Electron beam shaping and high gradient, high transformer ratio acceleration in a dielectric tube.

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Outline

- Background and motivation, MaRIE.
- DWAs and energy spread in a witness bunch.
- Bunch shaping with an emittance exchanger.
- Proposed experiment at ASTA.

Background and motivation, MaRIE

Motivation

• The pre-conceptual design for MaRIE is underway at LANL, with the design of the 12 GeV electron linac being one of the main research goals.

• Requirements the for linac: high gradient and high quality electron beam:

- electron bunch charges of 0.1 to 1 nC;
- normalized rms emittances of 0.1 to 1 μm;
- and rms energy spreads of less than 0.1%.

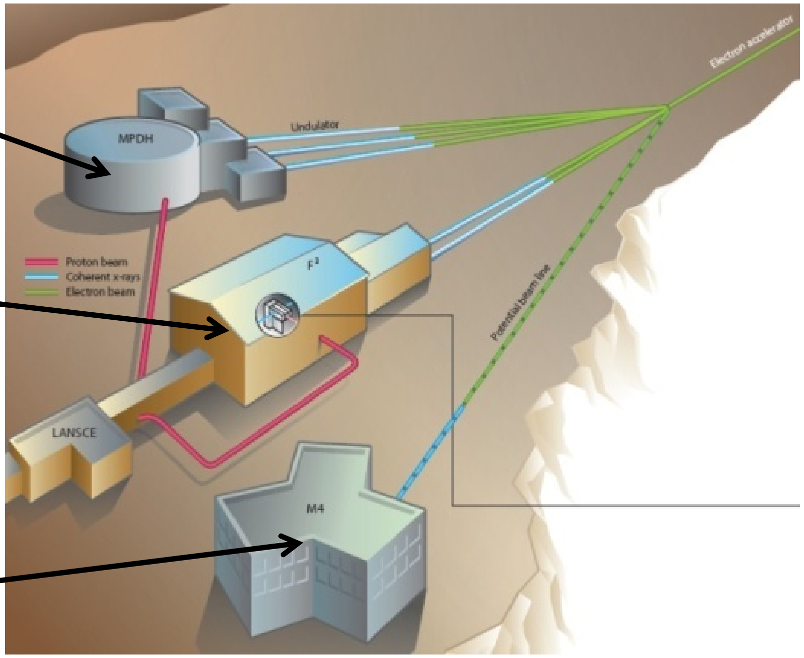
• Exactly the same phenomena, that causes the dominant energy spread effect in beams in conventional linacs can be used to generate extraordinary gradients and small energy spreads in and dielectric structures via wakefield acceleration.

First ideas: Workshop on Application of dielectric wakefield accelerators (DWAs) to next generation X-ray free-electron laser facilities, Argonne National Laboratory, April 20-21, 2011.

MaRIE

The pre-conceptual design for Matter-Radiation Interactions in Extreme (MaRIE) future signature facility is underway at LANL.

- **MPDH**: Multi-Probe Diagnostic Hall. The X-ray scattering capability at high energy and high repetition frequency with simultaneous charged particle dynamic imaging.
- **F³**: Fission and Fusion Materials Facility. In-situ diagnostics and irradiation environments beyond best planned facilities.
- **M4**: Making, Measuring & Modeling Materials Facility. Comprehensive, integrated resource for materials synthesis and control, with national security infrastructure .



