Charging and Radiation Damage Effects in Dielectric Wakefield Structures

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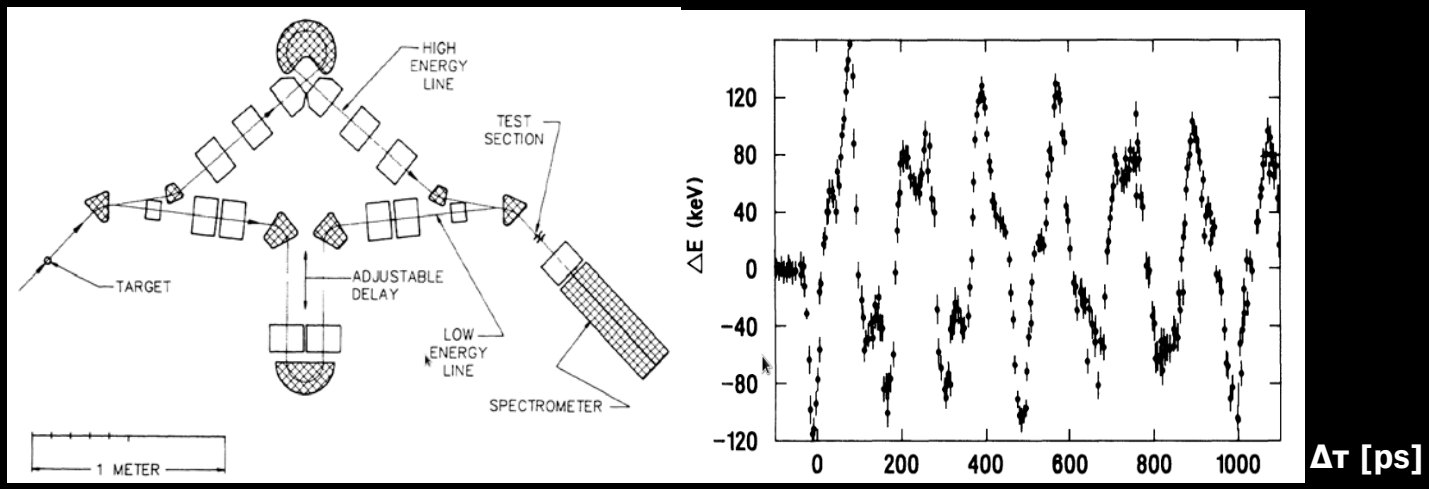
Physical processes involved with the unwanted interception of beam electrons by a dielectric

- Many complex and interacting effects potentially impacting performance of DLA:
- Asymmetric charging of the dielectric, leading to beam deflection;
- Breakdown with structure damage;
- Changes in material properties with absorbed dose (radiation damage) and DC breakdowns;
- The characteristic discharge times ($\tau_c=\varepsilon/\sigma$) for a number of dielectric materials used in DLAs do not reflect the observed resistance to charging.
  - Fused quartz has a discharge time longer than 30 days, while repeated experiments at the AWA and elsewhere have not observed DC charging effects with this material. Repetition rates used (typically 10 Hz) too low? other effects compensating? (e.g. ionization induced conductivity)
- Dynamics of the charging/discharge process in the presence of high dose rates.

A Brief History

- Charging effects were studied qualitatively by the Argonne group as part of the initial dielectric wakefield accelerator tests in 1988.



- Lore at the time: accelerators and dielectrics don't mix!
  - ✓ Initial experiment seemed to agree
  - ✓ Transverse deflection of the beam by the induced DC field bent the 22 MeV beam outside the acceptance of the spectrometer.

A Brief History (cont.)

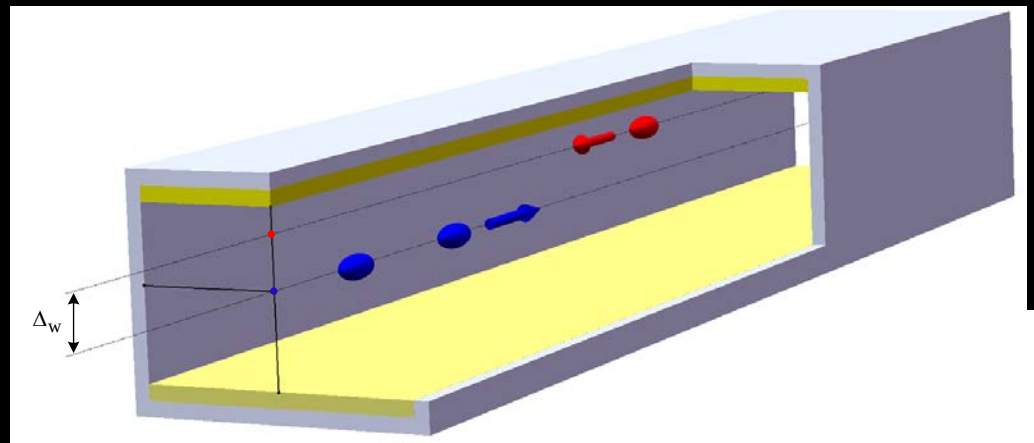
- Rexolite (polystyrene) and Nylon dielectrics showed rather different behaviors under charging.
  - Rexolite was found to charge until the beam was deflected and to hold its charge (and maintain the dc electrostatic field) for an extended time (~ 1 hr). No breakdowns were seen.
  - Nylon would charge up and deflect the beam until breakdown occurred, snapping the beam back to its nominal undeflected position. The charge-discharge period was found to be ~ 30 s.
  - No permanent damage to the nylon structure was observed (based on repeated longitudinal wakefield measurements) despite being subjected to many charge-discharge cycles.

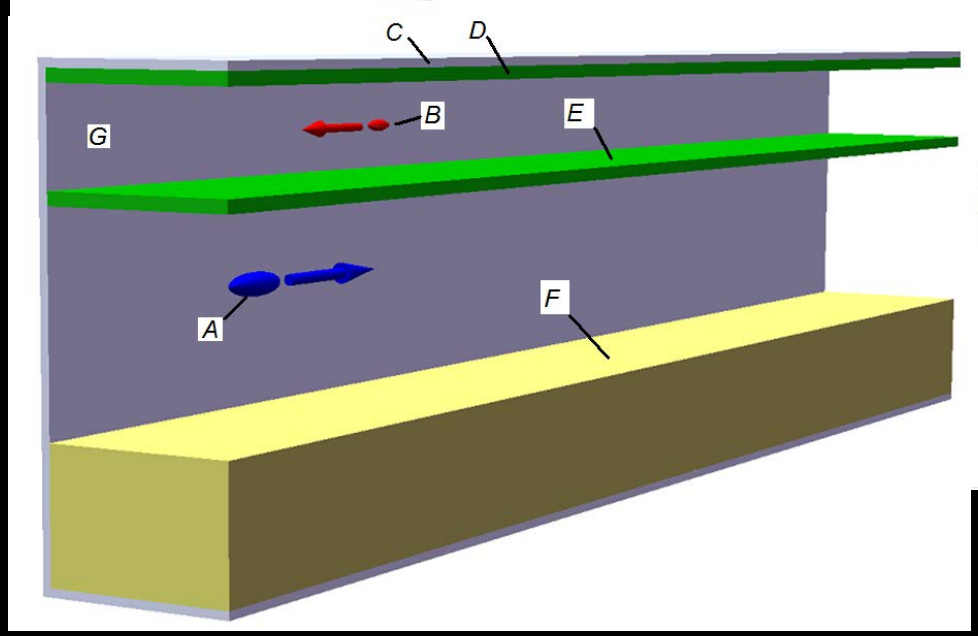
A Brief History (cont.)

