Solar Sails – Problems and Progress

Ulrich R.M.E. Geppert

Institute for Space Systems, Bremen, Germany
February 15th 2008

Why Solar Sail Propulsion?

- large s/c velocity achievable

$$v_2 \approx 11\,\mathrm{km/s},\ \text{with}\ a_{ss}\ (\leq 1\mathrm{AU}) \sim 5\,\mathrm{mm/s^2}\ \text{after}\ 1\mathrm{yr} \Rightarrow v_{ss} \approx 160\,\mathrm{km/s}$$

Missions into the deep space accomplishable only with solar sails!

- non-Keplerian orbits possible – even exotic ones

By an appropriate sequence of sail orientations, any point in the solar system – and beyond – can be reached!

- essentially open launch window

Acceleration Small BUT Long-Lasting

$$a_{\mathrm{rad}}(\alpha = 0^0, 1\mathrm{AU}) = \frac{L_s}{2\pi r^2 c\sigma} = \frac{9.12\eta}{\sigma[\mathrm{gm}^{-2}]}[\mathrm{mm\,s}^{-2}]$$

$\eta \leq 0.9$: efficiency, $\sigma < 10$ g m^{-2} $\rightarrow$ $a_{rad} \sim 1$ mm s^{-2}

BUT

we have plenty of time:

$a_{rad} \bullet$ 1000 days $\rightarrow$ $(100 < v_{sail} < 1000)$ km s^{-1}

Basic Advantage: Much Larger I_{sp}

I_{sp}= change of momentum per unit propellant

Ziolkowski 1897:

$$m_2 = m_1 \exp\left(\frac{-\Delta v}{g\, I_{sp}}\right) \Rightarrow I_{sp} = \frac{\Delta v}{g} \frac{1}{\ln\left(\frac{m_1}{m_2}\right)} \leq 450\,\mathrm{s} \text{ for rockets}$$

for solar sail $I_{sp} = \infty \rightarrow$ effective specific impulse measured by setting m_1 = mass(sail + payload), m_2 = mass(payload);

with $\Delta v = a_{rad} \bullet T$ and mass(payload) = mass(0.5 sail mass) for T = 1000 days and a_{rad} = 1mm s^{-2}:

$$I_{sp} = \frac{a_{\mathrm{rad}}\, T}{g} \frac{1}{\ln 3} \approx 8000\ s \ \text{ for solar sail propulsion}$$

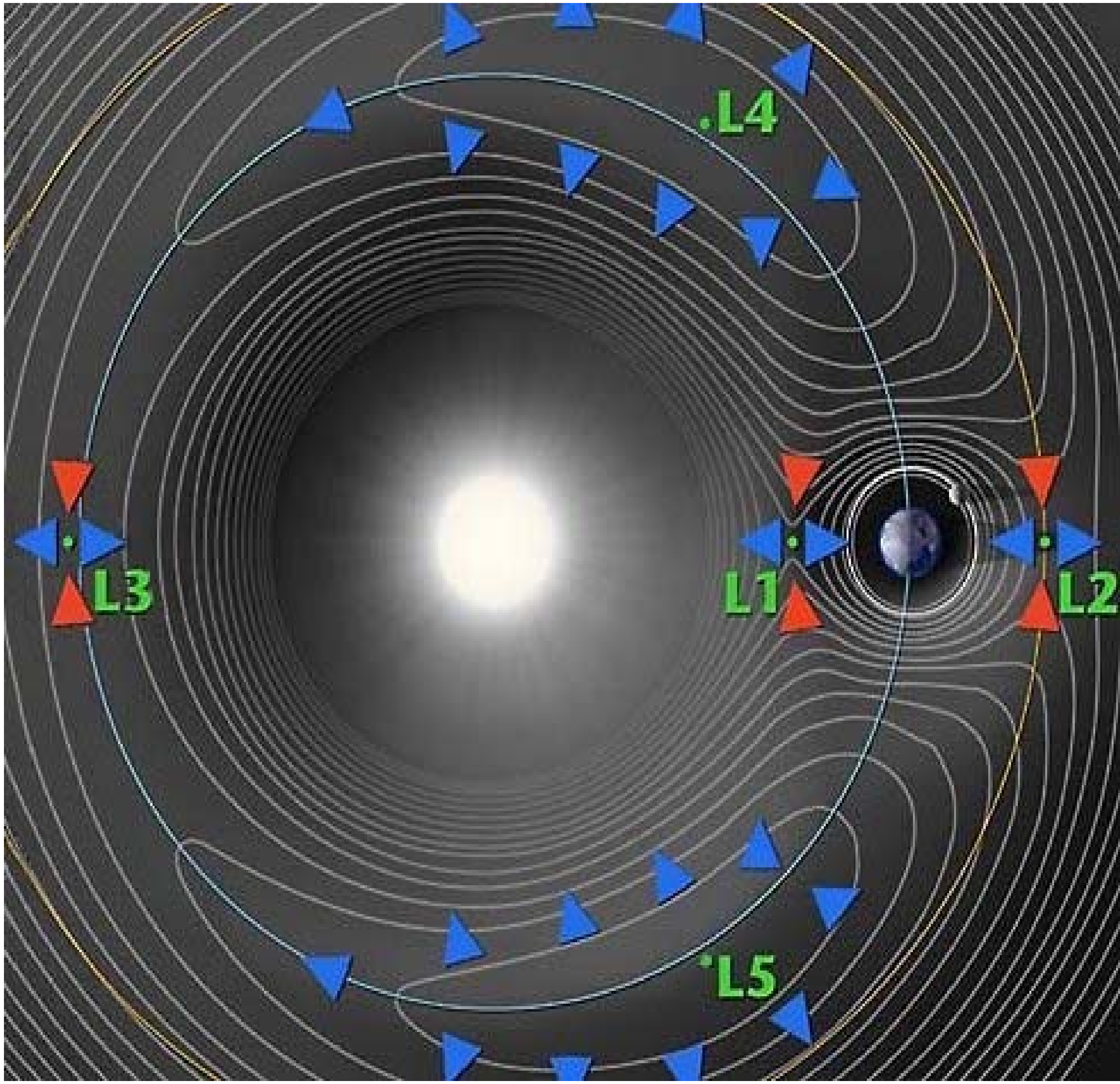
Non-Keplerian Orbits

- continuously available radiation pressure:

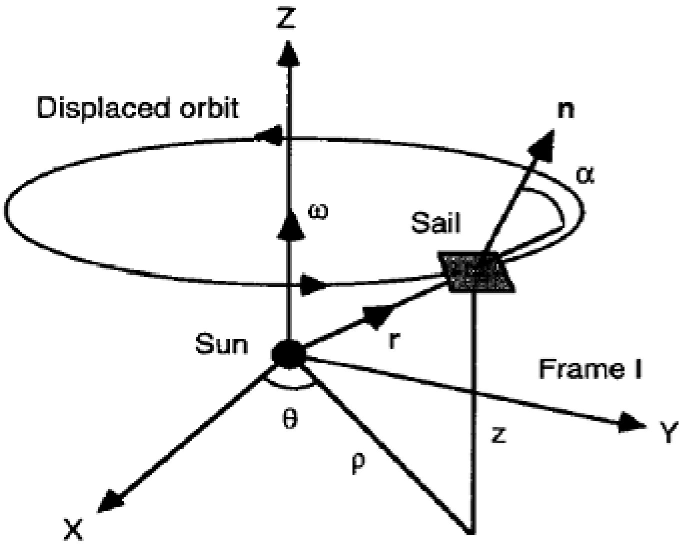
  all solar sail orbits are non-Keplerian

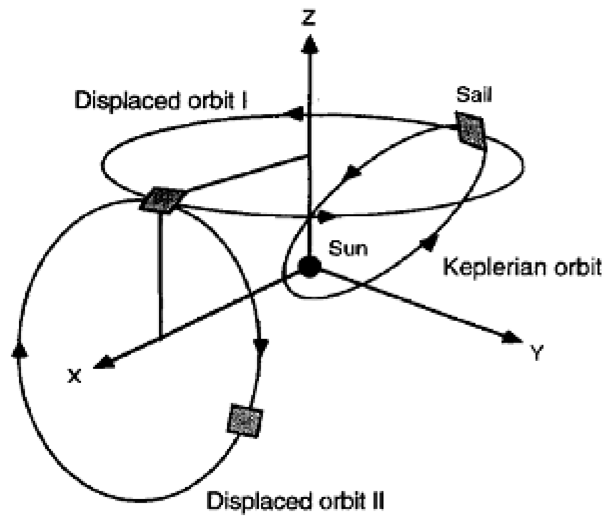
- some orbits so strongly perturbed → new family if

  $a_{rad} \sim a_{grav}$ (locally)



