Surface wave accelerator based on silicon carbide (SWABSiC)

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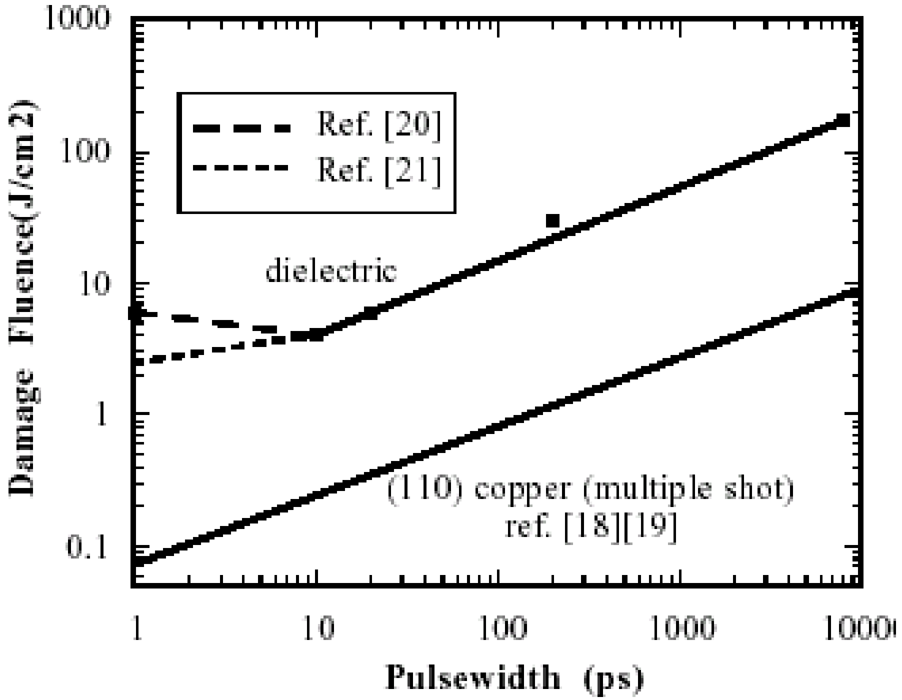
BNL/ATF

Laser Beam Damage: Dielectrics vs. Metals vs. Semiconductors



From Du and Byer (1999). Most measurements at 0.8-1 micron wavelength

(Most) Dielectrics + electron beams = charging
Pure semiconductors → few free carriers + full valence band

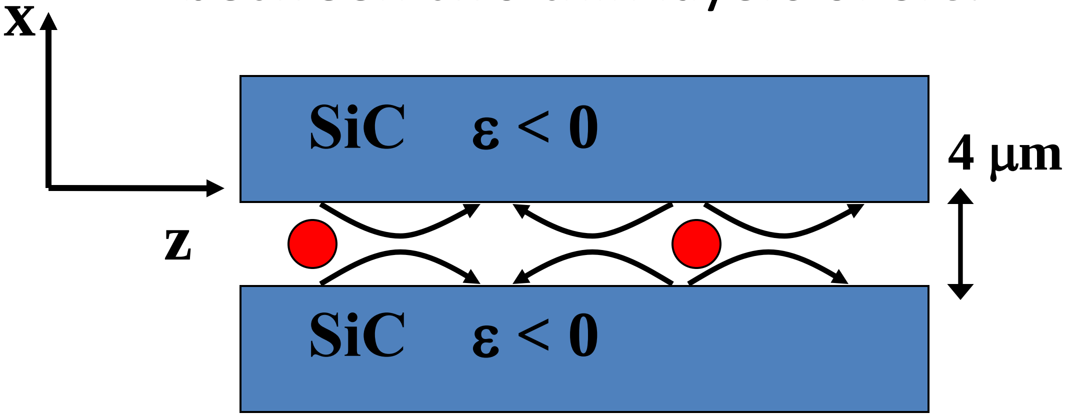
Silicon Carbide: -Can operate at high temperature (>1000^{o}C)
-Has high electrical breakdown voltage (DC threshold >300 MV/m)
-Is low-loss polaritonic material with ε < 0 in mid-IR

$$\varepsilon = \varepsilon(\infty)\frac{\omega_L^2 - \omega^2 - i\gamma\omega}{\omega_T^2 - \omega^2 - i\gamma\omega}$$

($\omega_L = 2\pi\, c/10.3\ \mu m$, $\omega_T = 2\pi\, c/12.5\ \mu m$)

Surface-wave accelerator driven by a high-power CO_2 laser

Consider vacuum channel between two thin layers of SiC.

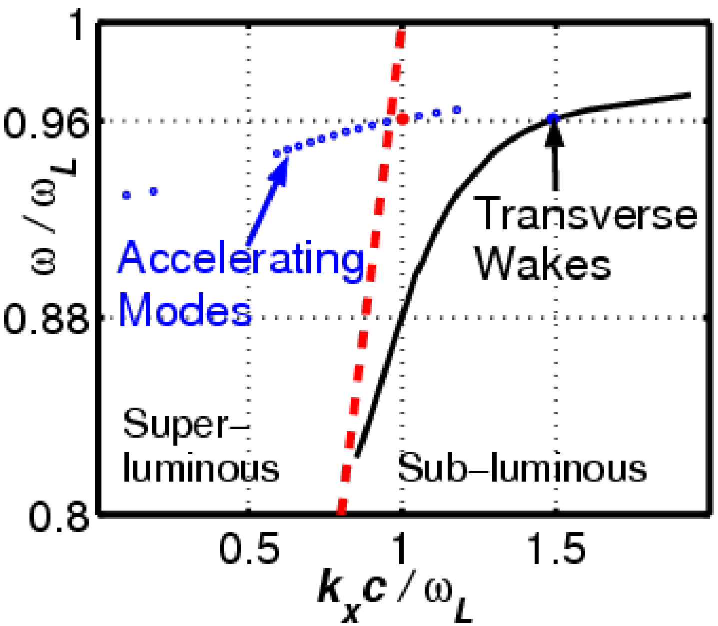


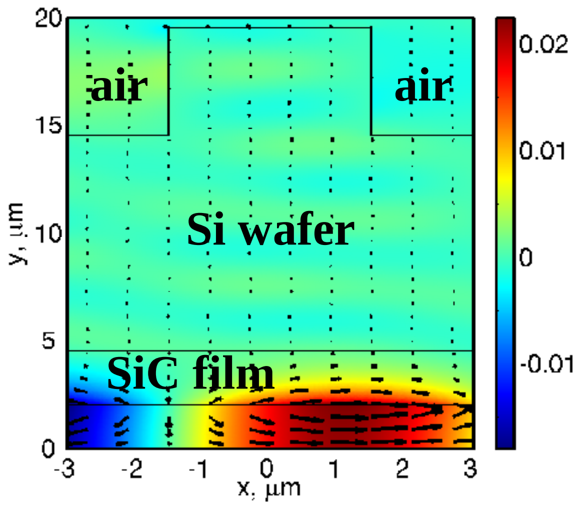
By widely available tunable CO_2 laser SiC/vacuum SPP's can be excited

- **Structure supports two modes (ω = kc mode) → can accelerate relativistic particles**
- **Near field (small gap) → attractive ratio E_z/E_x**
- **Application: injector into laser-plasma accelerator**
- **Cherenkov diagnostics for compressed ATF beam?**

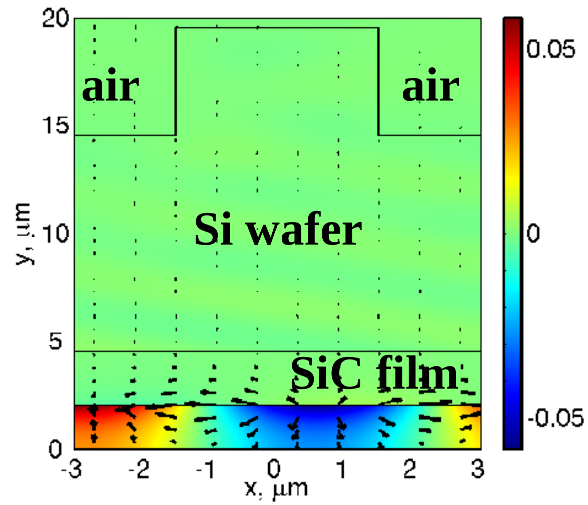
Kalmykov, Polomarov, Korobkin, Otwinowski, Power, and Shvets, Phil. Trans. Royal Soc. **364,** 725 (2006); AAC'08 Conf. Proc., p.538 (2009).

