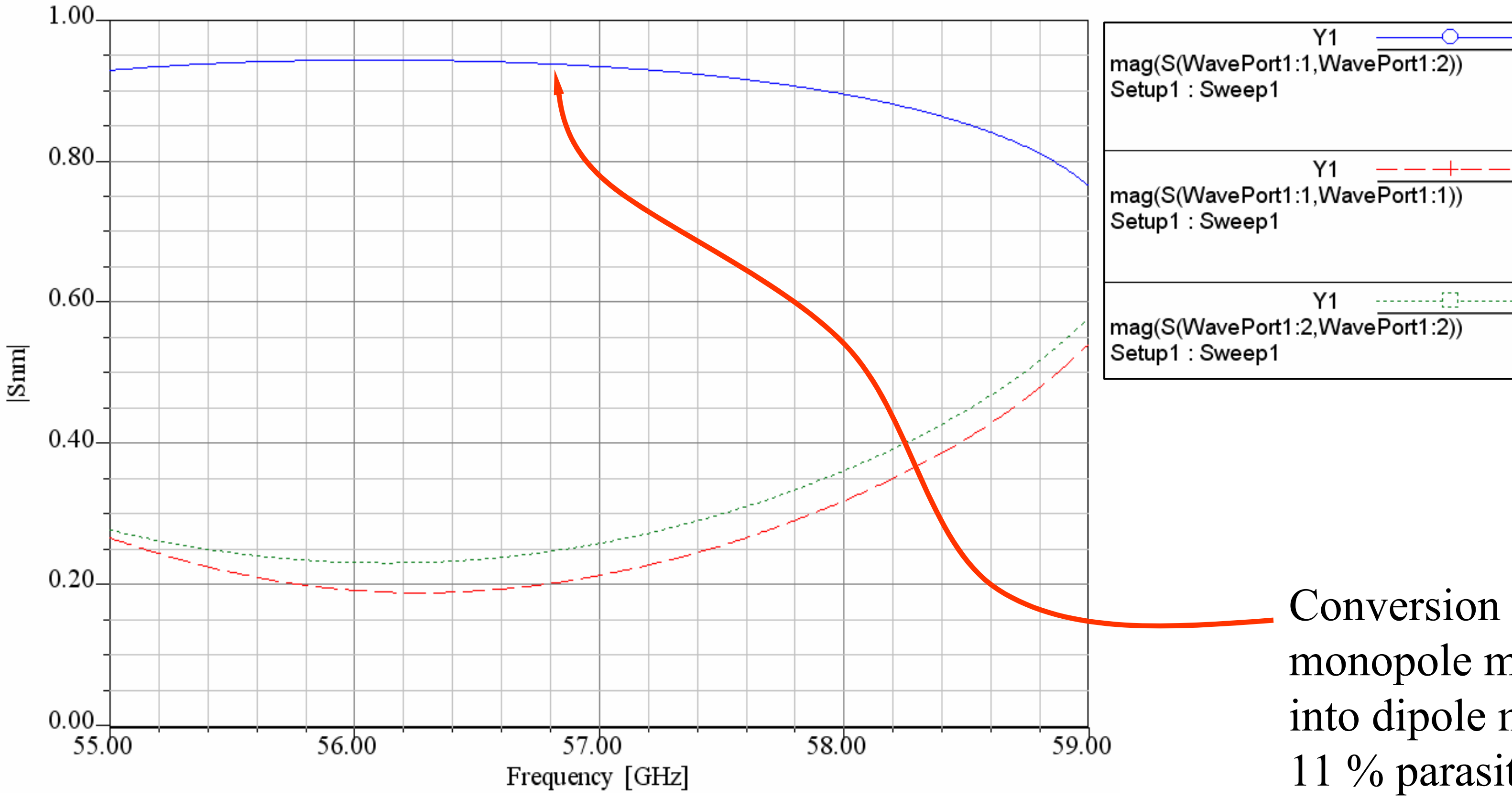


3D model



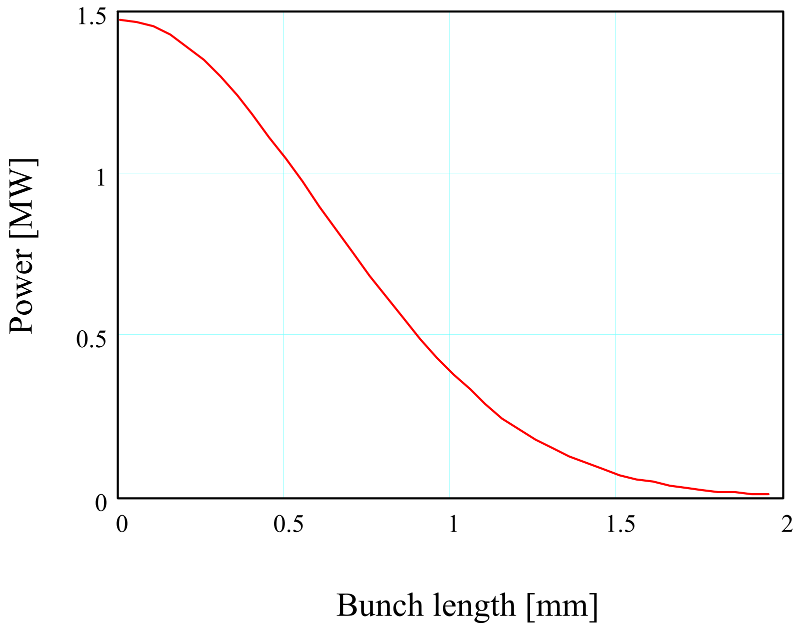
Amplitude of electric field for
1 MW of incident power in TE_{11} mode

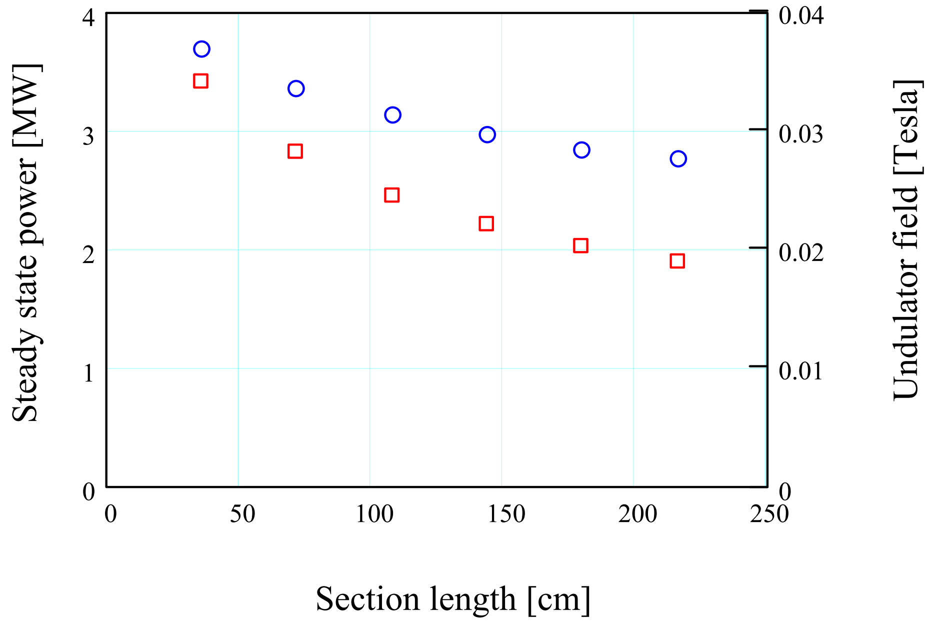
S-parameters of TM_{01} to TE_{11} mode converter



Conversion of the monopole mode into dipole mode, 11 % parasitic mode conversion

Parameters of 57 GHz rf undulator





Power generated in the corrugated waveguide by **1.6 nC** bunch *vs.* the bunch length.

Steady state power (boxes) and undulator magnetic field (circles) *vs.* undulator length. To be resonant with 1.4 ns bunch spacing the undulator length is in multiples of 32 cm. This power is calculated for a bunch length of 0.2 mm, bunch charge 1.6 nC,

Conclusion on beam-powered rf undulators

- Use of beam power might be a practical solution for ~1 cm aperture, ~1 mm period undulators.