Non-Keplerian Displaced Orbits

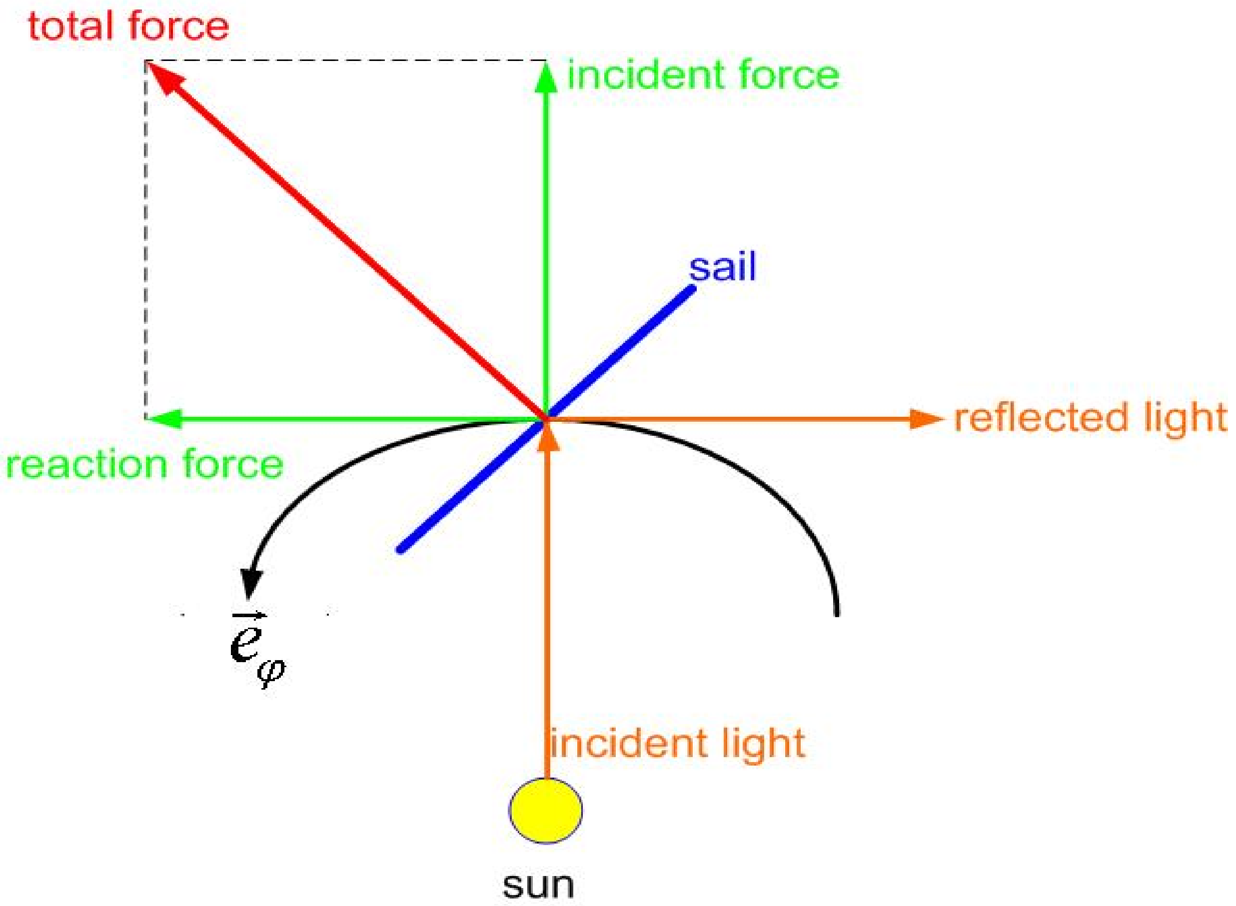




- mission circles the inertial Z-axis of the sun,
- observes coronal mass ejections on **all** sides of sun,
- constant communication with Earth,
- synchronization with Earth's rotation about sun possible,

- patched displaced orbits
- examine **much** more, environment around the sun,

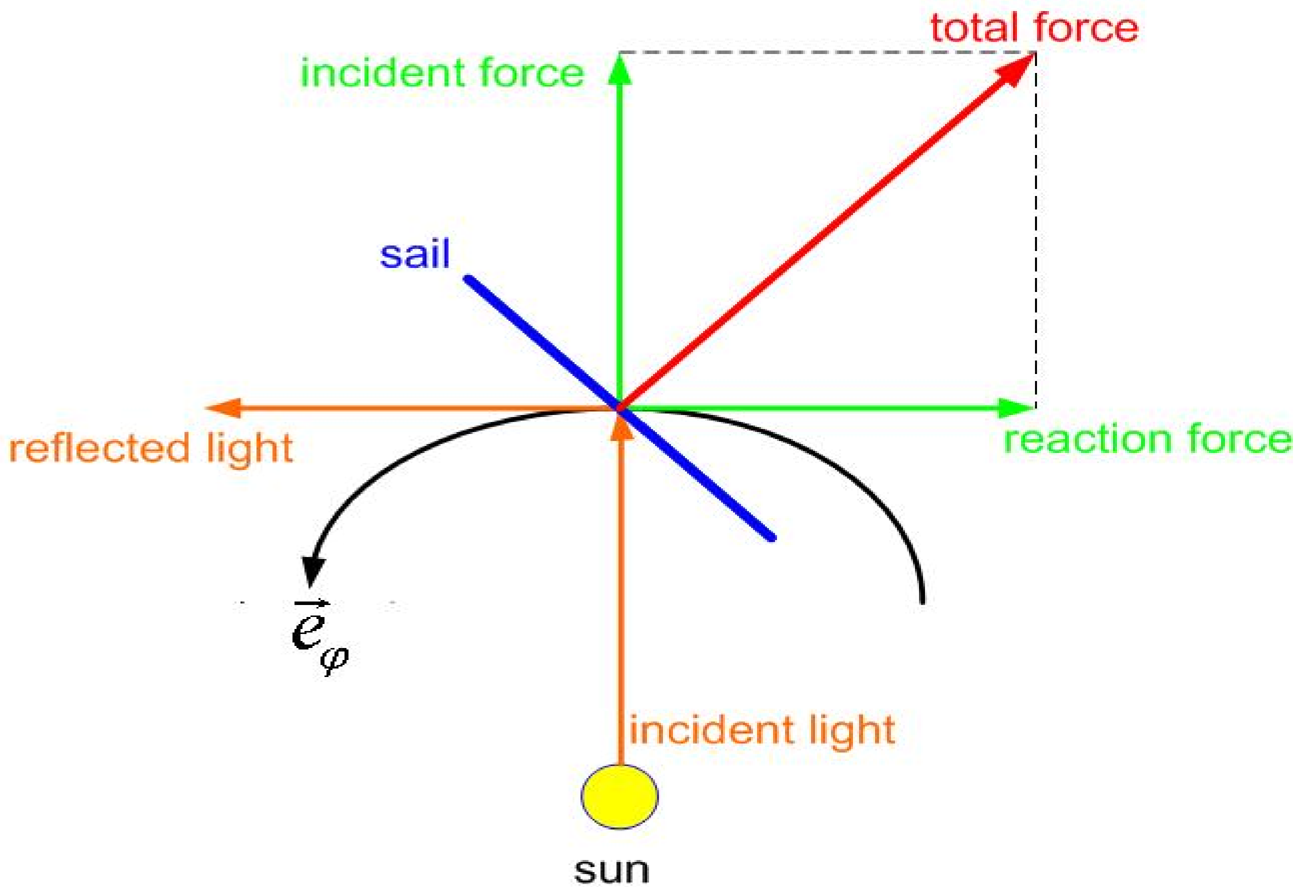
Maneuver into the Space



total force has component ↑↑ $\vec{e}_\varphi$:

sail spirals away from the sun

Maneuver towards the Sun



total force has component ↑↓ $\vec{e}_\varphi$:

sail spirals towards the sun

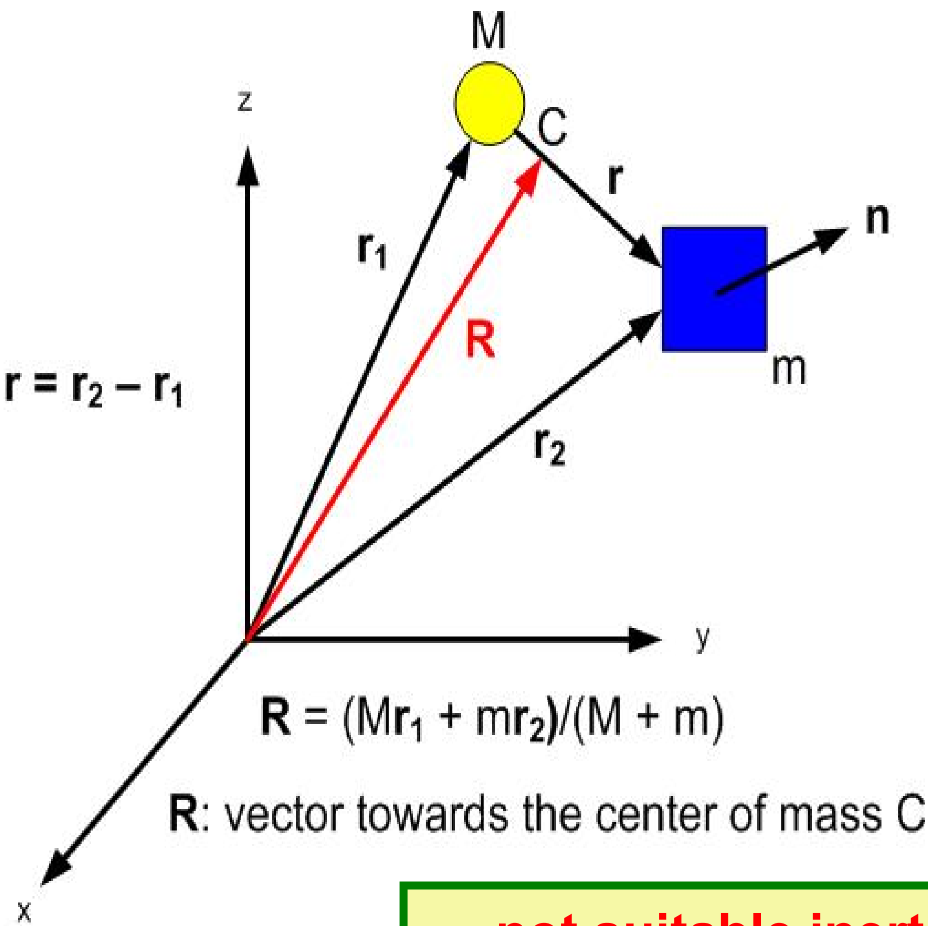
$\mathbf{a}_{rad}$ ~ Sail Lightness β

σ: sail loading, i.e. mass per sail area

$$\beta = \frac{\sigma_*}{\sigma} = \frac{L_s}{2\pi c G M} \frac{1}{\sigma}$$

σ_* : critical sail loading, follows from $\mathbf{a}_{grav} = \mathbf{a}_{rad}$

Equation of Motion



$$M\frac{d^2\vec{r}_1}{dt^2} = \frac{GMm}{r^2}\vec{e}_r$$

$$m\frac{d^2\vec{r}_2}{dt^2} = -\frac{GMm}{r^2}\vec{e}_r + \beta\frac{GMm}{r^2}\cos^2\alpha\,\vec{e}_n \quad +$$

$$\frac{d^2\vec{R}}{dt^2} = \beta\frac{GMm}{(M+m)r^2}\cos^2\alpha\,\vec{e}_n \approx 0$$

→ not suitable inertial frame of reference

→ better to use an inertial system with R=0 in C

Equation of Motion , Frame in C

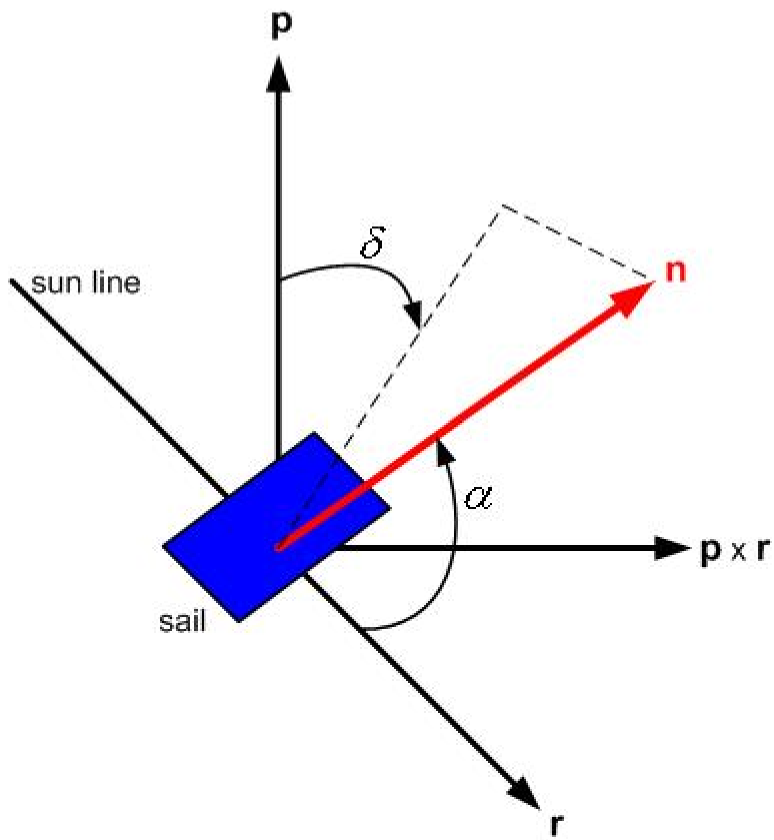
in C : $\vec{R}=0$, i.e.: $M\vec{r}_1 + m\vec{r}_2 = 0$; with $\vec{r} = \vec{r}_2 - \vec{r}_1$ follows:

$$\frac{\mathrm{d}^2\vec{r}}{\mathrm{d}t^2} = \left(1+\frac{m}{M}\right)\frac{\mathrm{d}^2\vec{r}_2}{\mathrm{d}t^2}$$

$$\Rightarrow \frac{\mathrm{d}^2\vec{r}}{\mathrm{d}t^2} + \frac{\mu}{r^2}\vec{e}_r = \beta\frac{\mu}{r^2}\cos^2\alpha\,\vec{e}_n\,, \text{ where } \mu = G(M+m) \approx GM$$

This vector equation of motion may now be transformed into scalar components in any convenient frame of reference.

Sail Coordinates



unit vectors:

r: sun line
p: normal to the orbital plane
p x **r**: transverse to **p** and **r**

cone angle α: between sun line and sail normal

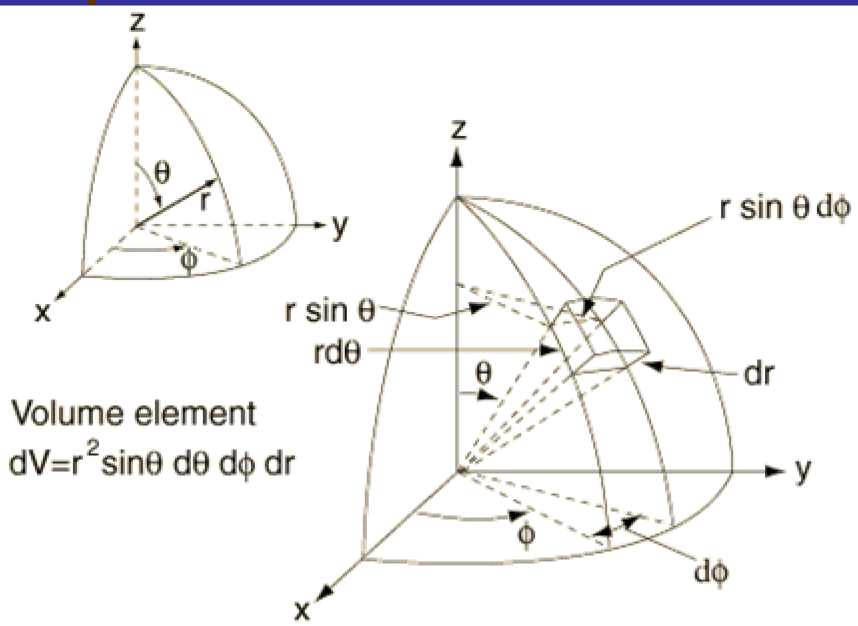
clock angle δ: between projection of sail normal and some reference direction onto a plane normal to the sun line

resolving **n** along the radial, orbit normal, and transverse directions:

n = cosα**r** + sinαcosδ**p** + sinαsinδ(**p** x **r**)

test: α=δ=0° → **n**~**r**, α=90°, δ=0° → **n**~**p**, α=δ=90° → **n**~(**p** x **r**)

Equation of Motion in Spherical Coordinates



We find the position of the sail **r**(r,θ,φ,t) as a function of ist cone and clock angle, α and δ, and as function of the solar luminosity L_s and the sail loading σ ($\beta \sim L_s/\sigma$)

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} - r\left(\frac{\mathrm{d}\varphi}{\mathrm{d}t}\right)^2 - r\left(\frac{\mathrm{d}\theta}{\mathrm{d}t}\right)^2 \cos^2\varphi = -\frac{\mu}{r^2} + \beta\frac{\mu}{r^2}\cos^3\alpha$$

$$\frac{1}{r}\cos\varphi\frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\frac{\mathrm{d}\theta}{\mathrm{d}t}\right) - 2r\left(\frac{\mathrm{d}\theta}{\mathrm{d}t}\right)\left(\frac{\mathrm{d}\varphi}{\mathrm{d}t}\right)\sin\varphi = \beta\frac{\mu}{r^2}\cos^2\alpha\sin\alpha\sin\delta$$

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\frac{\mathrm{d}\varphi}{\mathrm{d}t}\right) + r\left(\frac{\mathrm{d}\theta}{\mathrm{d}t}\right)^2 \sin\phi\cos\varphi = \beta\frac{\mu}{r^2}\cos^2\alpha\sin\alpha\cos\delta$$

Main Problems

- Deployment of the Sail
- Sail Loading < 1.53 gm^{-2}
- Degradation of the Sail by Solar Wind and Electromagnetic Radiation

Each of this Problems Demands the Work Capacity of a Department and/or Collaboration with Hightech Industry

Deployment of the Sail

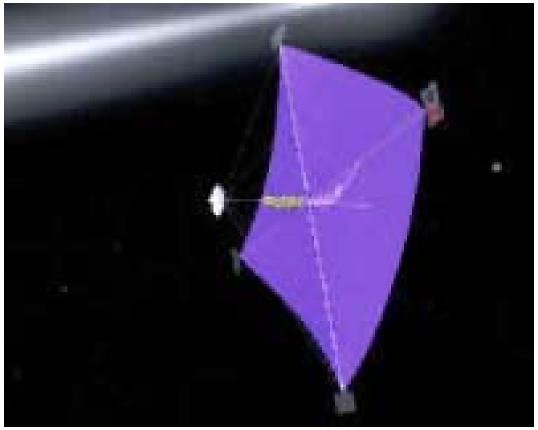
- up to now no successful attempt!