Electromagnetic modes of the Surface Wave Accelerator Based on SiC (SWABSiC)





Accelerating mode @10.708 µm



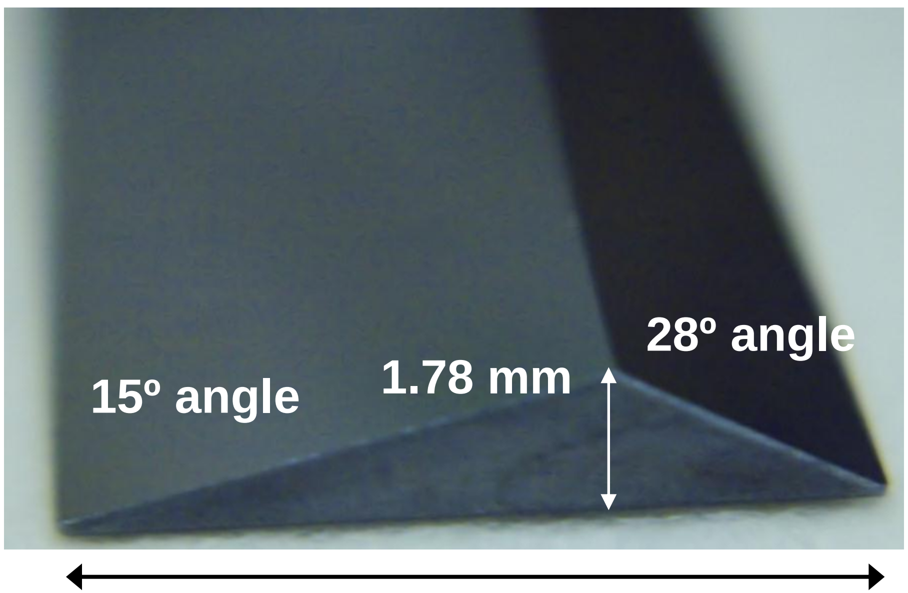
Parasitic transverse wake @10.708 µm

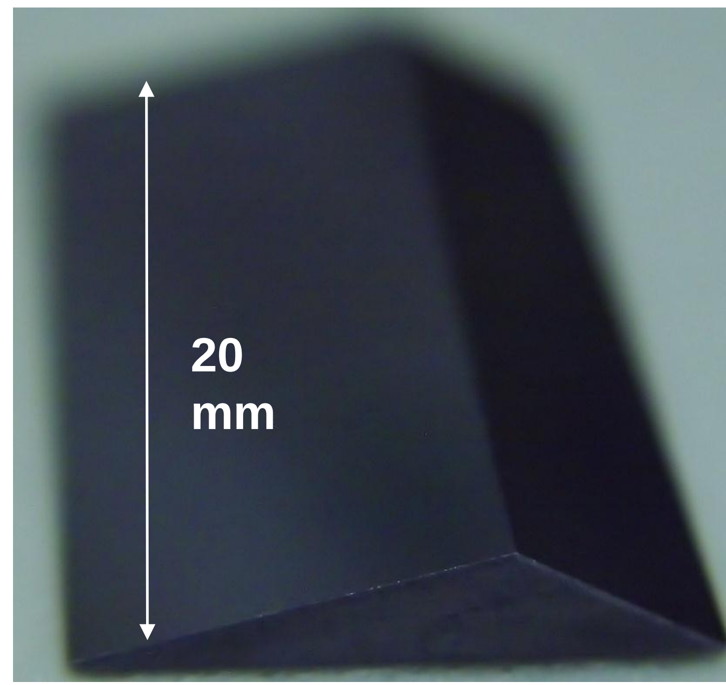
($\omega_L = 2\pi\, c/10.3\ \mu m$, $\omega_T = 2\pi\, c/12.5\ \mu m$)

Coupling and propagation challenge: how to couple 10.6 µm radiation into a 4 µm hole → not only the hole small, the mode's symmetry is not good for coupling!