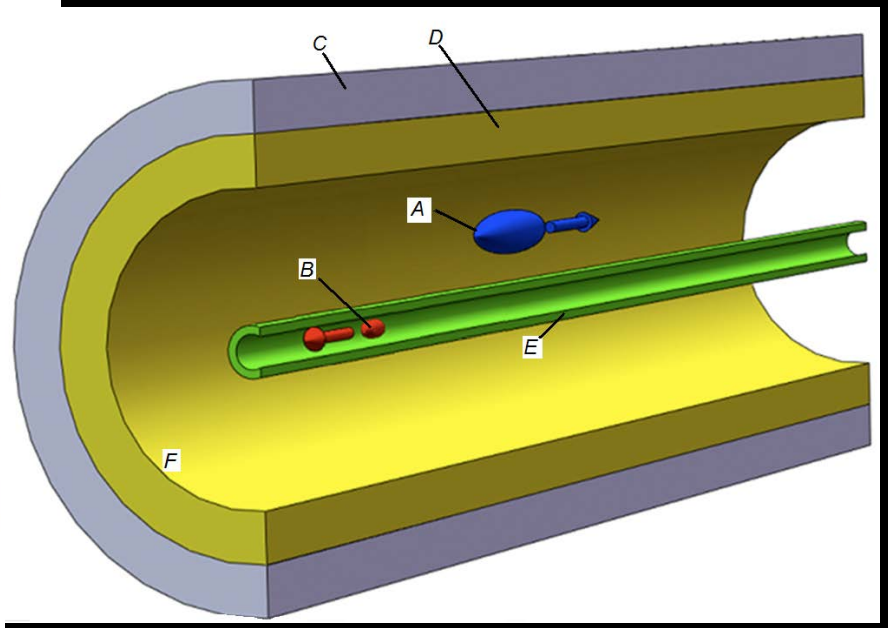
- The rexolite structure was field-modified by depositing a thin layer of graphite powder on the interior surface of the tube.
  - A thin (<< 1 skin depth) conducting layer can short out the static field
  - Without significantly effecting acceleration by the wakefields
- Later AATF and AWA experiments used borosilicate glass as the dielectric (large temperature dependent conductivity)
- Charging and breakdown have not been problematic for alumina and other ceramics used in wakefield experiments.
- No observed change in microwave dielectric properties (but visible changes in appearance…)
- Need to reevaluate and quantitatively study radiation effects in dielectrics is motivated by X-ray FEL and other high current applications.

Alumina	>0.78 s
Delrin(R)	310 s
Kapton (R)	3.5 d
Mylar (R)	3.1 d
Polystyrene	37 min
Fused Quartz	>38 d
Borosilicate glass	0.41s (variable)
Teflon (R)	2.1 d

The characteristic discharge time $\tau_c = \varepsilon\varepsilon_0/\sigma$, where σ is the dc conductivity and ε is the relative permittivity.





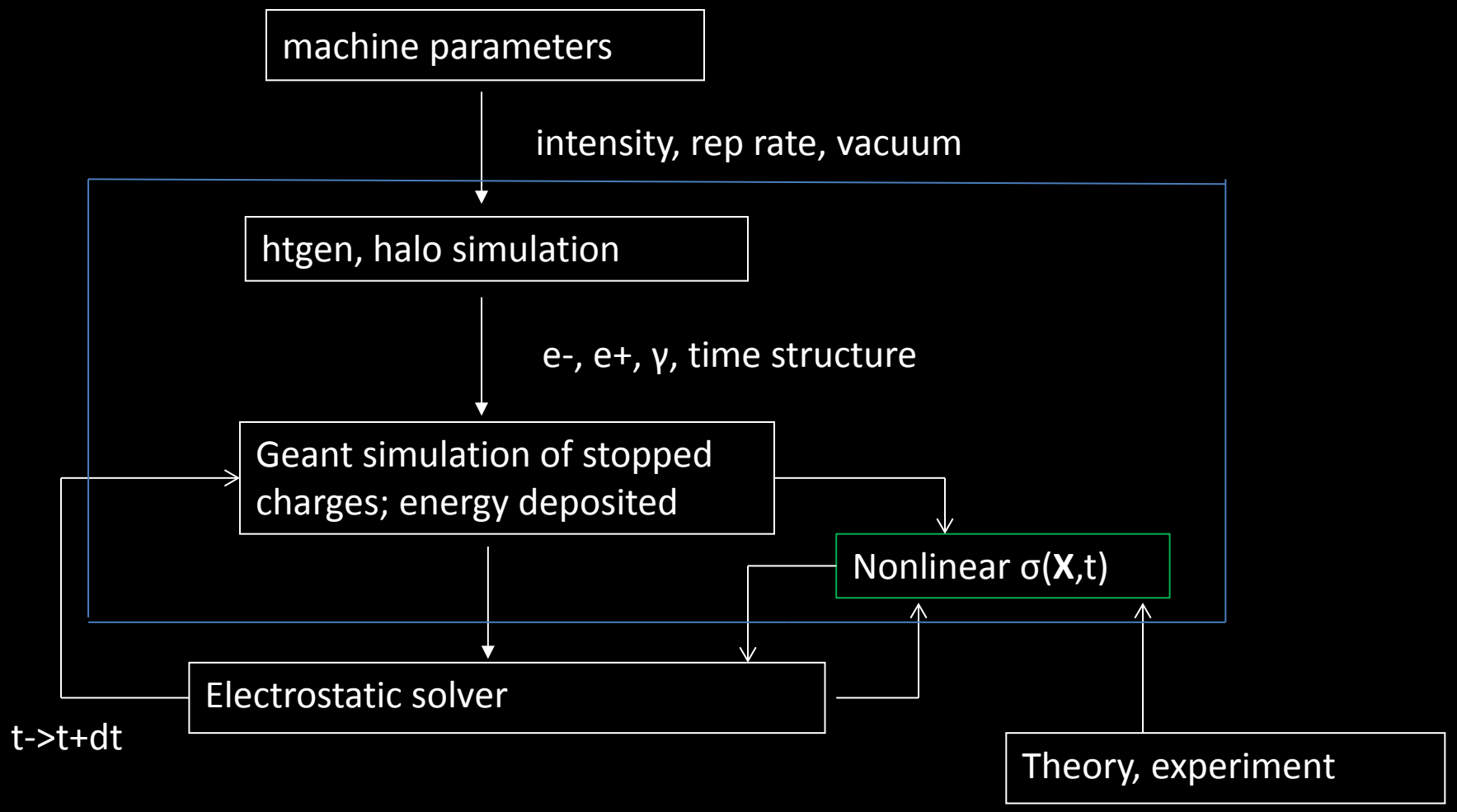


Conceptual designs for beam-driven short period undulators for X-ray free-electron lasers.