- most recent entry at the DLR solar sail hompage: Dec. 1999:1997 DLR-NASA/JPL solar sail mission pre-phase-A study

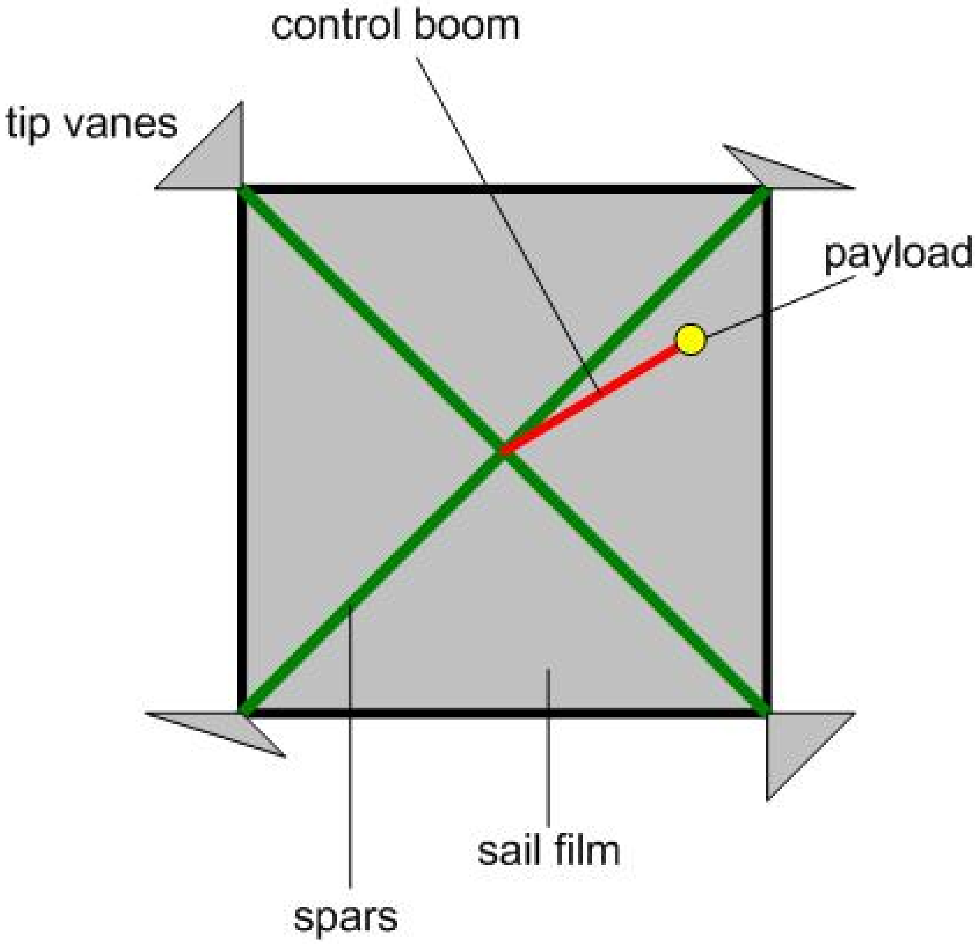
- in the 90th:

  - Znamya deployment test 1993, 20m,
    ~ successful, illumination of northern Russia
  - inflatable antenna deployment, NASA 1996, 14m, not successful

Sail Design Square Sail

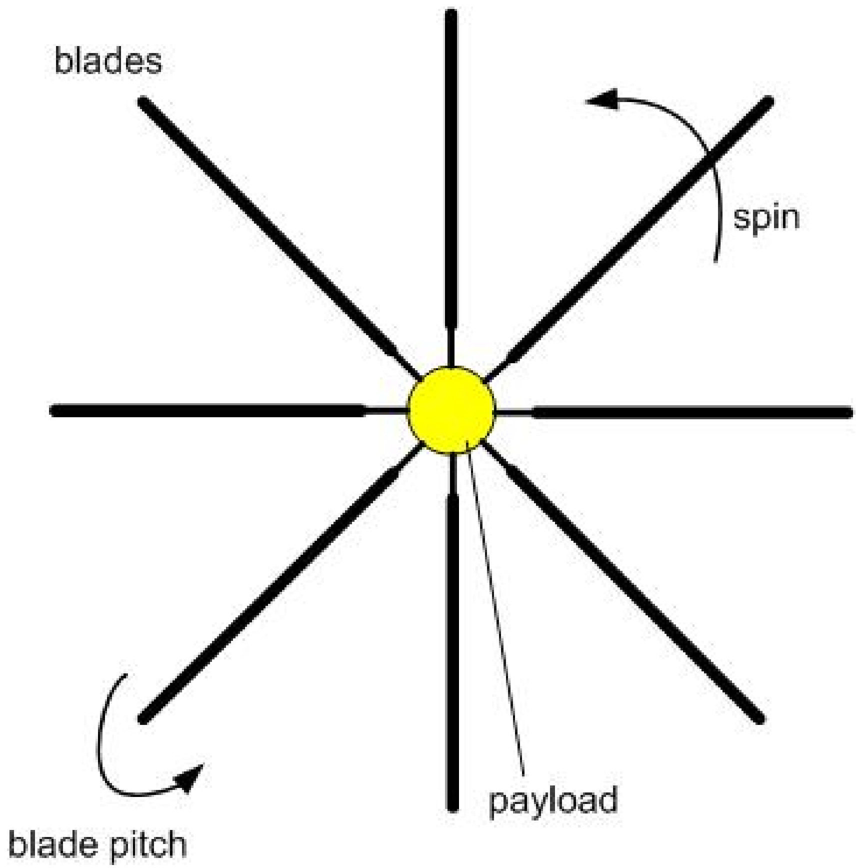


NASA/JPL



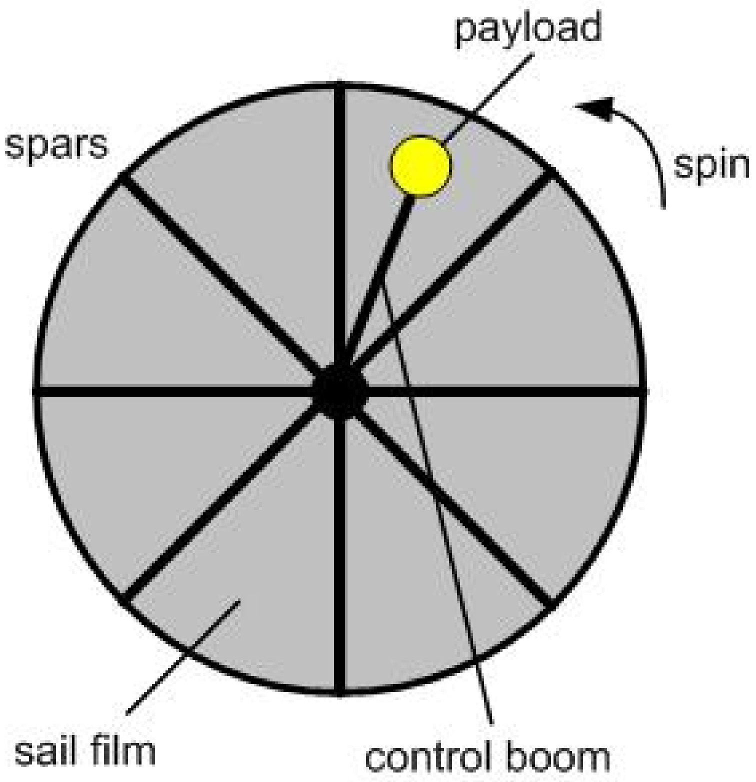
requires booms to support the sail material

Sail Design Heliogyro



bladed like a heliocopter, sail must be rotated for stabilization

Sail Design Disc Sail



circular sail, controlled by moving the center of mass relative to the center of light pressure