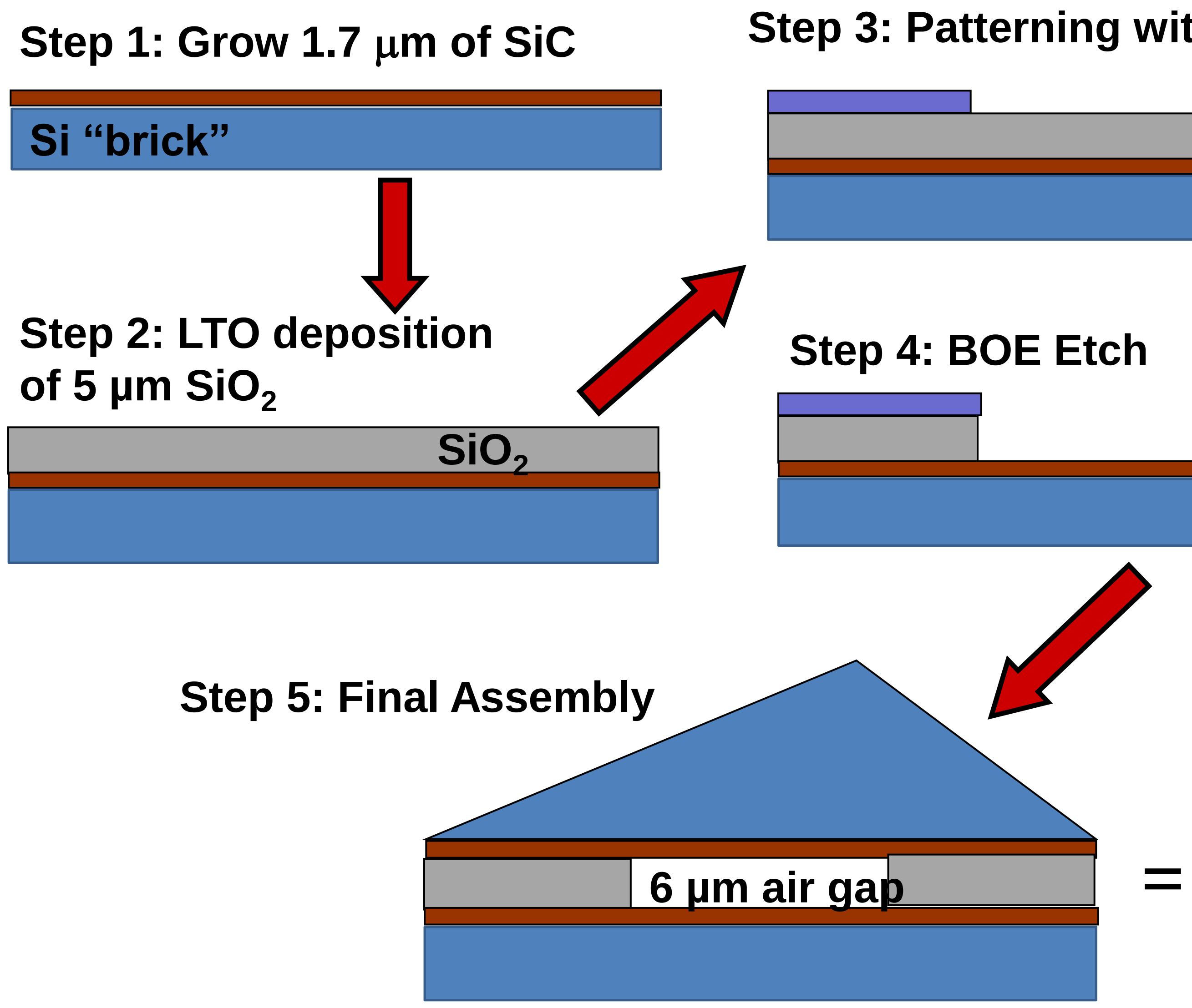
Si Prism + SiC Film Fabrication

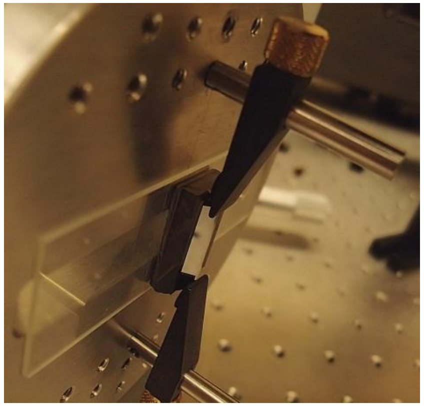
- Step 1: cutting Si discs (D=5cm, t=5mm) into 22x12x5 mm “bricks”
- Step 2: growth of 1.7 μm SiC in Lyon, France
- Step 3: cutting Si “bricks” into prisms (ISP Optics)



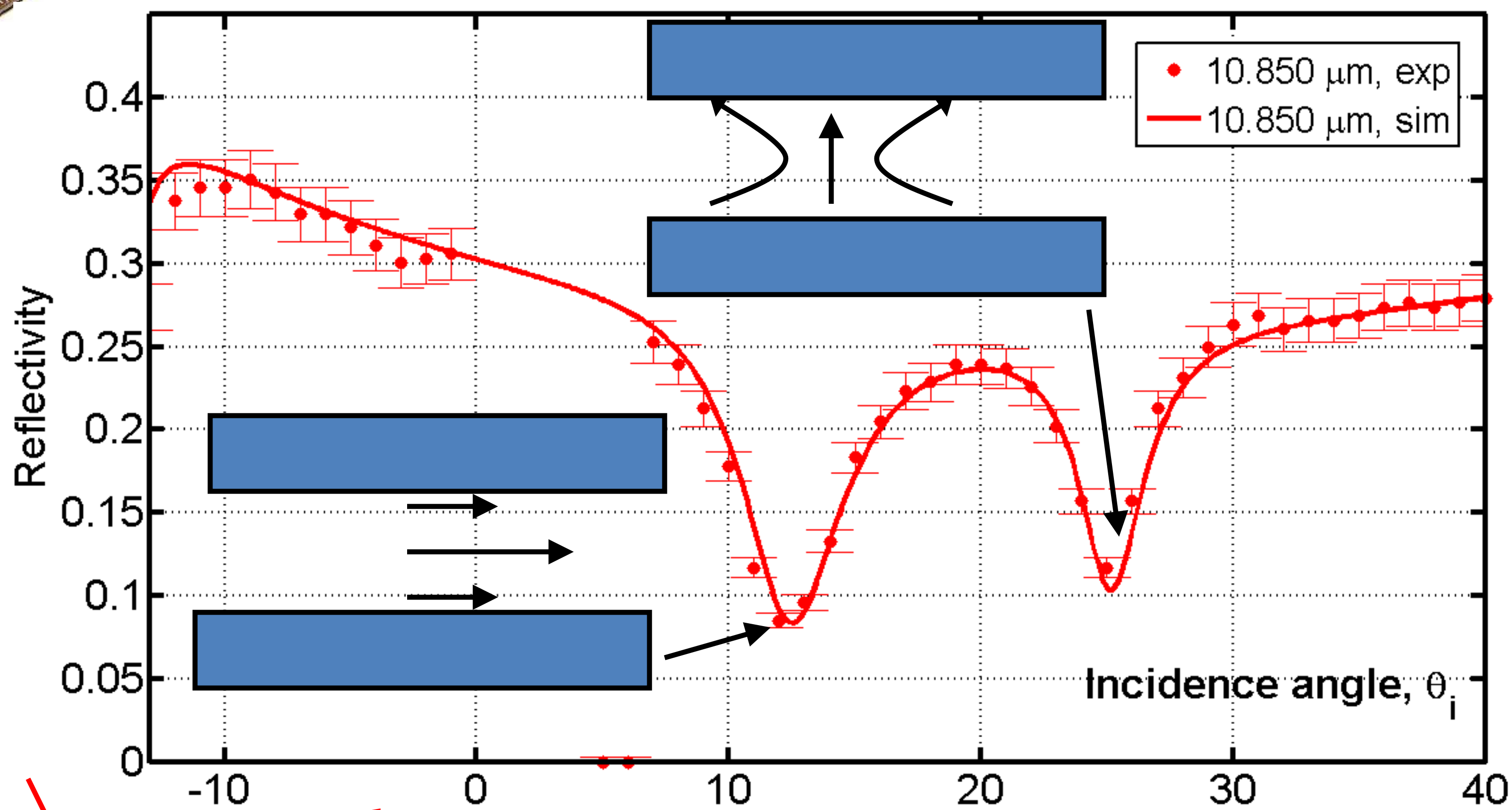


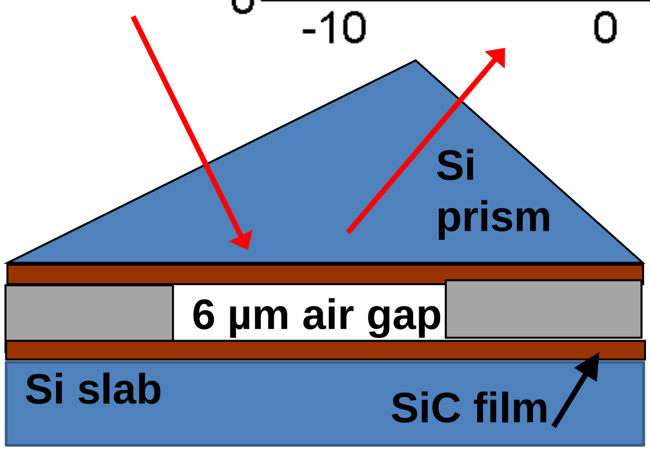
SWABSiC: two interface SPPs



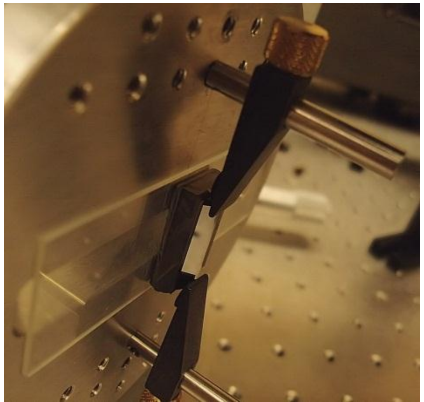


Longitudinal and Transverse Wakes





Left: schematic
Right: target assembly



Cherenkov diagnostics for compressed (or sliced) ATF beam?