A reexamination of radiation effects in DLAs

- Simulations
  - Halo (Placet-htgen codes) from CERN
    - Different emphasis from CLIC/ILC detector background studies
  - Dose rates, distribution of stopped charges (Geant)
- Experiments (NRL, AWA…)
  - Quantitative
  - Beam interactions with thin dielectrics
  - Stopped charge distributions
  - Dose rate dependence of conductivity, permittivity
  - Long term, aging effects
  - …

Simulation Approach (work in progress)



There are a number of empirical relations used in the literature to parameterize dependence of the dielectric conductivity σ on the radiation field.

$$\sigma(t) = \sigma_0 + \varepsilon\varepsilon_0 \frac{dD}{dt}(K_p + \sum_i K_{di}\tau_{di}[1-(1-\exp(-t/\tau_{di})])$$

(during and shortly after irradiation)

$$\sigma(\frac{dD}{dt}) = \sigma_0 + k_p(\frac{dD}{dt})^{\Delta}$$

(long term exposure)

D is the absorbed dose (rads). The constants are obtained by fitting to measurements.

Additional (semi)empirical conductivity relations

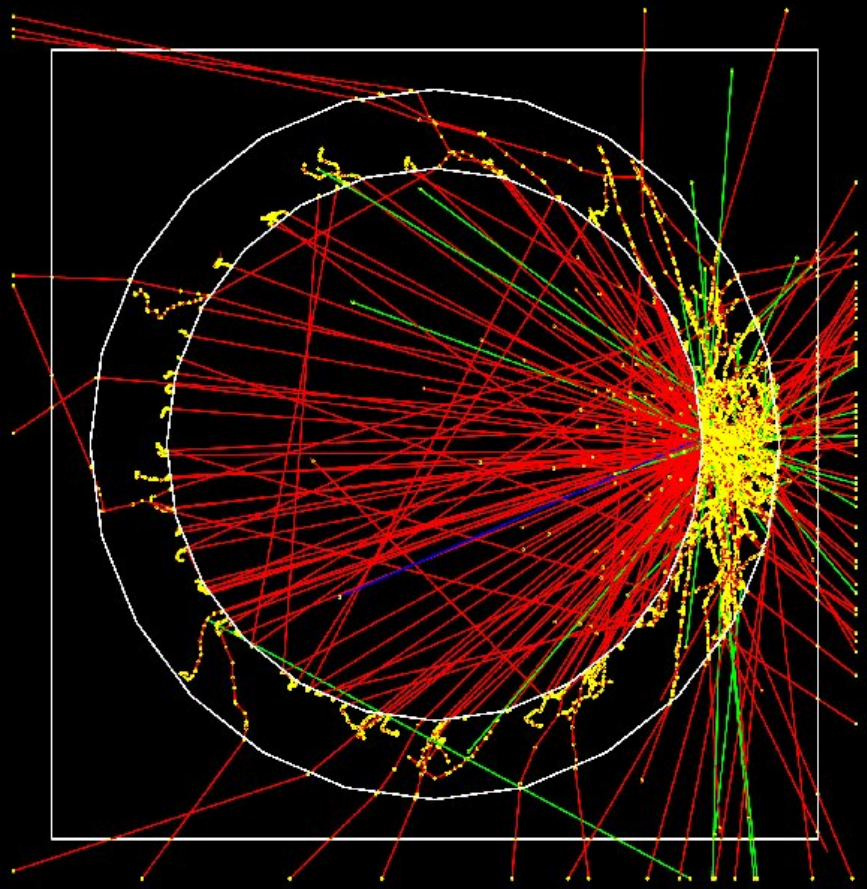
$$\sigma(E,T) = \frac{1}{3}\sigma(T)[2+\cosh(\frac{\beta_F E^{1/2}}{2kT})][\frac{2kT}{eE\delta}\sinh(\frac{eE\delta}{2kT})]$$

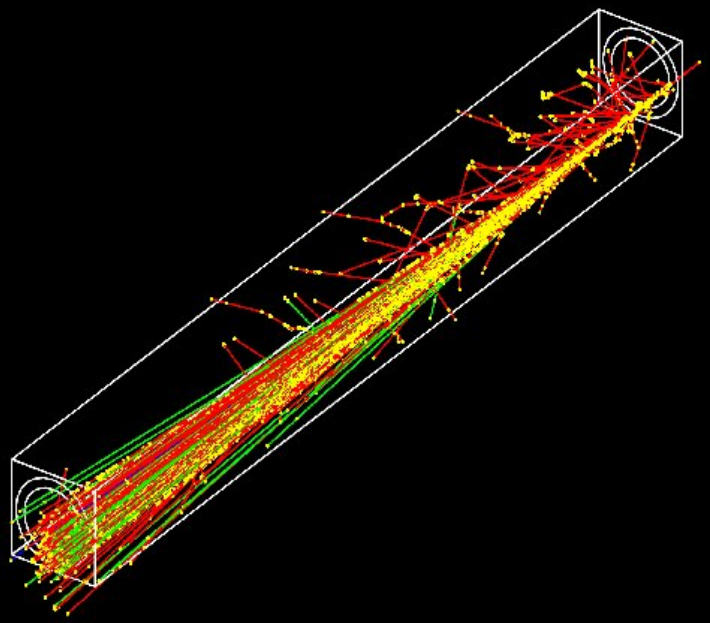
$$\left(\beta_F \equiv \sqrt{e^3/\pi\varepsilon}\right)$$

(Internal electric field)

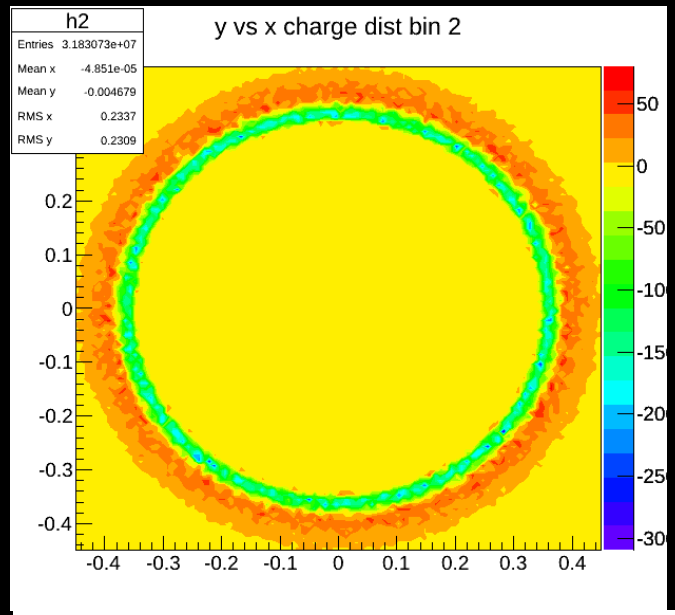
$\sigma(t)=(\sigma_1/F)/(1+bt)$ (time-- non ohmic discharge)

$\sigma(T)=\sigma_\infty exp(-E_A/kT)$ (temperature)