Critical Sail Loading σ* (Roughly)

$$\vec{a}_{\mathrm{rad}} = \frac{2AP}{M_{\mathrm{sail}}}\cos^2\alpha\,\vec{n} \qquad P = \frac{W}{c} = \frac{W_{\mathrm{E}}}{c}\left(\frac{R_{\mathrm{E}}}{r}\right)^2 = \frac{L_{\mathrm{s}}}{4\pi c r^2} \qquad \vec{a}_{\mathrm{rad}} = \frac{L_{\mathrm{s}}}{2\pi c r^2 \sigma}\cos^2\alpha\,\vec{n}$$

$$\vec{a}_{\mathrm{grav}} = \frac{GM_{\mathrm{sol}}}{r^2}\vec{e}_{\mathrm{r}}$$

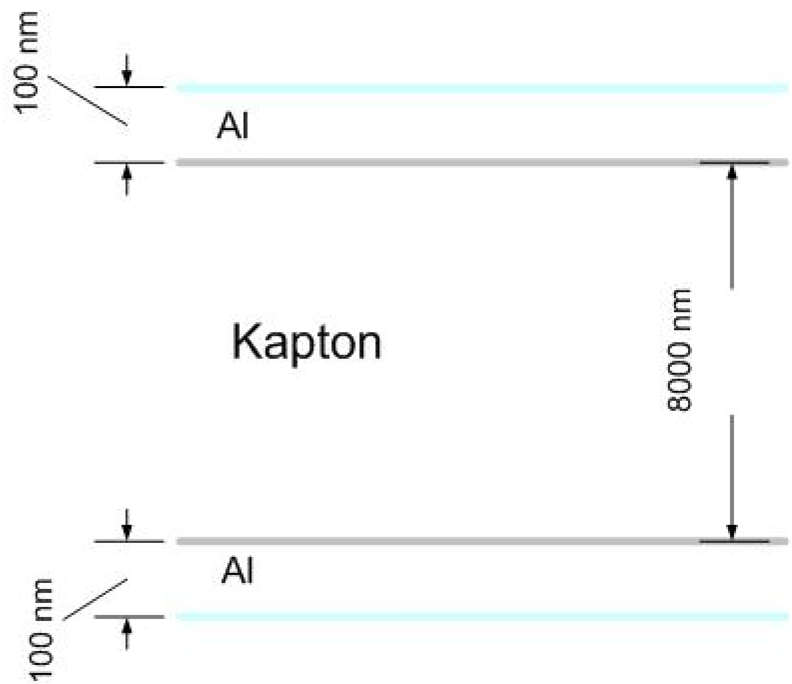
$$\text{condition for propulsion}: a_{\mathrm{rad}} \geq a_{\mathrm{grav}}\,,\ \text{if } \alpha = 0,\ \vec{n} \,\|\, \vec{e}_{\mathrm{r}} \Rightarrow$$

$$\sigma_* = \frac{L_{\mathrm{s}}}{2\pi c G M_{\mathrm{sol}}} = 1.53\,\mathrm{g\,m^{-2}}$$

A: sail area, P: photon pressure, M_{sail}: sail mass, L_s= 3.827• 10^{27} W: solar luminosity, σ = M_{sail}/A: sail loading, r: distance sun – s/c, α: angle (sun – sail normal)

Sail Loading < 1.53 gm^{-2}

- balance of solar gravitational and radiative acceleration: $\sigma_* = 1.53\ gm^{-2}$
- up to now available:

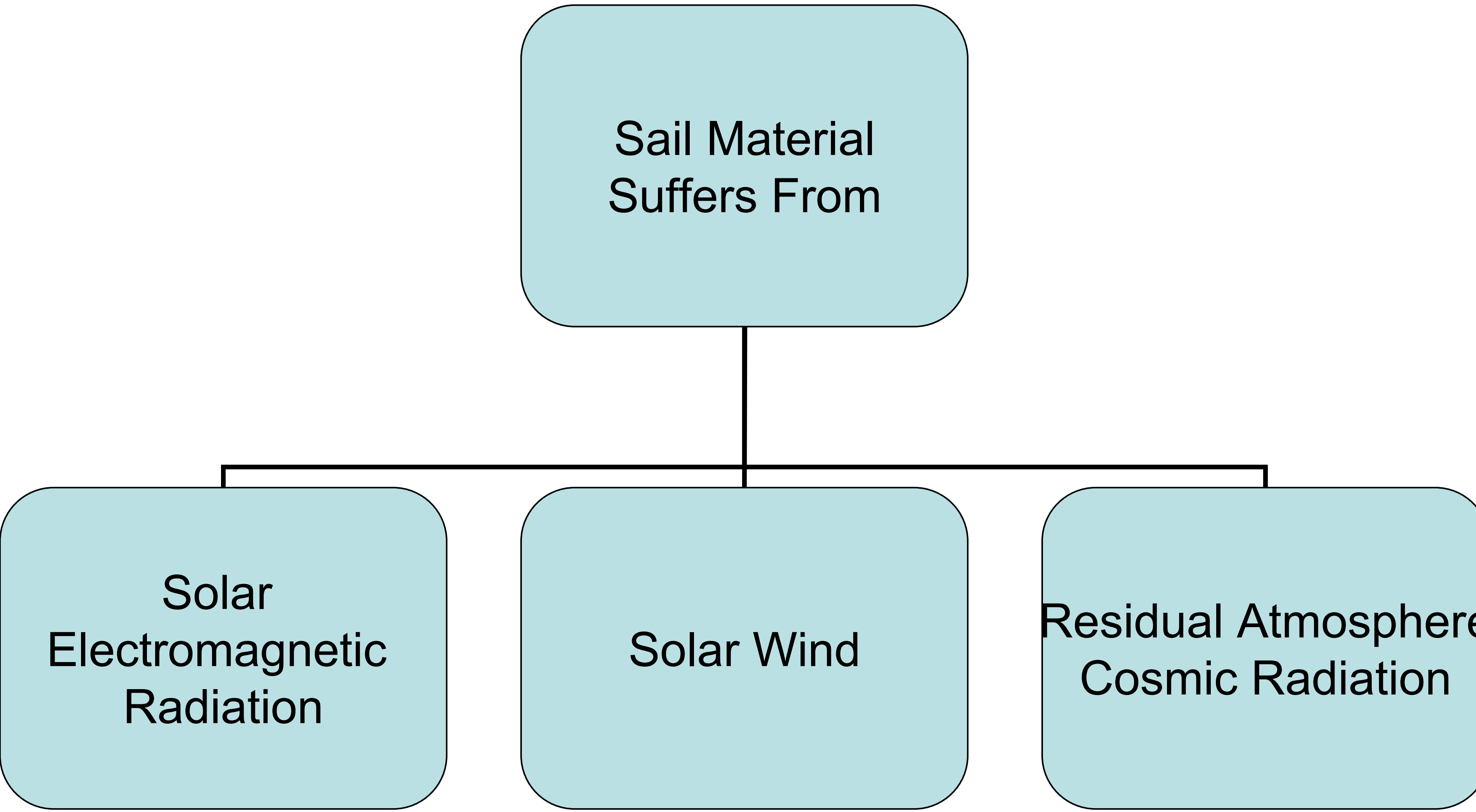


$\rho_{Al} = 2.7\ gcm^{-3}$, $\rho_{Kapton} = 1.43\ gcm^{-3}$

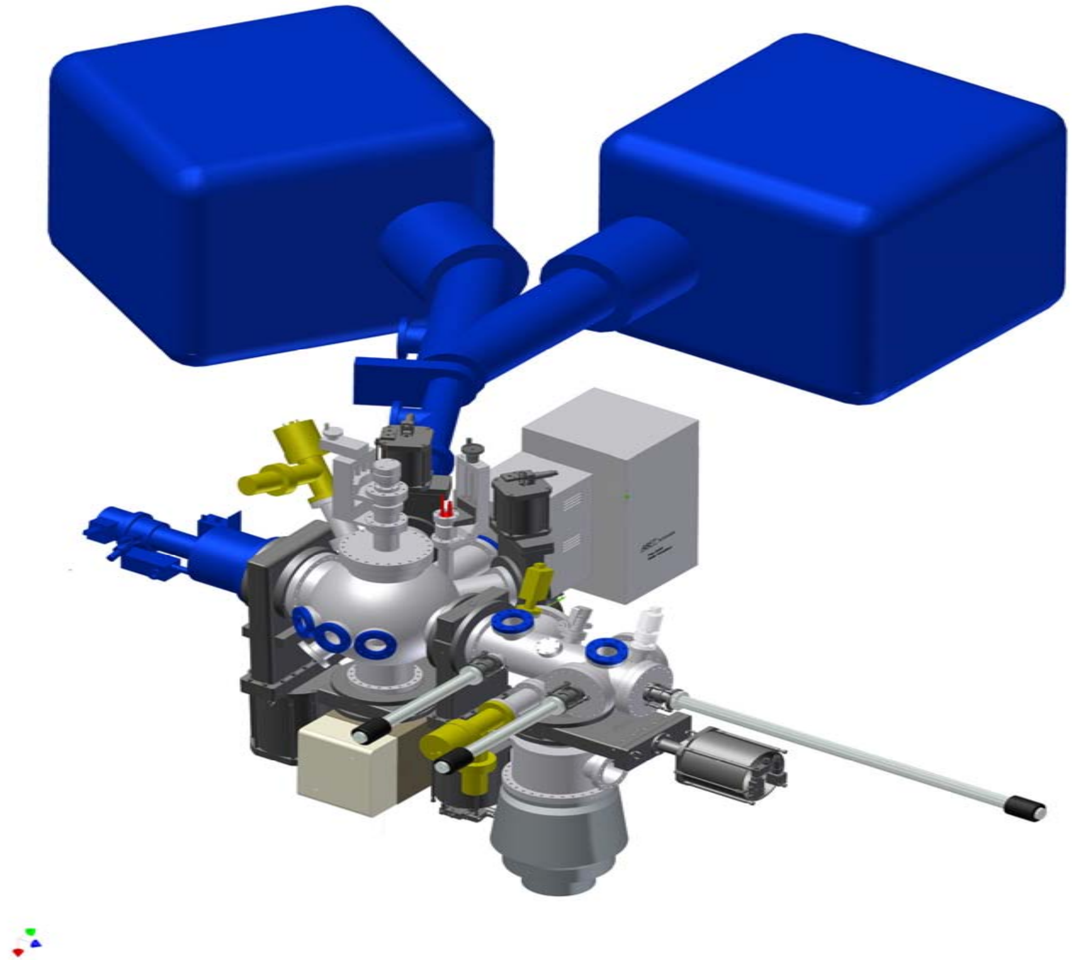
$\sigma = (0.54 + 11.44)\ gm^{-2} \approx 12\ gm^{-2}$