MaRIE requirements on the photons and FEL beam

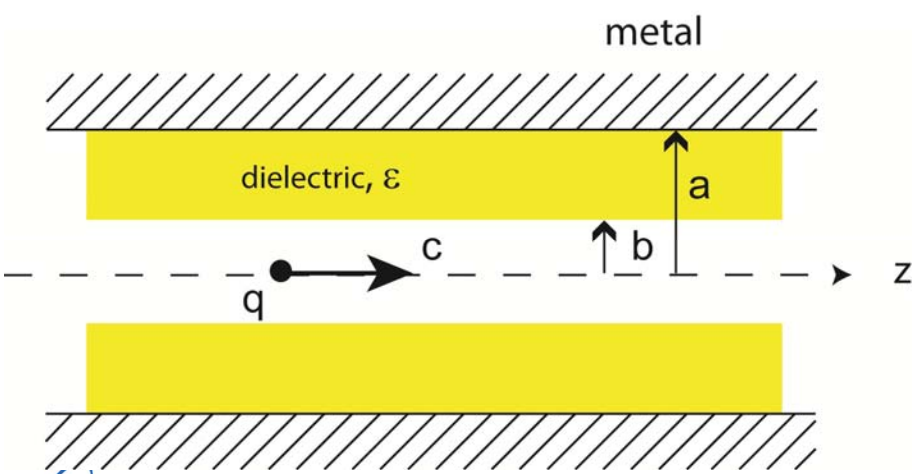
	MPDH	FFF		M4	
Design energy is normally top of range (keV)	5-42 (122)	~10 to >50	10 to 400	0.1 to 1.5	10 to 42
Photons per image	~10^{10}	10^{11}	10^{9}	10^{9}	~10^{10}
Time scale for single image	<1 ps	>1 s	0.001 s	10-500 fs	50 fs
Energy Bandwidth (ΔE/E)	10^{-4} to <10^{-5}	10^{-4}	$3x10^{-3}$	10^{-4}	10^{-4}
# of closely spaced bunches within a fixed temporal window	30/1.5 microsec	1 ms	1 ms	Not specified	Not specified
Minimum pulse separation (ps)	350	Not specified	Not specified	Not specified	Not specified
Multiple pulse rep. rate/duration	60 Hz/day; 1 shot/day	0.01 Hz/mo.	1 Hz/month 1 kHz / 5 sec 0.02 Hz / day	1 KHz/day	10 Hz/day; 1 Hz over several days
Polarization	Linear	linear	no	Linear/circular	linear
Tunability in energy (ΔE/E per unit time)	2%/pulse	fixed	5% in 2 µs	10%/s	Factor of 5 over a day
Expected typical spot diameter(s) at target (microns)	1 to 100	100	1 to 10000	0.1 to 10	0.1 to 10
Simultaneous radiation probes in use at one time and what types (i.e. XFEL and incoherent insertion device - ID)	1 XFEL	1 XFEL	1 ID	1 XFEL	1XFEL, 2 ID
Number of hutches (H) (each H is fed by a beamline), total end station (ES) how many of the total ES are available (A) for general flexible use as opposed to dedicated operation	1H, 3ES, 2A	2H,3ES,0A		1H, 1ES, 1A	

DWAs and energy spread in a witness bunch

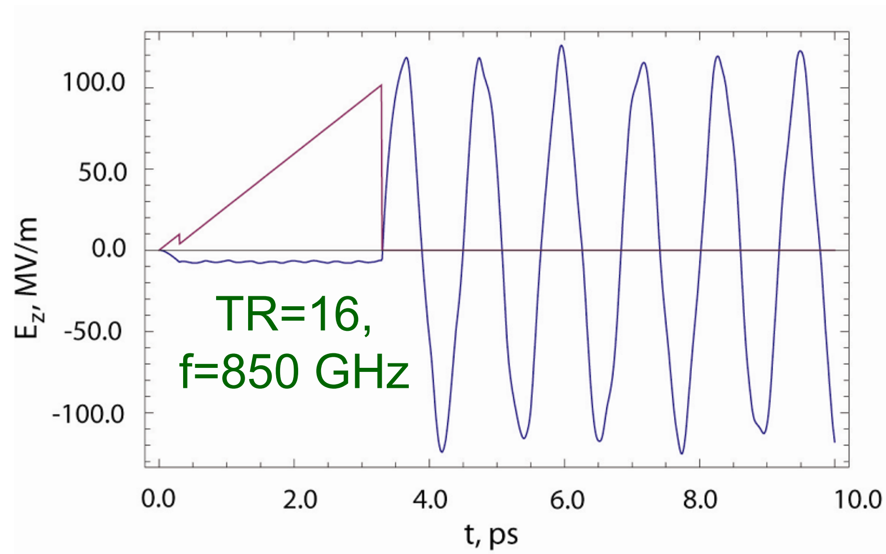
DWAs and high transformer ratios

By shaping the drive electron beam in a DWA into a double-triangular shape one may achieve high transformer ratios, way higher than TR=2, which is the limit for the Gaussian-shaped beam.