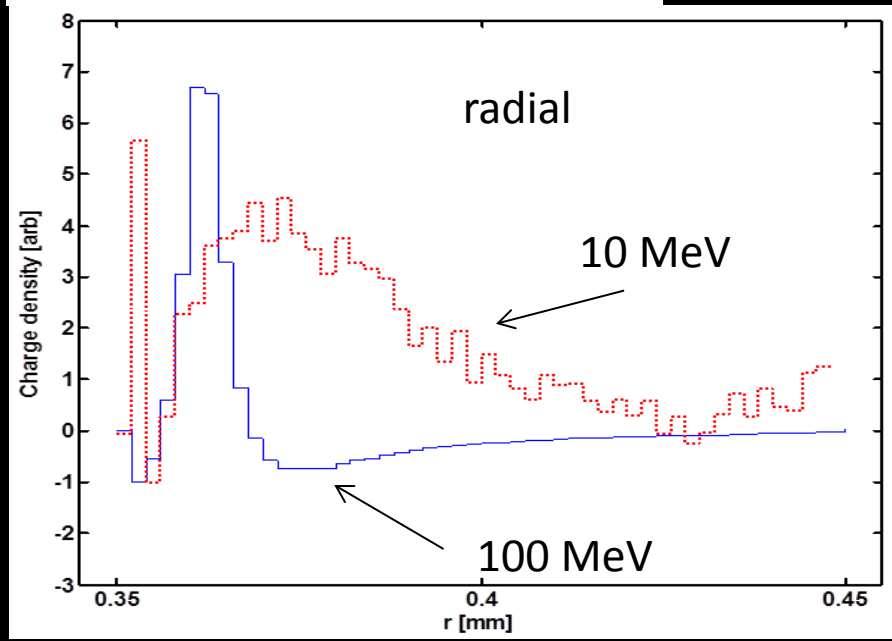


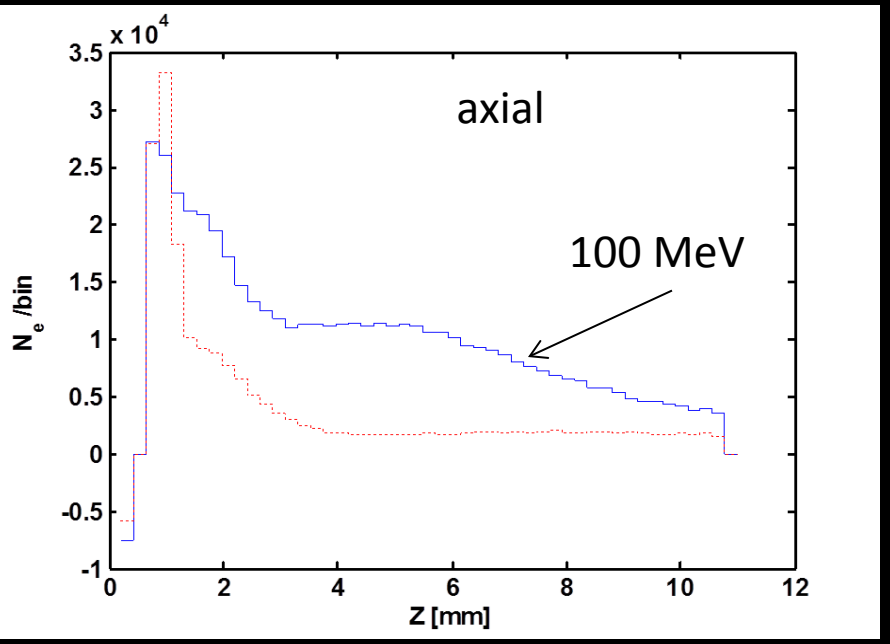


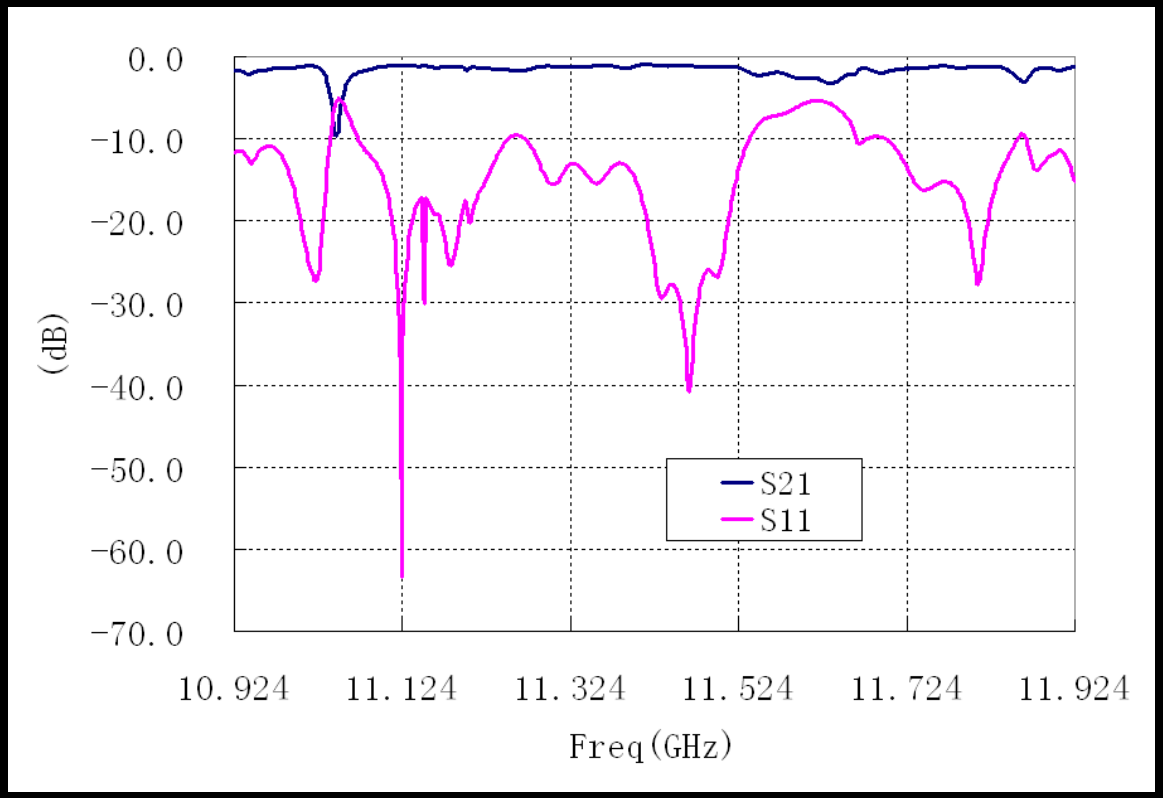
Geant4 simulation of 100 MeV electrons striking a quartz tube (0.35 mm inner radius, 0.45 outer radius, 10 mm long, 336 GHz fundamental TM_{01} mode) at glancing incidence to a point on the inner surface. The plots are a sum of 100 events. Red tracks: photons; green: e^+ and e^-. The yellow rectangles indicate the segmentation of the tracks.



Trapped charge distributions in a 1 mm axial segment for 100 MeV electrons incident symmetrically around the circumference assuming zero conductivity. Note that regions with excess electrons and depleted in electrons both occur.