- **Goal: Pre-bunched electron beam to generate coherent mid-IR Cherenkov radiation.**

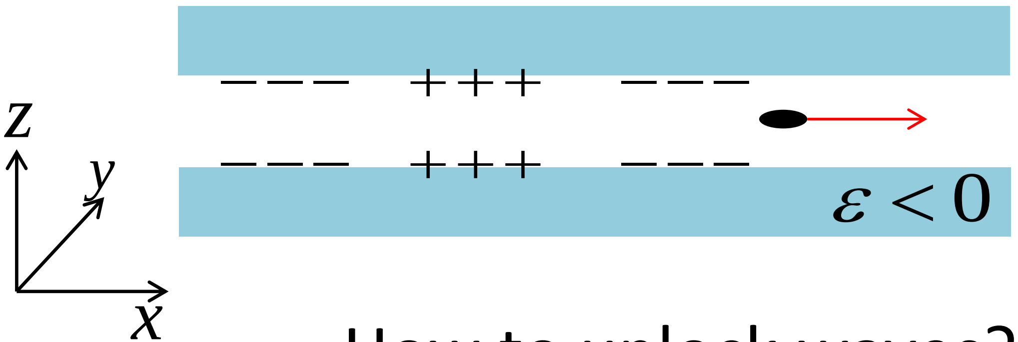
- **Application: Diagnostic tool for high-energy electron bunches.**

  - Angular and spectral distribution of the coherent IR radiation can be used to characterize the bunch length and transverse size.

Resonant interaction of beam propagating in channel

To avoid scattering, beam can be launched in vacuum channel. It can excite surface waves there.

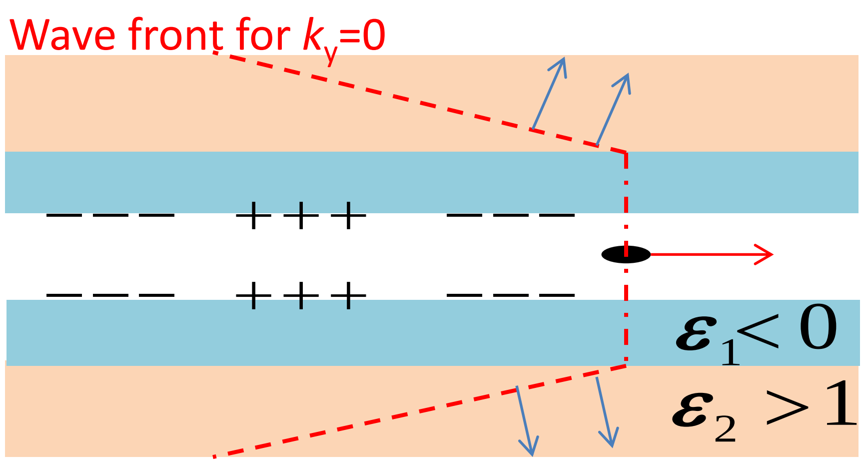
$$k_{\parallel} = \omega / c$$



In this wave, polarization charges are located on surfaces.
Waves are localized near the channel.

How to unlock waves?

$$k_x^2 + k_y^2 + k_z^2 = \frac{\omega^2}{c^2}\varepsilon$$



Surface waves with

$$k_y < \frac{\omega}{c}(\varepsilon - 1)^{1/2}$$

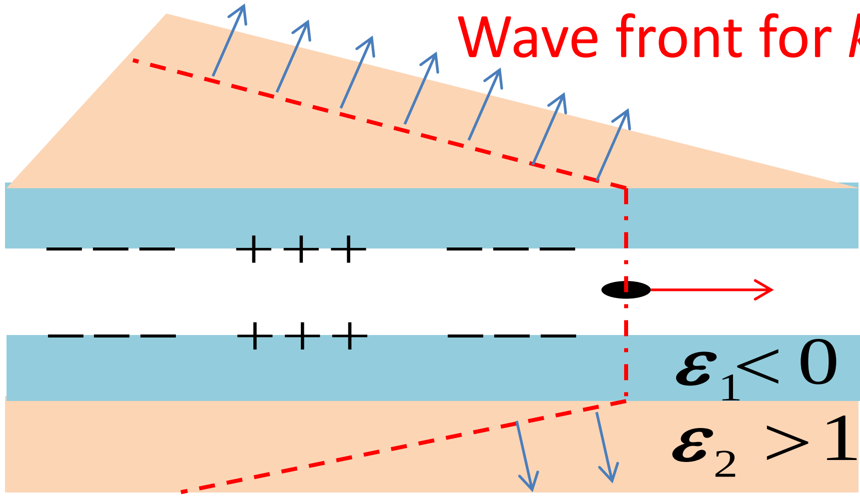
leak in the second medium

Problem: still, these waves cannot leak into vacuum!

Accelerator/Radiation-Source Structure

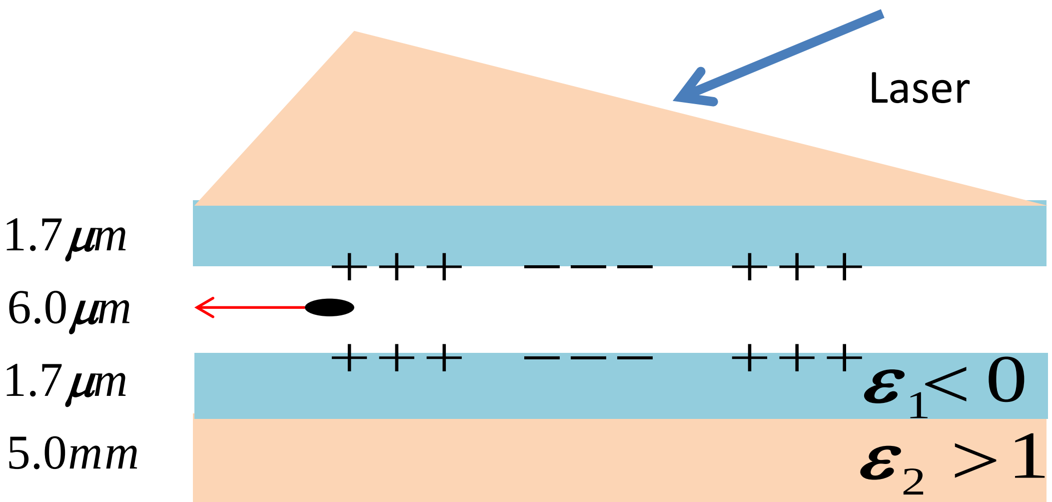
Solution: use Si-prism!

Wave front for k_y=0: $\theta_{wedge} = 15^\circ, \quad \theta_{front} = 17^\circ.$



Radiation is incident almost normally to air-prism interface!

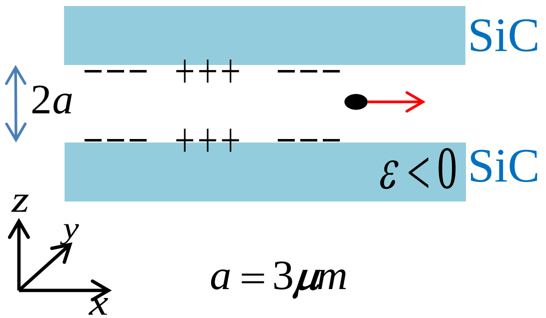
Beam is slowly decelerating.



Remember the accelerator configuration:

Burton Neuner III, Dmitriy Korobkin, Gabriel Ferro, and Gennady Shvets, **Phys. Rev. ST Accel. Beams (2012)**

Dispersion Equation for waves in SiC Structure.



Do the simple case, the electric field in thick SiC plates. Make inverse Fourier transform:

$$\vec{E}(\vec{r},t) = \frac{i}{(2\pi)^2} \iint d\vec{k}_\parallel e^{i\vec{k}_\parallel \vec{r}_\parallel - i\omega t} \frac{4\pi q e^{-\sigma(z-a)}}{D(\omega,\vec{k}_\parallel)} \frac{(\sigma\vec{k}_\parallel + i\vec{e}_z k_\parallel^2)}{k_\parallel^2}$$

In this mode, E_x is symmetric with respect to the plane $z = 0$.