A schematic of the dielectric wakefield accelerator



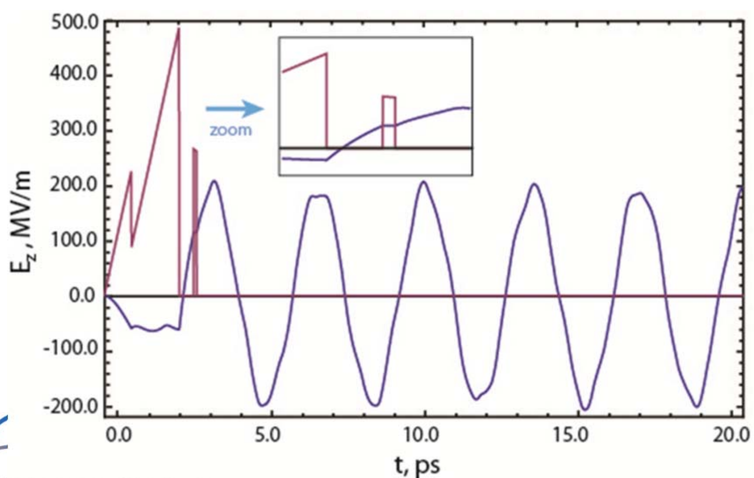
High transformer ratio wakes excited by double-triangular beams in DWAs



Minimization of the energy spread in a witness bunch

By additionally customizing the shape of the main bunch we designed the configuration which minimizes the wakefield-induced energy spread in the main bunch. The energy spread may be made as low as 0.001%.

Beam pipe ID, *2b*	1.14 mm
Dielectric tube ID, *2a*	1.24 mm
Waveguide cutoff	298 GHz
Charge of the drive bunch	5 nC
Length of the drive bunch	2.350 ps
Charge of the witness bunch	250 pC
Length of the witness bunch	100 fs
Time between the bunches	2.8017 ps
Transformer ratio	3.38
ΔG/G	$9*10^{-6}$

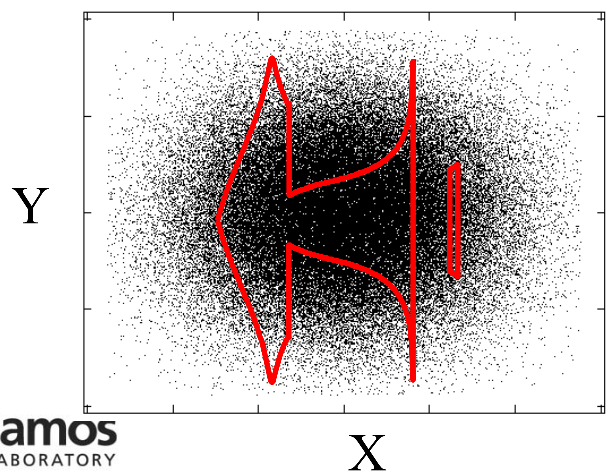


Cutting out the shaped bunches out of a Gaussian bunch

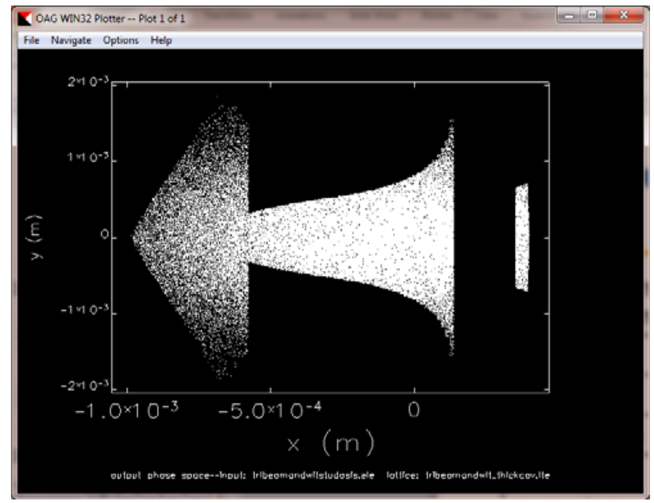
Parameters of a Gaussian bunch (from FNAL folks):

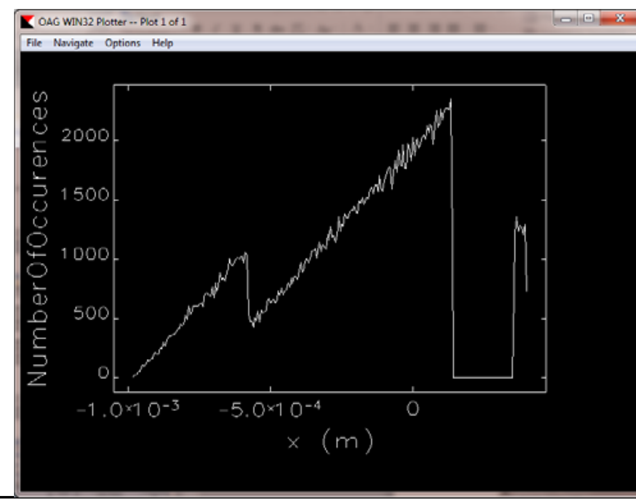
ε_{nx}	5.33 mm*mrad
ε_{ny}	10 mm*mrad
Bunch length	1.2 mm
Fract. mom. spread	0.001

The shape of the mask that cuts out the correct bunch shapes out of the Gaussian distribution.