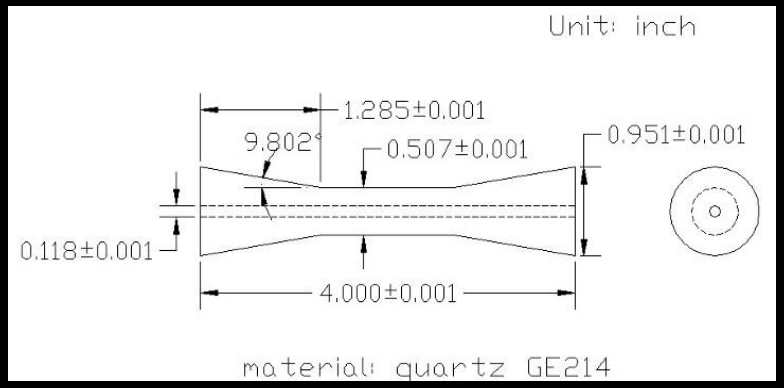


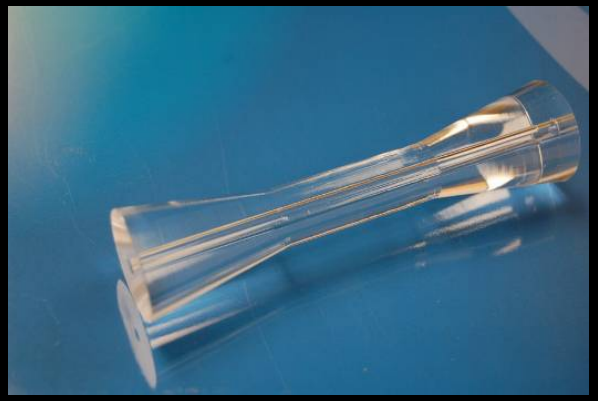
Proposed NRL experiment

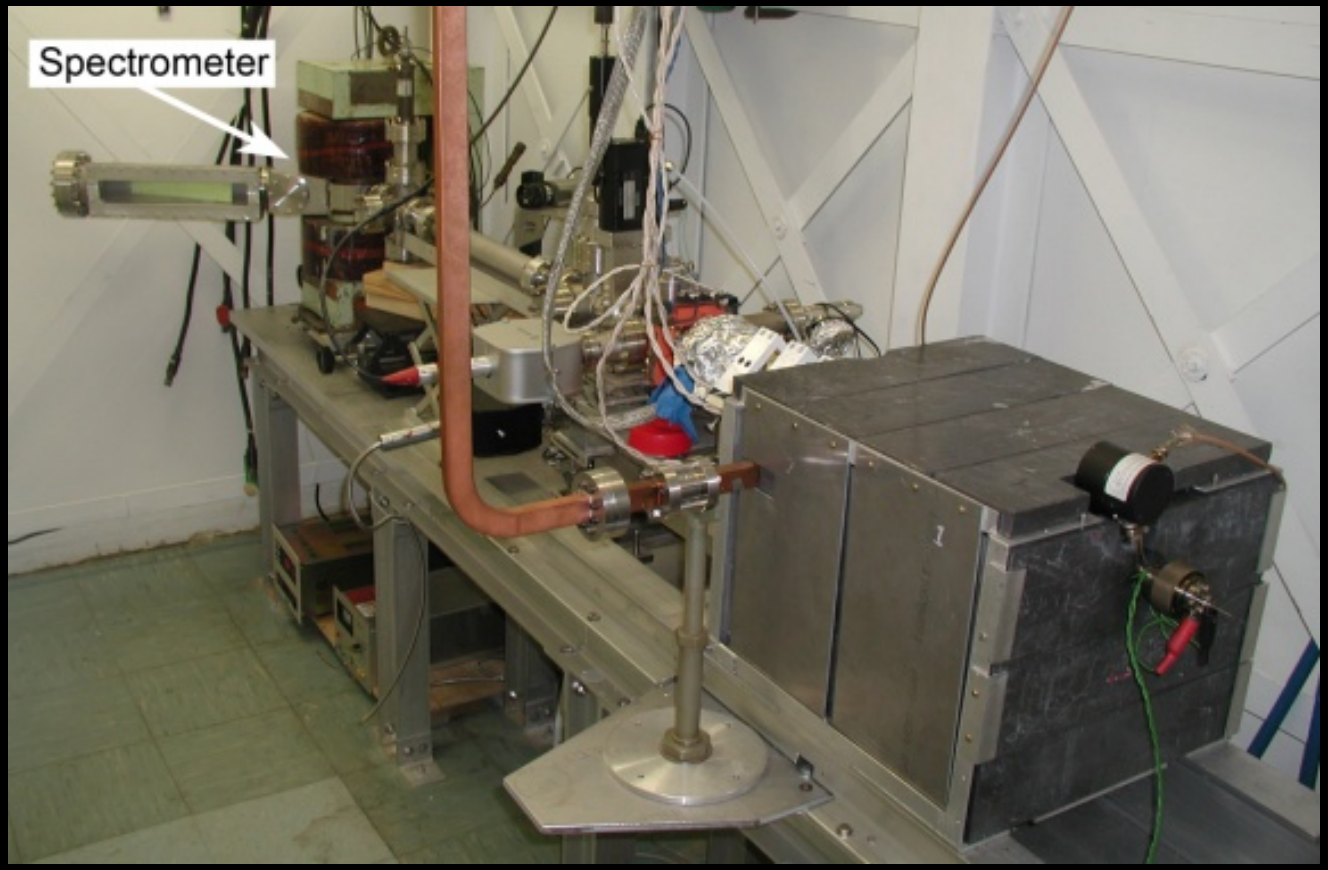
Area-selective irradiation of existing X-band quartz structure

$$\frac{df}{d\varepsilon} \approx -2\,\mathrm{GHz/(unit\,\varepsilon)}$$

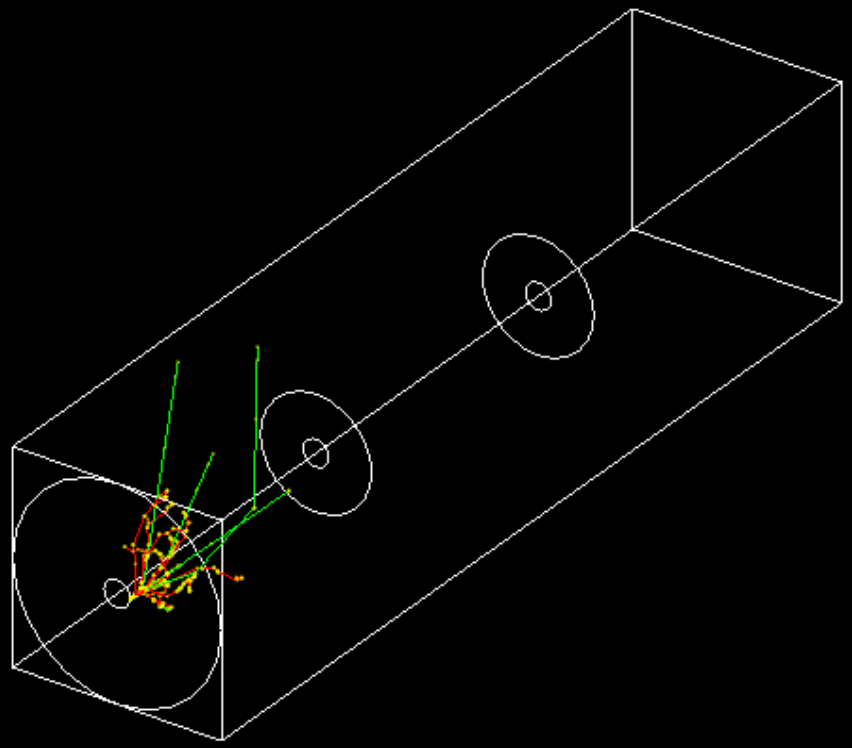
A 1% change in ε corresponds to an easily detectable shift in the TM_{01} frequency of 75 MHz.