Either thickness of Kapton < 1µm or other foil material

Degradation



Complex Irradiation Facility (KOBE)



Solar Electromagnetic Radiation

- Averaged solar irradiance ≈ 1370 Wm^{-2}
- 47% visible light, 380…780nm ~ 1.6…3.3eV
  → thrust
- 46% infrared radiation, ≥ 780nm ~ ≤ 1.6eV
  → heat
- 7% UV, X, Γ, 6·10-6…380nm ~4eV…200MeV
  → ionization

Solar Wind Constituents

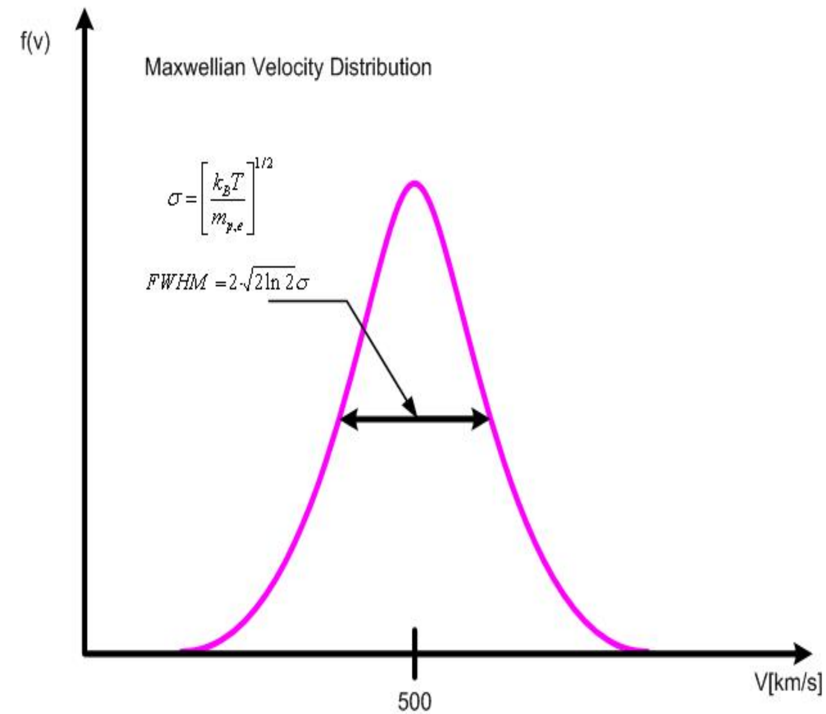
- protons 2keV…200MeV
- electrons 1eV…2MeV
- low energy particles:

  electron 1…2eV

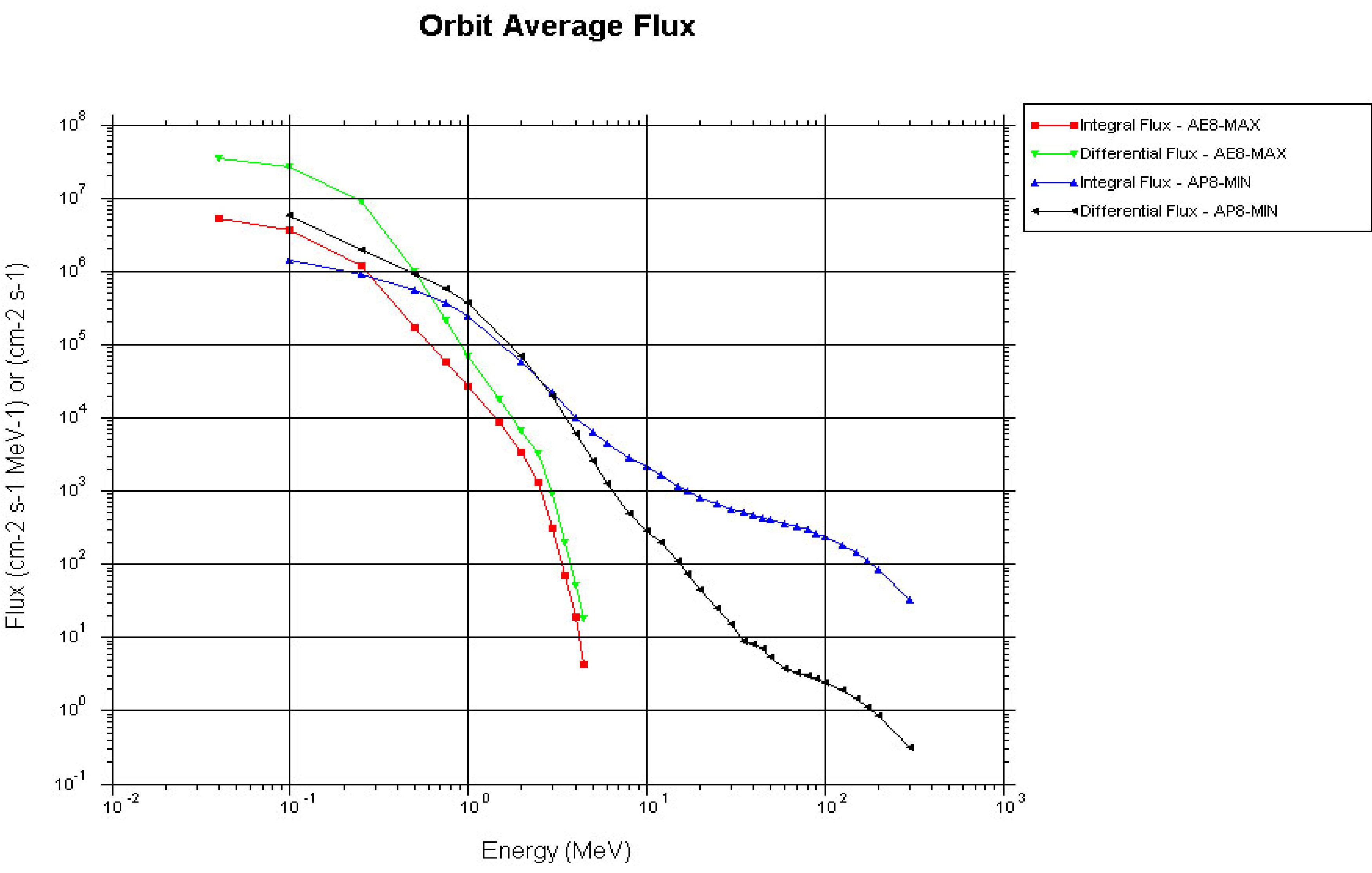
  protons 2…4keV

  → ionizing Al
- higher energetical particels:

  → destroying Kapton structures



Proton & Electron Fluxes (400000-1000km)



Scaling of Proton/Electron Currents

$$j_{\text{scale}} = \frac{\Phi \times A_{\text{KOBE}}}{6.2415 \times 10^{18}\,\text{p}^{+}/\text{e}^{-}} \times \frac{t_{\text{real}}}{t_{\text{lab}}}$$

j_{real} [A]: p^{+}/e^{-} current necessary to simulate a solar sail flight of t_{real}