Main contribution is from poles where $D(\omega,\vec{k}_\parallel) = 0$

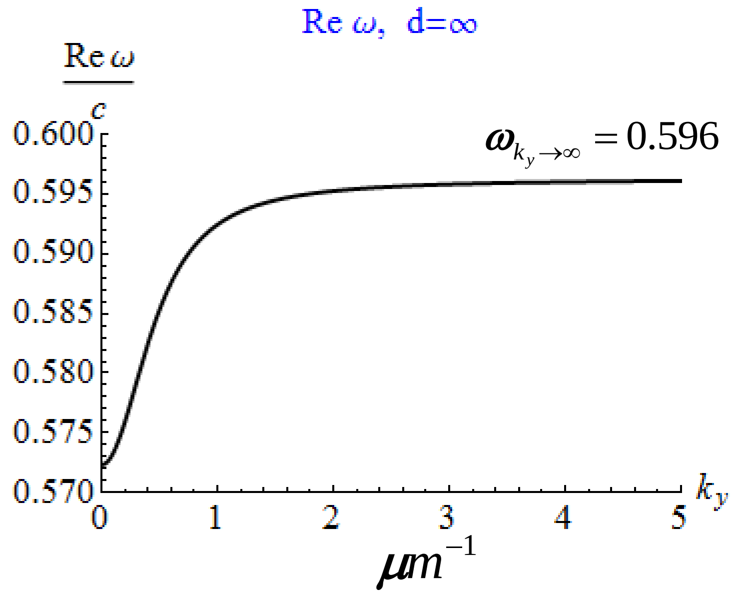
$$D(\omega,\vec{k}_\parallel) \equiv e^{k_y a}(\varepsilon + \sigma / k_y) + e^{-k_y a}(\varepsilon - \sigma / k_y) = 0,$$

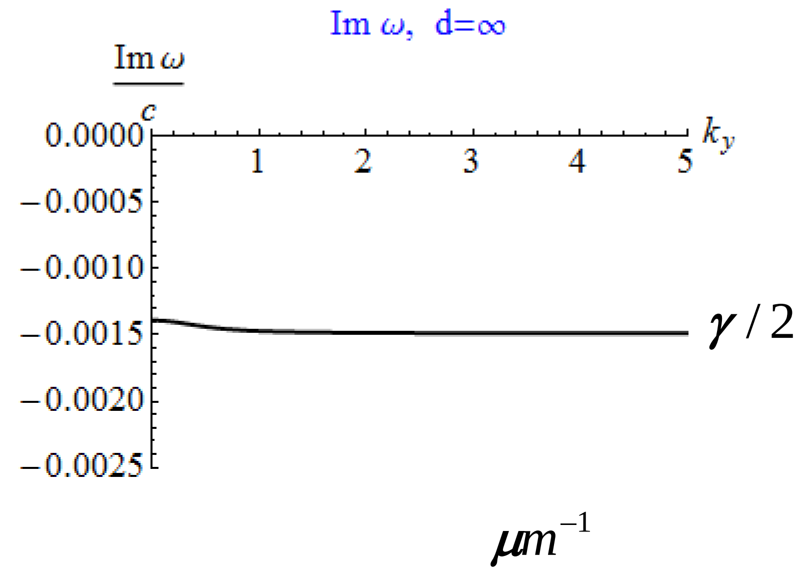
$$\sigma = (k_\parallel^2 - \varepsilon\omega^2 / c^2)^{1/2},$$

$$\omega = \vec{k}_\parallel \cdot \vec{v},$$

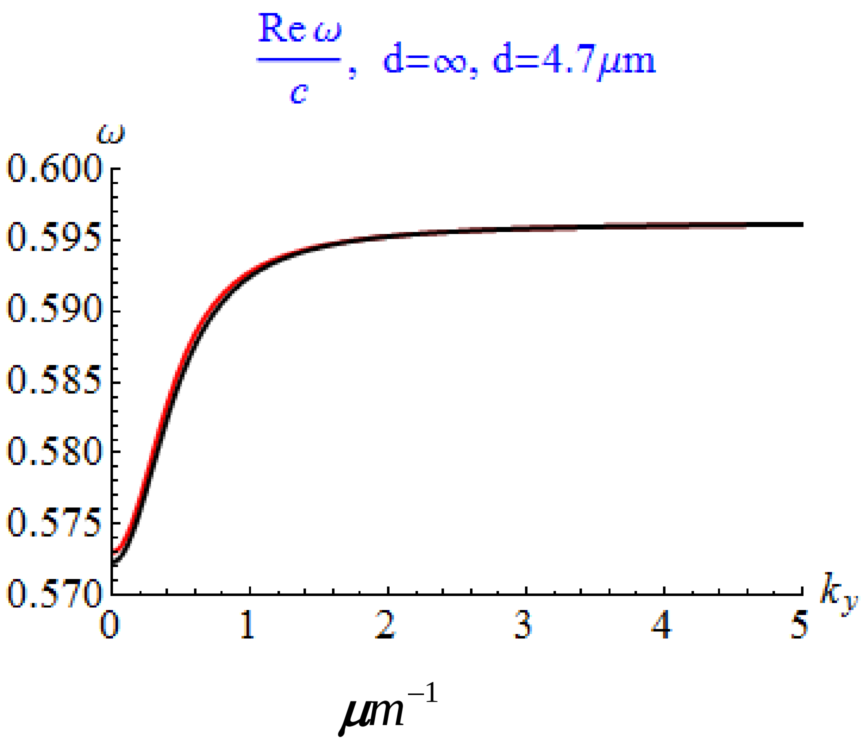
$$\varepsilon = \varepsilon_\infty \frac{\omega^2 - \omega_{LO}^2 + i\gamma\omega}{\omega^2 - \omega_{TO}^2 + i\gamma\omega}$$

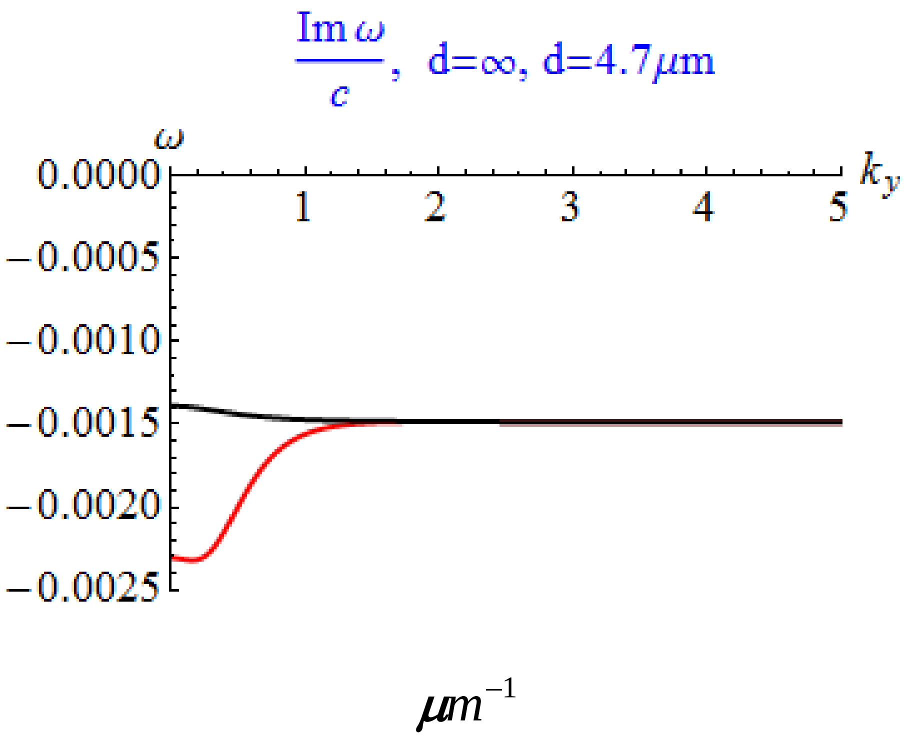
Solve dispersion equation and find $\omega = \omega_*(k_y)$





Dispersion Equation for Waves in Si-SiC Structure II.