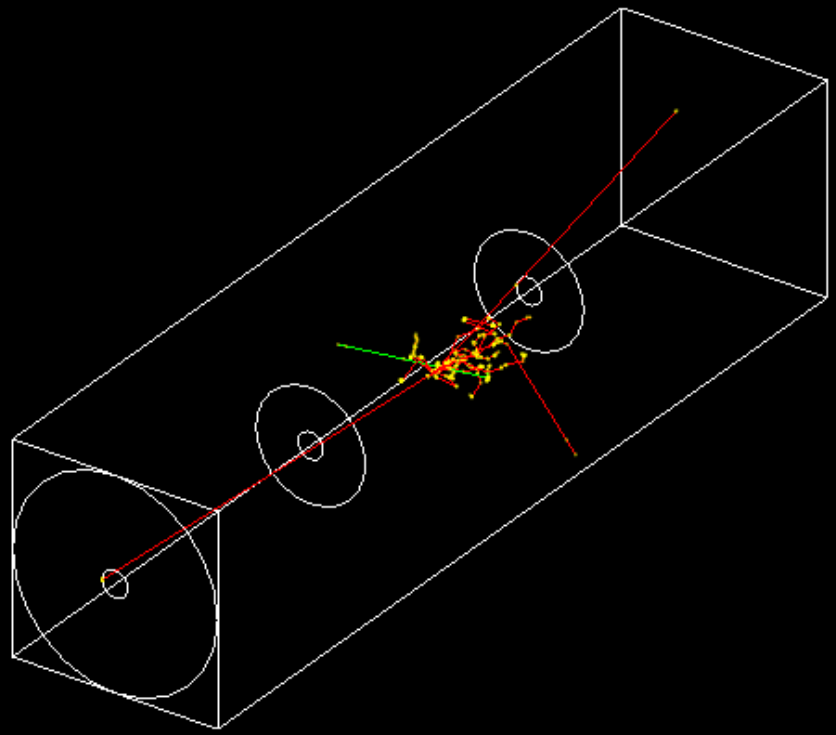




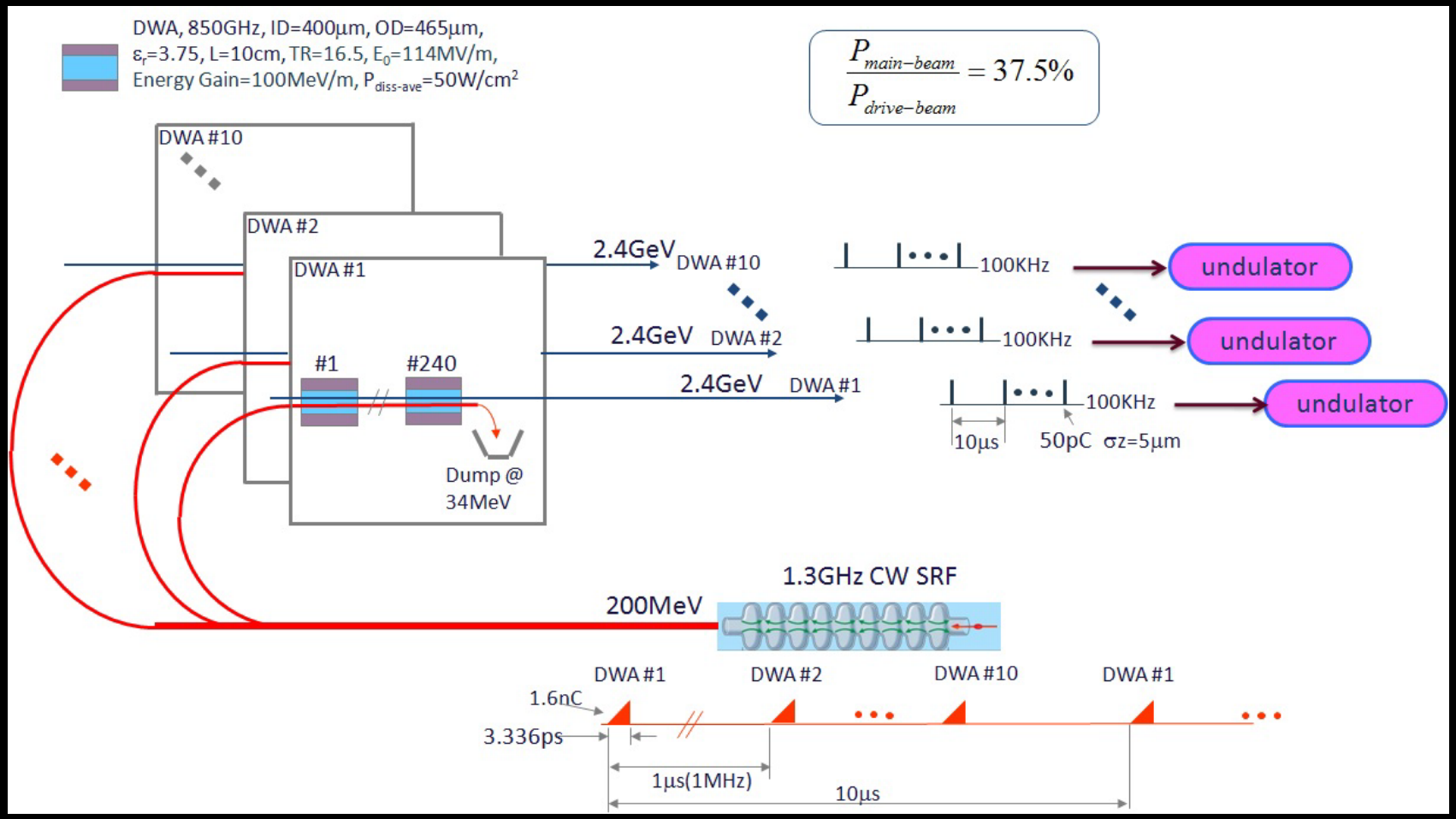


Beamline of the NRL X-band test accelerator (5 MeV 10 mA CW beam).
The spectrometer is at the far end



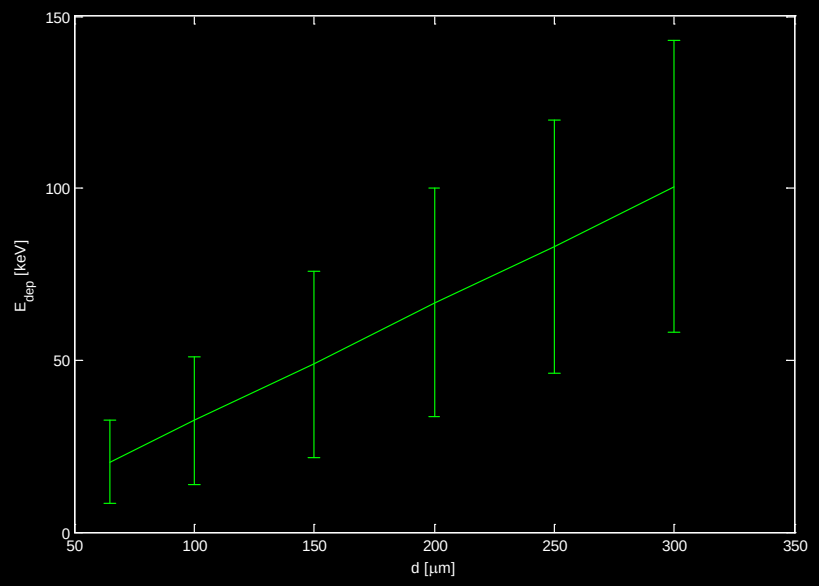


Geant4 simulations of 5 MeV electrons striking the clamped quartz structure at different angles of incidence. (Sum of 10 events. The downstream tapered section is not shown. For clarity only the edges of the upstream taper and accelerating sections are indicated.) (l) Beam parallel to axis and offset by 0.1 mm from the edge of the vacuum channel. The beam and secondary particles are confined to the tapered rf matching section. (r) Beam entering at a small angle with respect to the axis. This allows the dielectric in the accelerator part of the structure to be irradiated along its length.