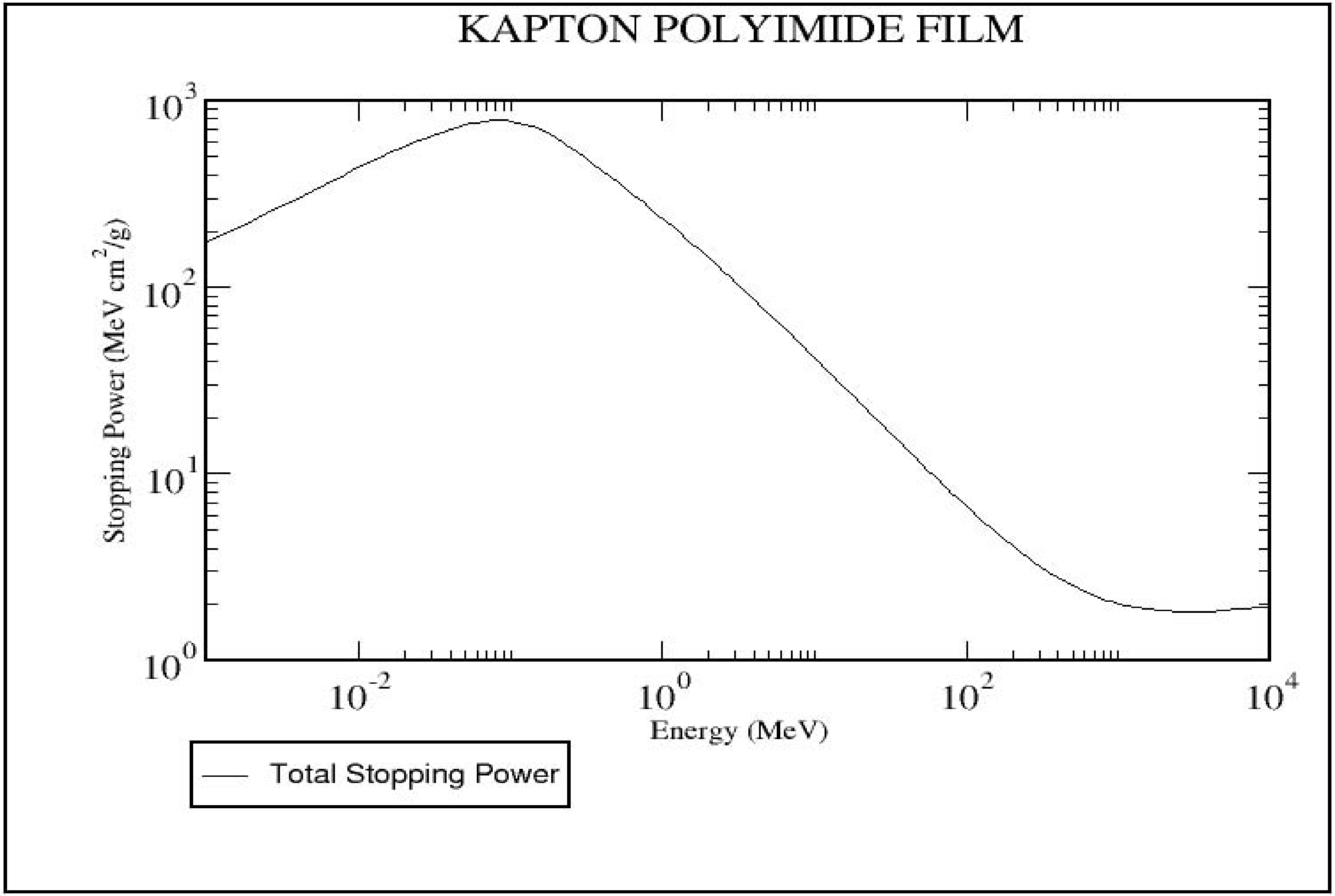
Φ[cm^{-2} s^{-1}]: p+/e- flux expected (by OMERE) for a given sail trajectory,

A_{KOBE}[cm^{2}]: irradiated area in the KOBE experiment,

t_{real}[s]: real solar sail flight time, t_{lab}[s]: time available in the lab to simulate the flight,

e.g. at 300keV: $\Phi = 10^{7} p^{+} cm^{-2} s^{-1}$ = 1.6pAcm^{-2},
if we intend to simulate a 20 years flight during 1 week
→ we have in KOBE to apply a j_{scale} = 1.67µA

Proton Energy Loss within the Kapton



Energy Loss = Density × Total Stopping Power

Heat Release by High-energetic p^+/e^-

energy balance: $Q_{in} = Q_{out}$

Q_{in} = dE/dx(per p^+/e^-) · foil thickness · p^+/e^- current

$Q_{out} = \sigma_{SB} \cdot \varepsilon_{Al} \cdot A \cdot (T_s^4 - T_{env}^4)$

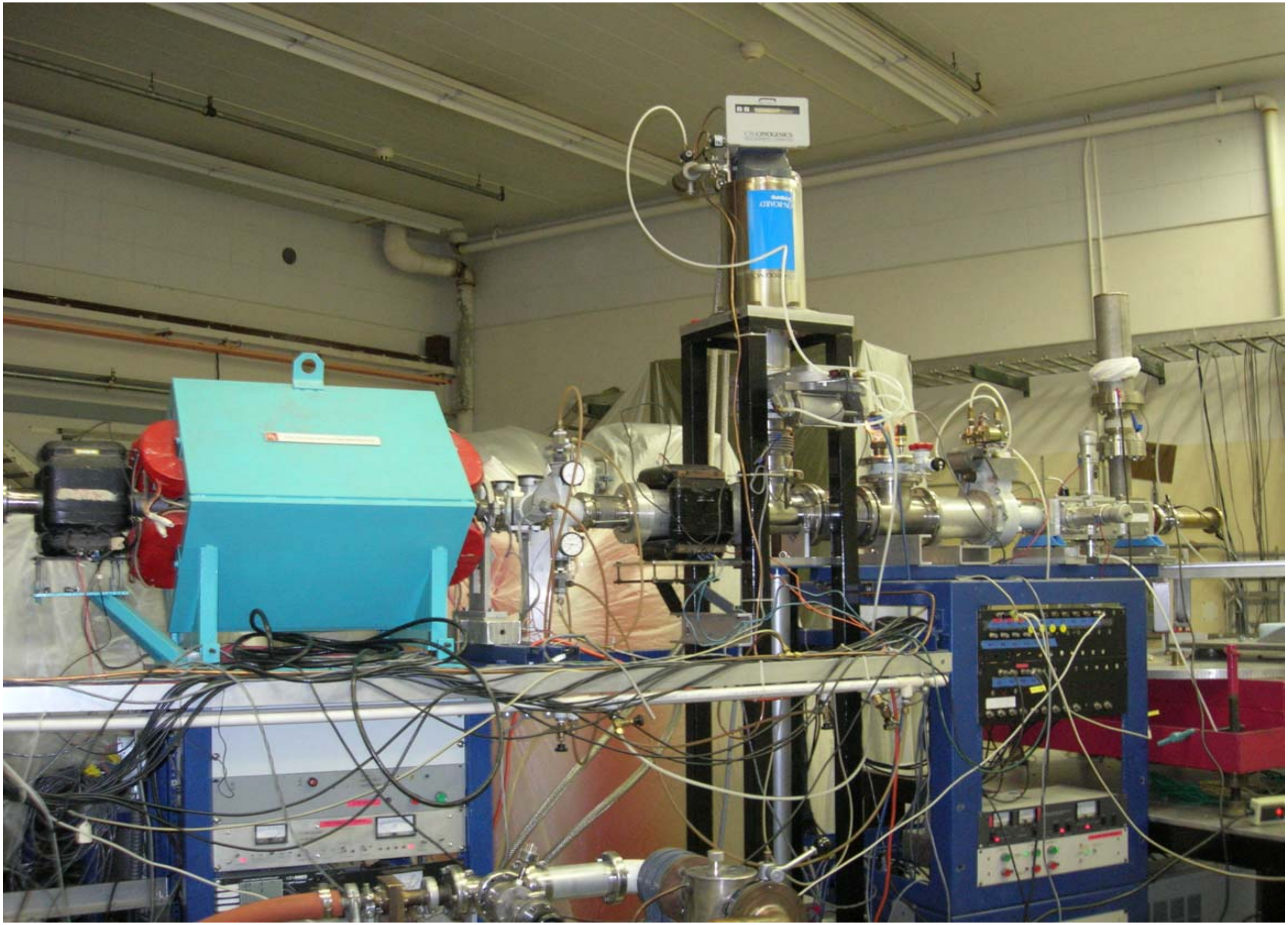
$$T_s = \left(\frac{Q_{in}}{\sigma_{SB} \varepsilon_{Al} A} + T_{env}^{\ 4} \right)^{1/4}$$

For 1MeV proton and a current of 1μA with ε_{Al} and A = 200 cm^2 we should obtain $T_s \approx 335$ K. A doubling of the proton current would endanger the stability of Kapton.

Protonirradiation of „Our“ Foils at Notre Dame, U.S.A.