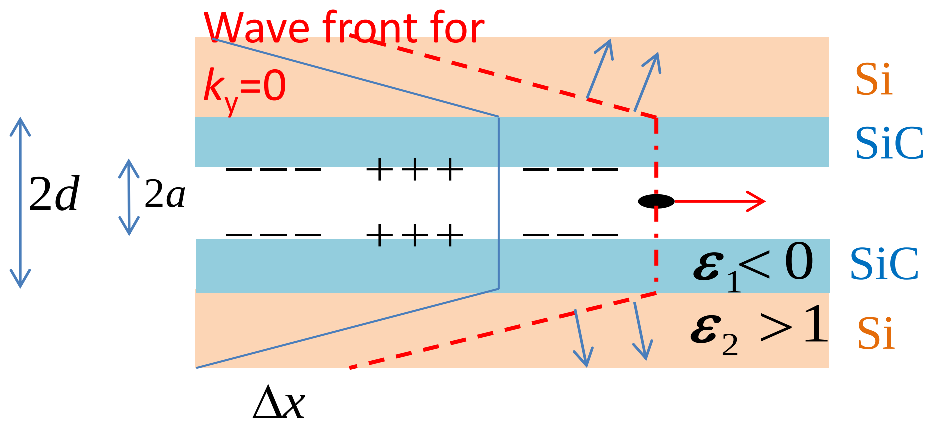
The second plot tells us that radiation occurs at $k_y \leq 1\mu m^{-1} \rightarrow \theta_{out} \approx 30^{\circ}$.

Intensity vs. wavevector of the waves entering Si plate

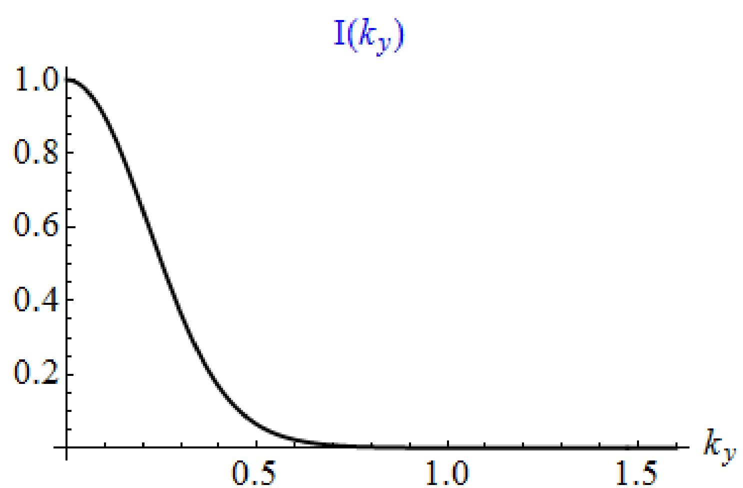
$a = 3\mu m$

$d = 4.7\mu m$

$\varepsilon_{Si} \approx 11.7$

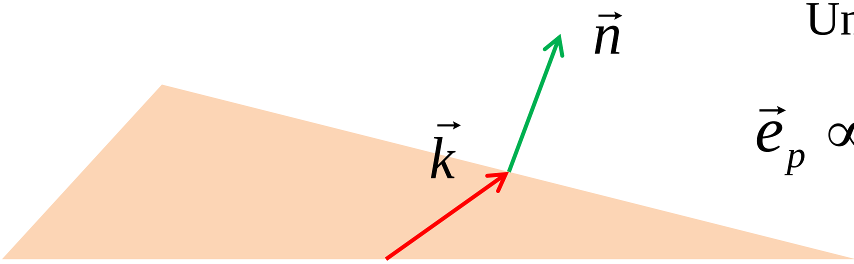


Pulse length of the generated radiation $\Delta x \approx \dfrac{1}{\mathrm{Im}(\omega)/c} \sim 50\lambda$



The radiation occurs at $k_y \leq 0.6\mu m^{-1} \quad \rightarrow \quad \theta_{out} \approx 18^{\circ}$.

Refraction at the prism (Fresnel formulas).



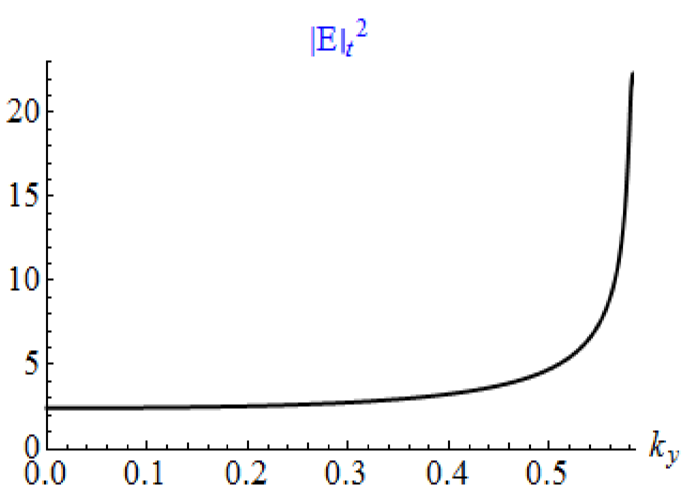
Unit vectors $\vec{e}_s \propto \vec{n}\times\vec{k}$,

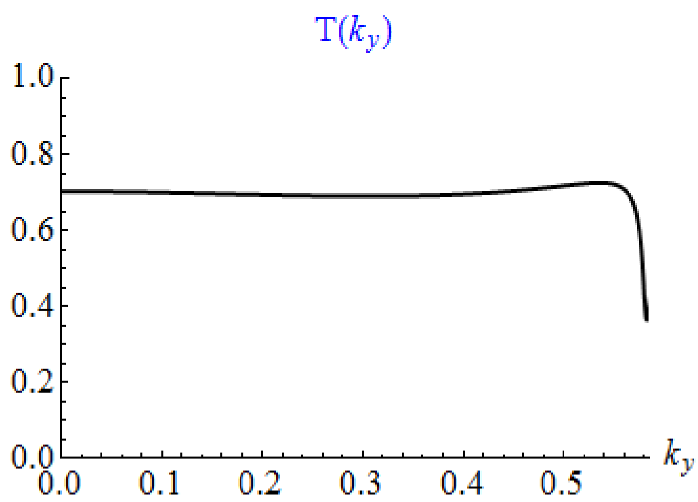
$\vec{e}_p \propto \vec{e}_s \times \vec{k}$, $\quad \vec{e}_{p,r} \propto \vec{e}_s \times \vec{k}_r$, $\quad \vec{e}_{p,t} \propto \vec{e}_s \times \vec{k}_t$

$\vec{k}_r = \vec{k} - 2\vec{n}(\vec{n}\cdot\vec{k})$, $\quad \vec{k}_t = \vec{k} - \vec{n}(\vec{n}\cdot\vec{k}) + \vec{n}\sqrt{\frac{\omega^2}{c^2} - [\vec{k} - \vec{n}(\vec{n}\cdot\vec{k})]^2}$,

$$k_{t,x}^2 + k_{t,z}^2 = \frac{\omega^2}{c^2} - k_y^2$$

$$\vec{E}_t = \frac{2(\vec{n}\cdot\vec{k})}{(\vec{n}\cdot\vec{k}) + (\vec{n}\cdot\vec{k}_t)}(\vec{E}\cdot\vec{e}_s) + \frac{2(\vec{n}\cdot\vec{k})}{\varepsilon^{-1/2}(\vec{n}\cdot\vec{k}) + \varepsilon^{1/2}(\vec{n}\cdot\vec{k}_t)}(\vec{E}\cdot\vec{e}_p)$$