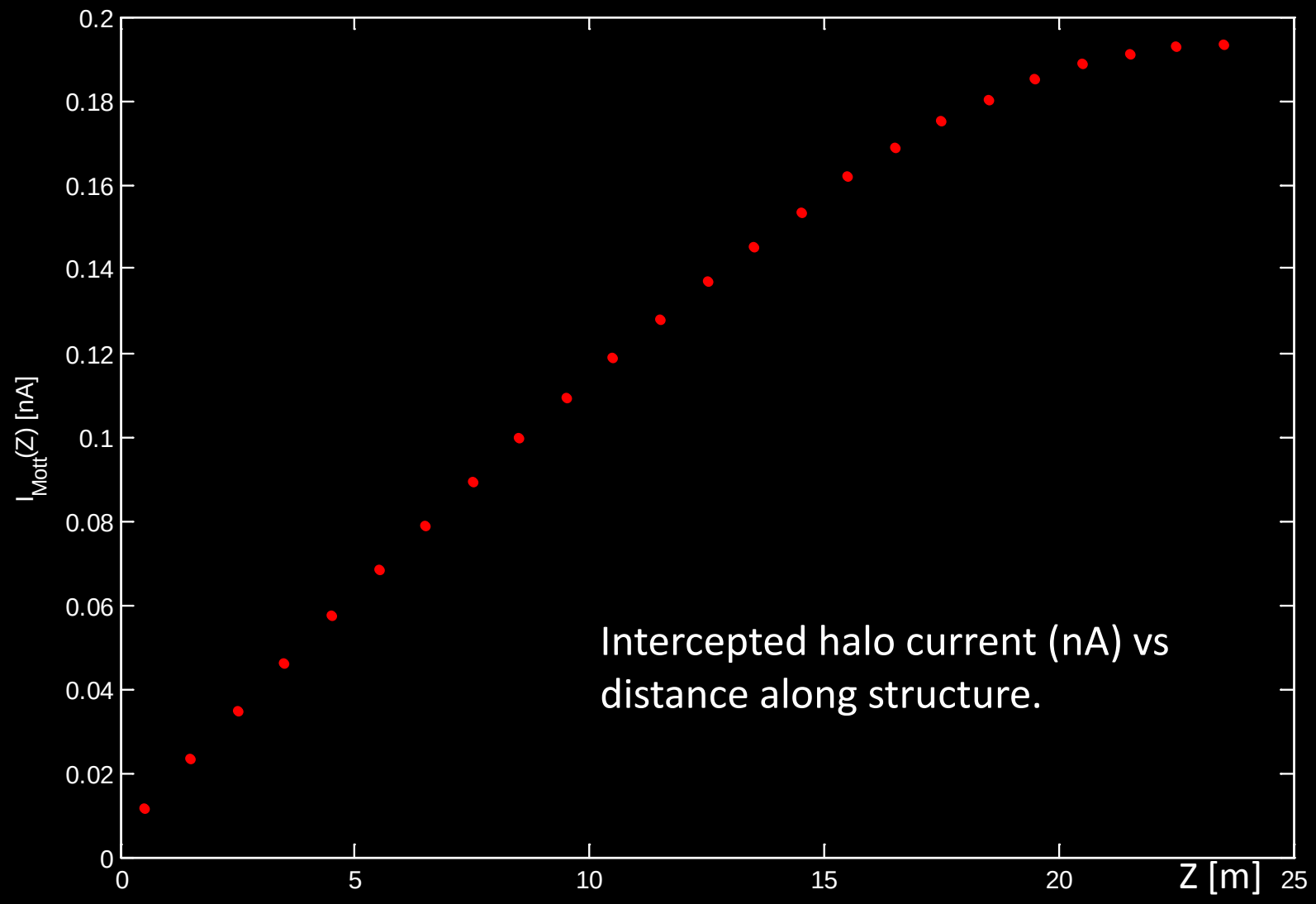


A schematic of an FEL light source facility showing a cw superconducting linac, transport lines, and an array of dielectric wakefield accelerators.

- Scattering rate from beam-gas in 24 m, 400/460 µm quartz structure
- 1.6 nC, 100 kHz
- Energy varies along structure, initially 200 Mev.
- Loses 7 MeV/m to wakefield



Energy deposited in quartz by 200 MeV electrons vs slant depth.

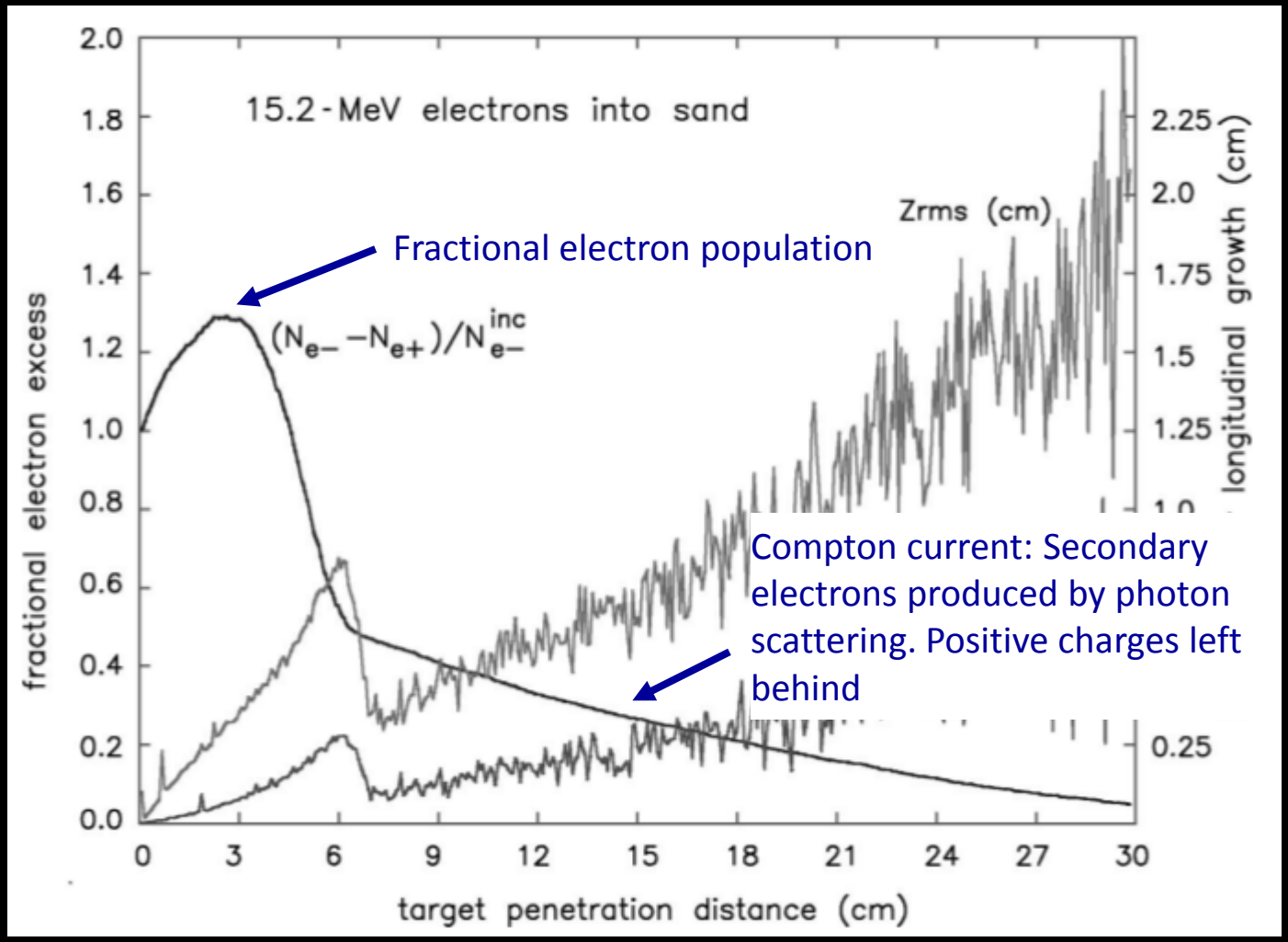


Intercepted halo current (nA) vs distance along structure.