Particle distribution in Elegant:





Bunch shaping with an emittance exchanger

Emittance Exchange

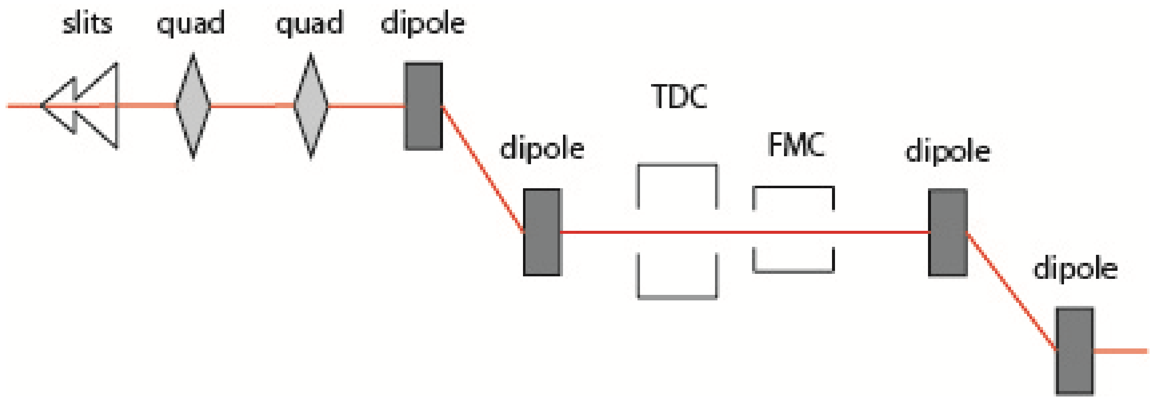
We have to turn the x-y distribution into z-y distribution with an emittance exchanger. We need to construct the emittance exchanger with the following matrix elements:

R_{51}=1 (or whatever stretch factor)

$R_{52} \approx R_{53} \approx R_{54} \approx R_{55} \approx R_{56} \approx 0.$

First order

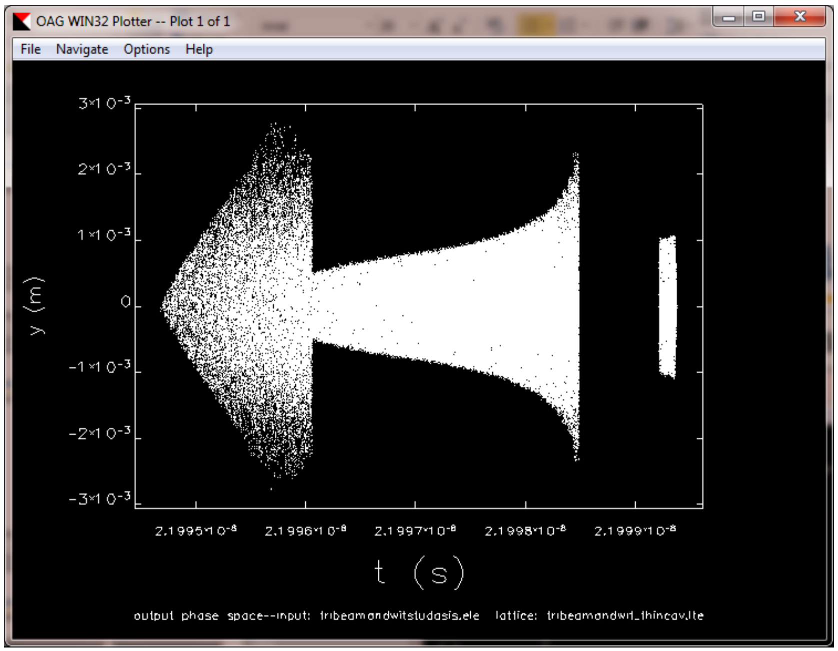
The following set of elements allows one to have the correct R-matrix in the first order:

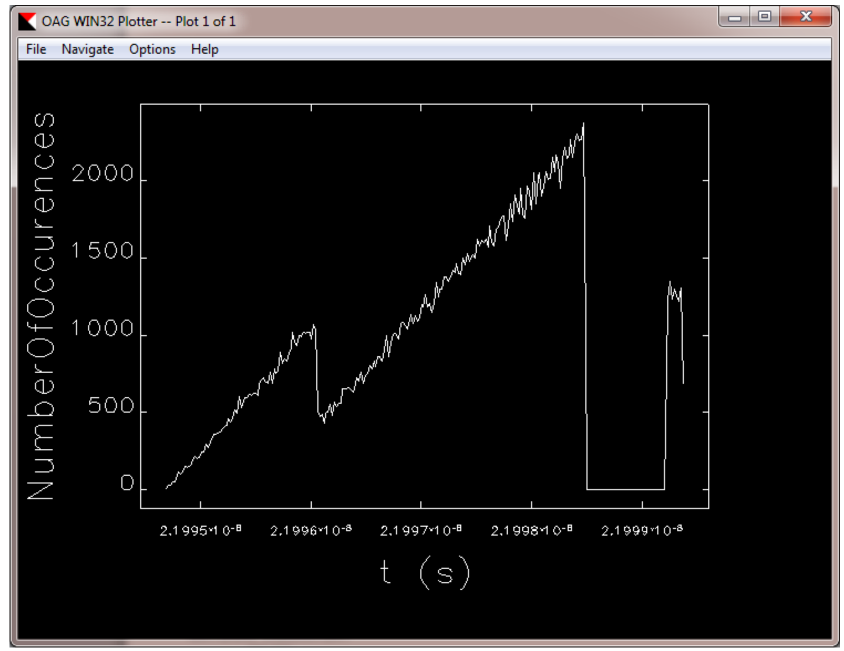


- Thick TDC produces a momentum kick and non-zero R_{55} , R_{56} .
- This can be compensated with a FMC.
- Two quads allow us to have zero R_{52} and whatever R_{51} .

First order (continued)

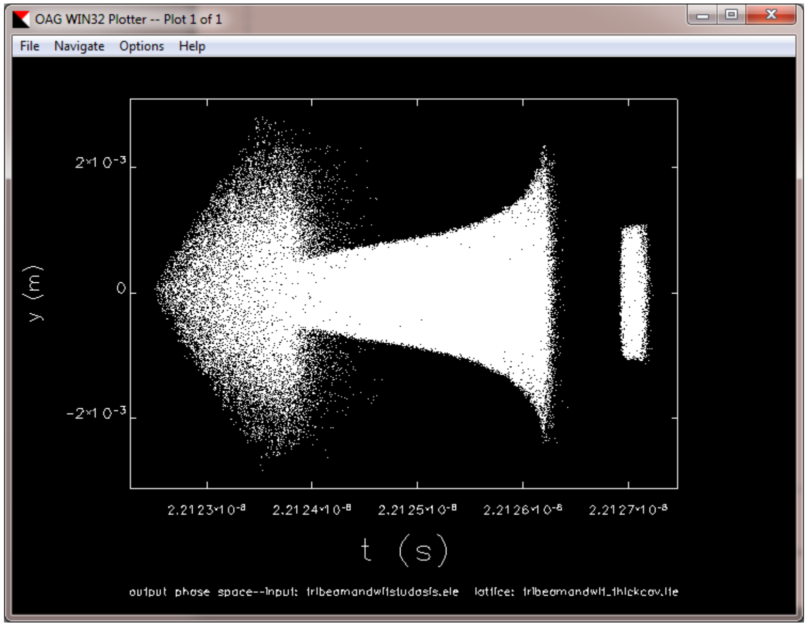
Output from Elegant:

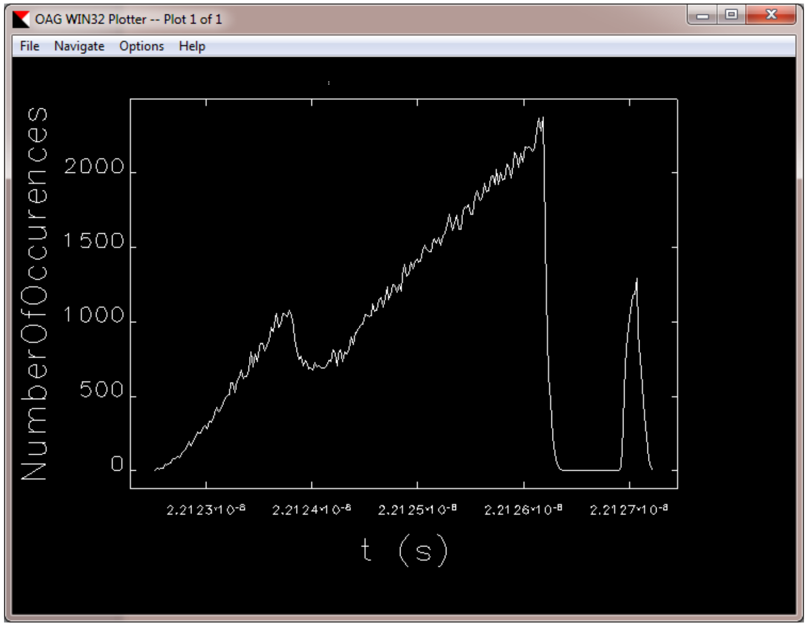




Second order

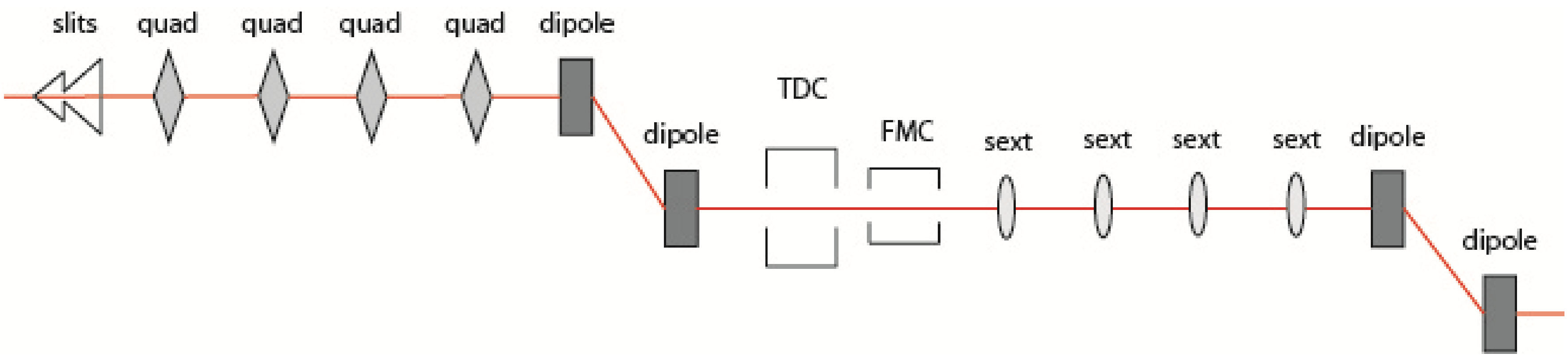
T-matrix (second order) produces visible aberrations:





EEX with corrective elements

We may need a number of corrective quadruples and sextuples on the beamline to correct for aberrations:



Proposed experiment at ASTA

Current plans

We have an active proposal with LANL LDRD to experimentally demonstrate a high-brightness DWA with an acceleration gradient above 100 MV/m and less than 0.1% induced energy spread in the accelerated beam (funded 10/12-09/15).

- The experiment will be conducted at ASTA.

- In the planned experiment we expect to demonstrate
  - simultaneous generation of a drive bunch and main beam with EEX,
  - significant increases in a DWA transformer ratio, and
  - possibly, significant decreases in the measured energy spread from a main beam accelerated through a wakefield process.

Facility needs

• At LANL we have 2 staff members working at 0.33 FTE level each.

• We plan to use the 50 MeV user area at ASTA.

• We are asking for 3 weeks of beamline time at ASTA in FY14 and 3 weeks in FY15.

• We collaborate with Prof. Philippe Piot group at FNAL.

• We will need the support of beamline operators and technicians.

• We provided the 1.3 GHz deflecting cavity to FNAL and we expect FNAL to provide the rest of elements for the EEX optics. LANL will provide the beam mask and dielectric tubes and holders.

Impact of DWA acceleration for MaRIE

- An 8.8-GeV DWA afterburner for the MaRIE upgrade will boost the energy of the electron beam from 12 GeV to 20.8 GeV.
- With the current 12 GeV MaRIE linac design, generation of the third harmonic (126 keV) photons is suppressed in the wiggler.
- Photon energy above 120 keV is required for the K-shell ionization of uranium and other actinides, an important MaRIE mission and part of its funding justification.
- The DWA afterburner upgrade would allow an order of magnitude greater production of 126-keV photons.