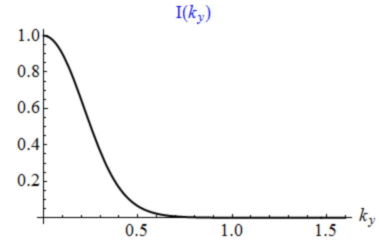


In vacuum propagation possible for

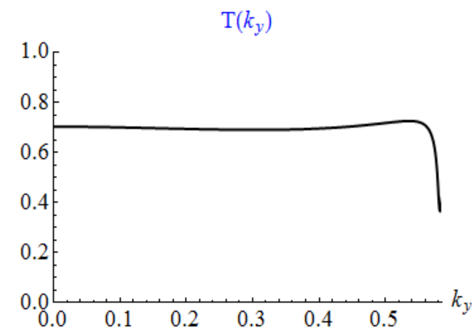
$$k_y < 0.6\mu m^{-1}$$

Dependence of Emission on various parameters

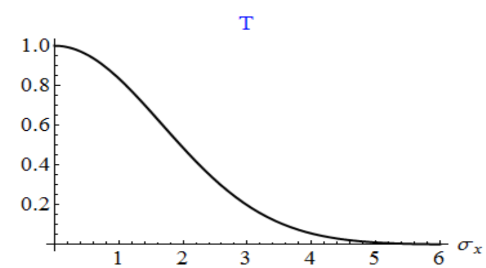
- *Radiation into Si-plate:*



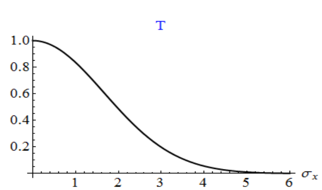
- *Radiation into vacuum:*



- *Beam shape:*



Final output:



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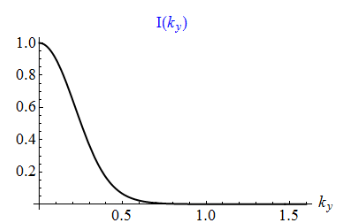

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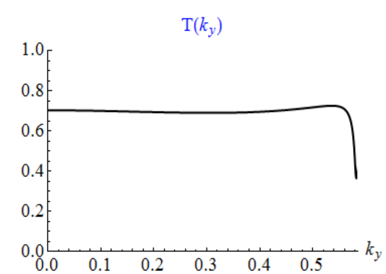


Lower and upper estimates of radiation energy

Coherent radiation of the point charge:

$$W \sim \frac{2 \times FF \times q^2 k_x^2 L_x}{4\pi\varepsilon_0}$$

L_x - 1cm – length of the structure

k_x - 0.6μm – x-component of wavenumber of the radiation

q - charge

FF ~ 0.01/3 - form factor

Radiation energy for 100pC (coherent) $W \approx 2*10^{-3}\,J$

Radiation energy for 1pC (coherent) $W \approx 2*10^{-7}\,J$

Incoherent radiation

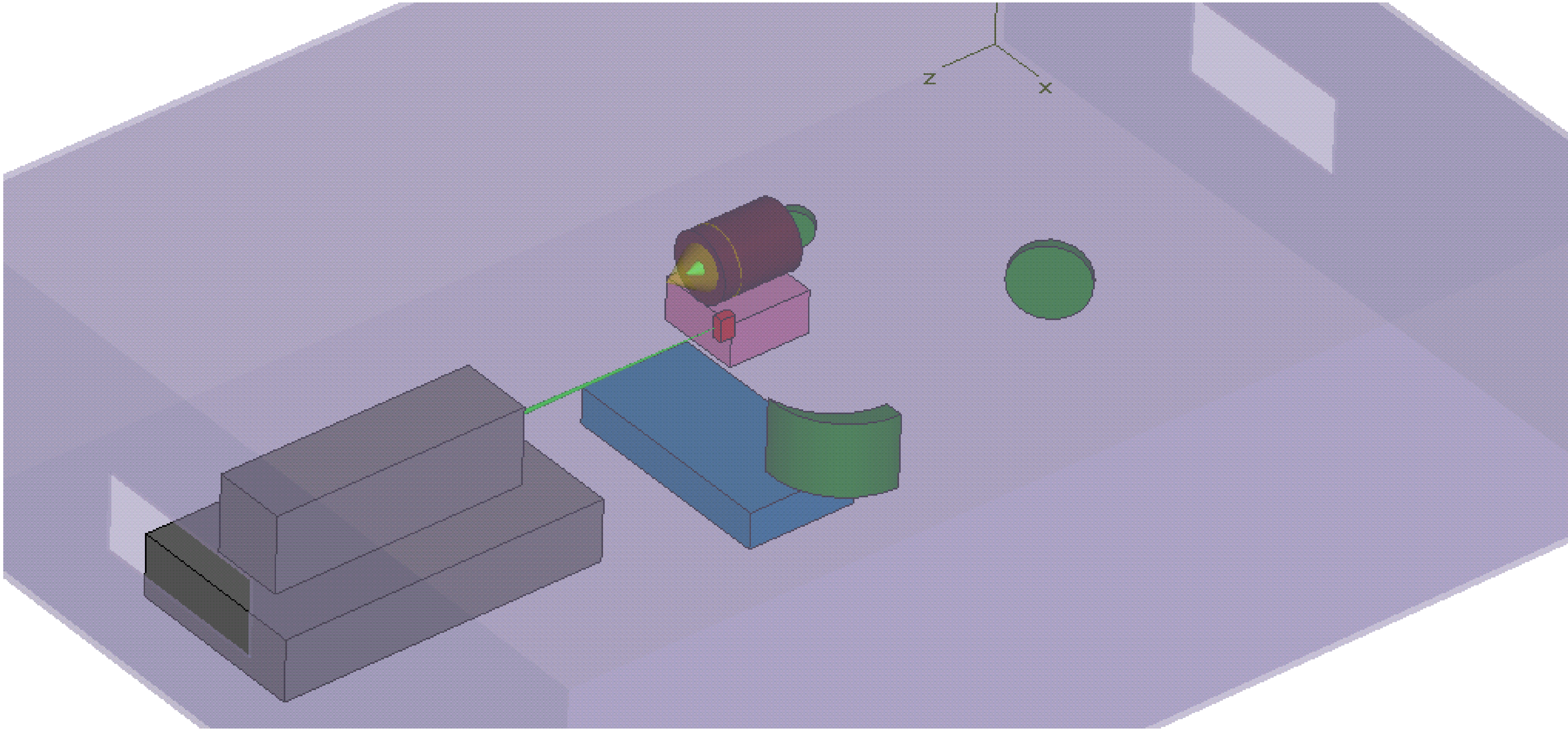
e – electron charge

$$W \sim \frac{2 \times FF \times e^2 k_x^2 L_x}{4\pi\varepsilon_0}\frac{q}{e}$$

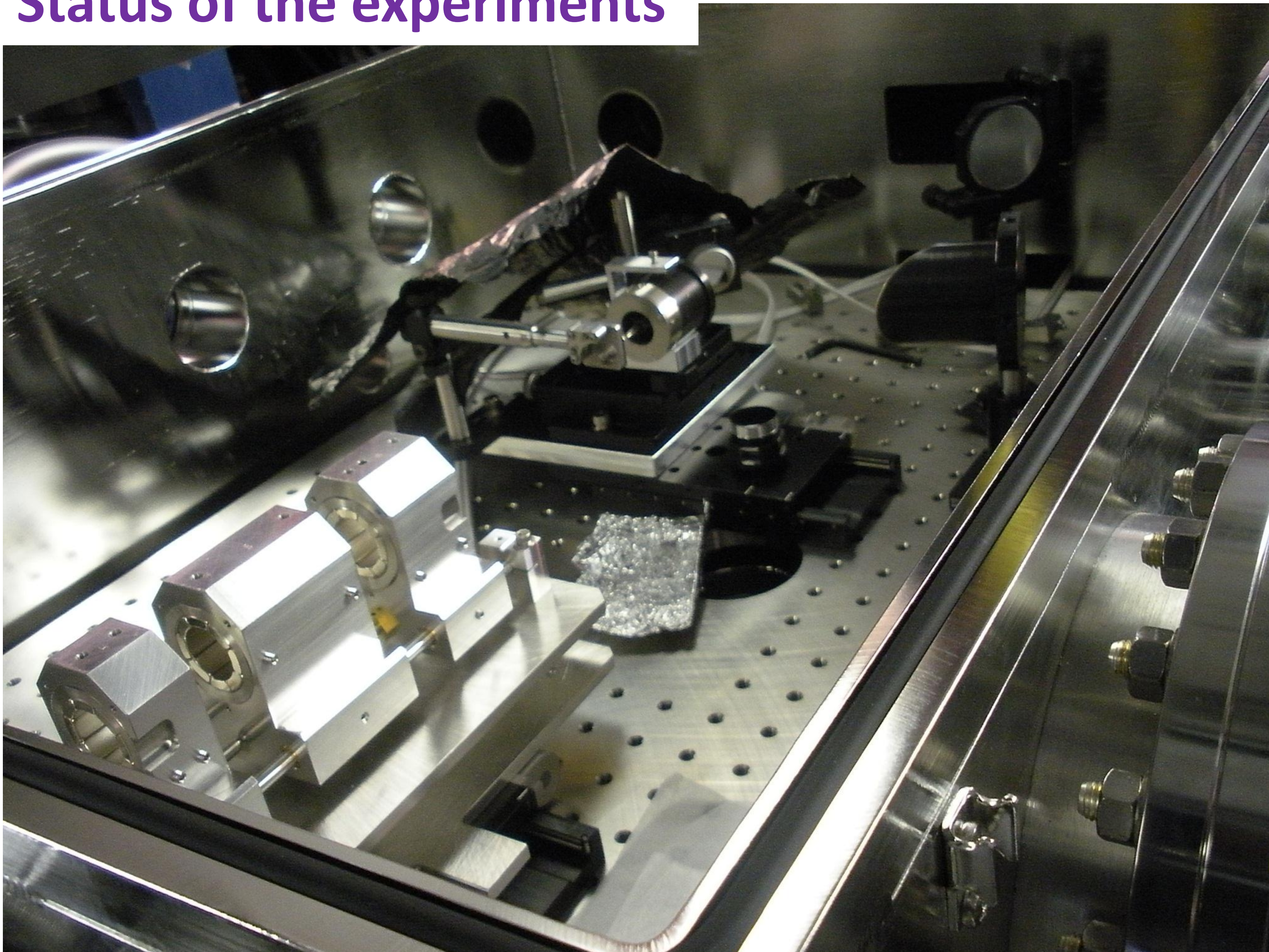
Radiation energy for 100pC (incoherent) $W \approx 3.5*10^{-12}\,J$

Radiation energy for 1pC (incoherent) $W \approx 3.5*10^{-14}\,J$

CAD preparation



Status of the experiments



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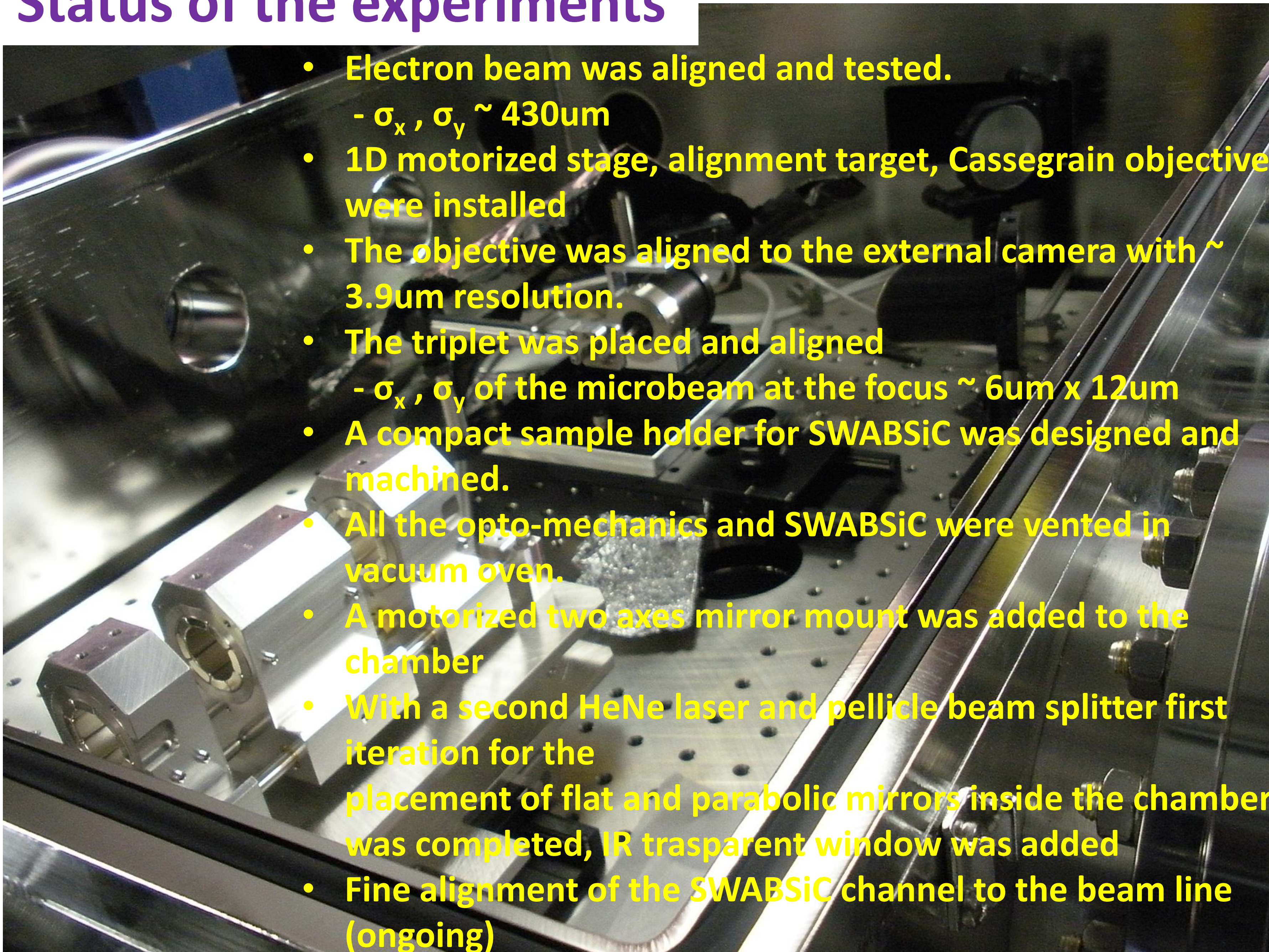

- Electron beam was aligned and tested.
  - σ_x , σ_y ~ 430um
- 1D motorized stage, alignment target, Cassegrain objective were installed
- The objective was aligned to the external camera with ~ 3.9um resolution.
- The triplet was placed and aligned
  - σ_x , σ_y of the microbeam at the focus ~ 6um x 12um
- A compact sample holder for SWABSiC was designed and machined.
- All the opto-mechanics and SWABSiC were vented in vacuum oven.
- A motorized two axes mirror mount was added to the chamber
- With a second HeNe laser and pellicle beam splitter first iteration for the
  placement of flat and parabolic mirrors inside the chamber was completed, IR trasparent window was added
- Fine alignment of the SWABSiC channel to the beam line (ongoing)