Summary

It is important, as dielectric devices may move from objects of research to bona fide accelerator components, to obtain quantitative experimental data on radiation damage and related effects. Euclid has initiated a program to simulate radiation effects in DLAs, evaluate actual dielectric accelerating structures for charging and radiation damage, and testing materials that are candidates for use in dielectric accelerators.

Supplemental Slides



EGS4 simulation of the expected electron shower distribution in sand for a 15.2 MeV AWA electron bunch. (Phys. Rev. E 62(6) 2000 p. 8590).

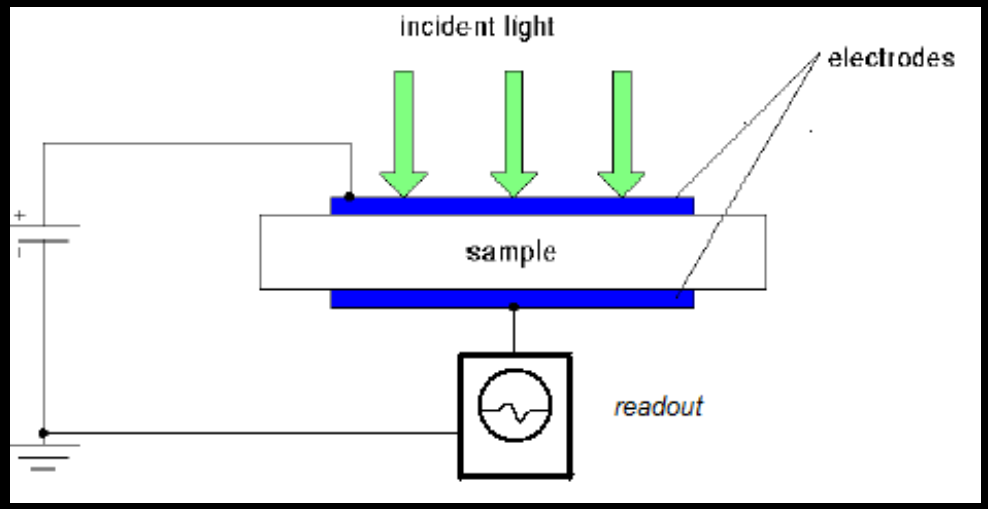
A simplified outline of the algorithm

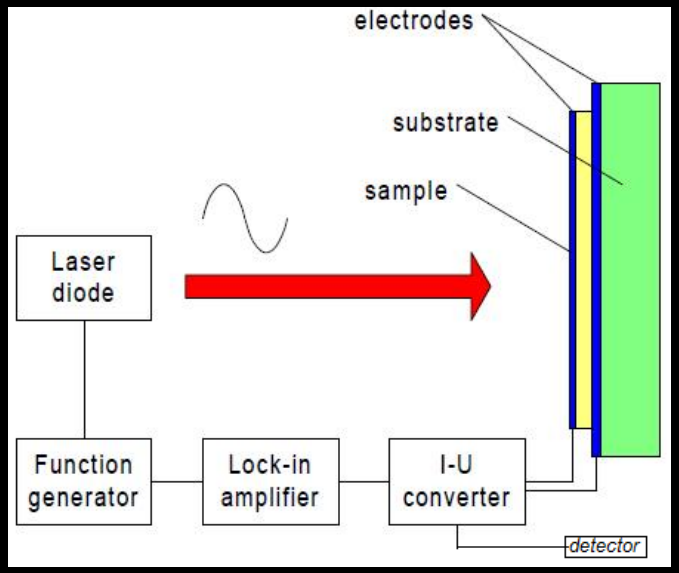
3D Poisson solver (based on components of Arrakis-3D) incorporating the nonlinear conductivities.

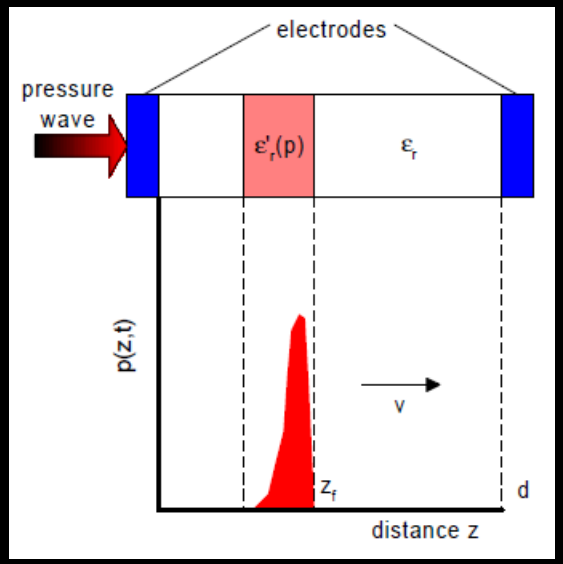
1. generate the halo or test beam electrons at time *t* (using placet/htgen)
2. transport electrons into the dielectric (Geant4)
3. update the distribution of charge ρ_t and the dose rate in each mesh cell)
4. calculate the electrostatic potential *V* in the dielectric using a finite difference or relaxation algorithm to solve $\nabla^2 V = \rho_t / \varepsilon$
5. compute $\vec{E} = -\nabla V$ and $\vec{J} = \sigma \vec{E}$ in each mesh cell using NL conductivity.
6. update the local charge density ρ_t using the continuity equation
7. increment and return to step (1).

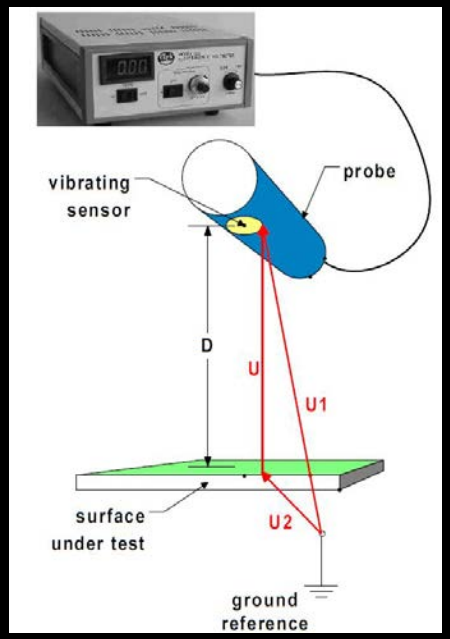
Charging of thin dielectrics by a relativistic beam is complicated

- most primary electrons don't stop
- secondary, tertiary…
- photons-> Compton scattering
- e+ annihilation
  - (create stationary positive charges)
- dE/dx - ionization deposits energy through the medium, may change the conductivity
- photoelectric effect









Static charging measurement techniques