Van de Graaff Accelerator 30 MeV

Proton Beam Line



Irradiation of Al-Covered Kapton Foils with Protons of 300 and 600 keV

- 600 keV: all protons are transmitted
- 300 keV: all protons are stopped within the foil
- effects of

  - beam thickness

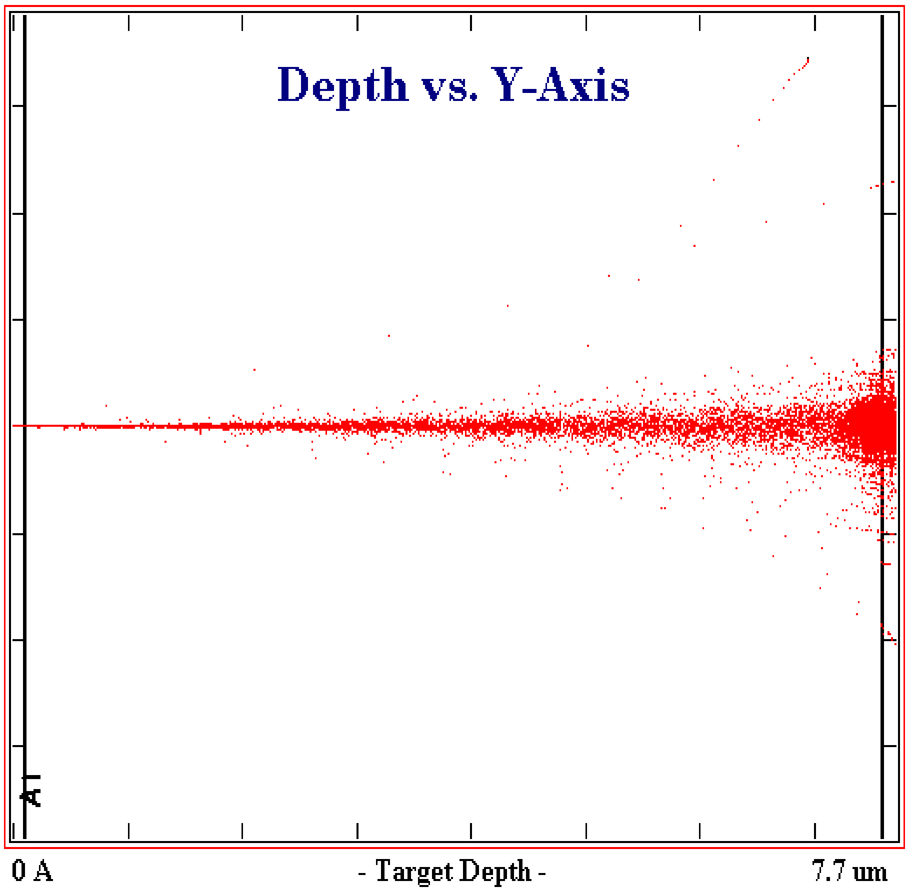
  - wobbling

  - intensity

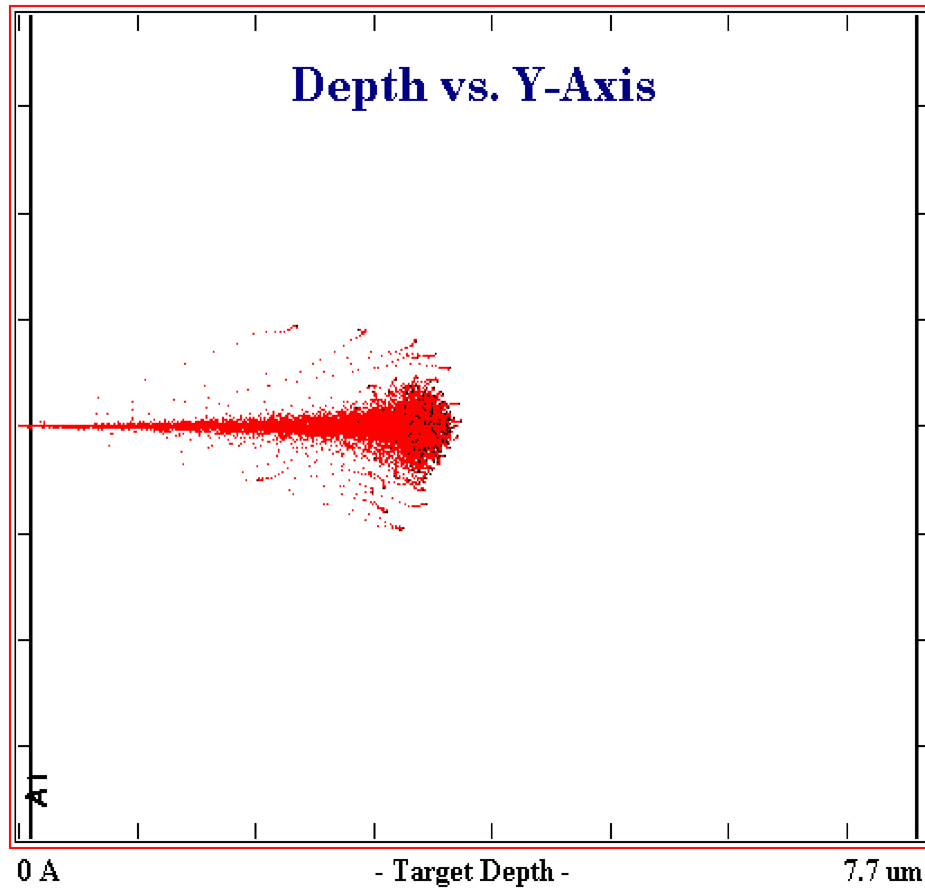
all probes are irradiated with the same dose of 2 mC

SRIM Simulation of Proton Stopping

600 keV



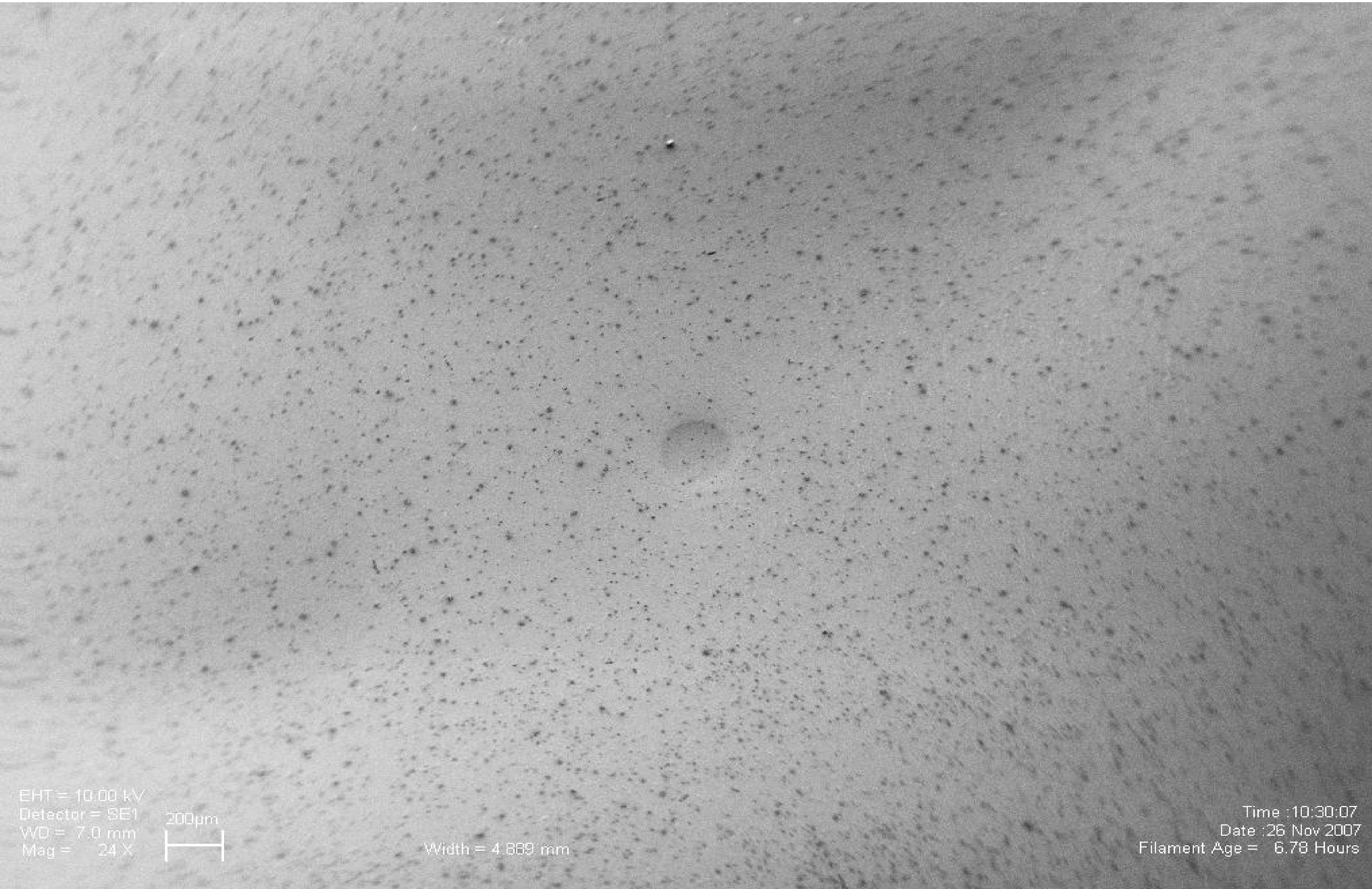
300 keV



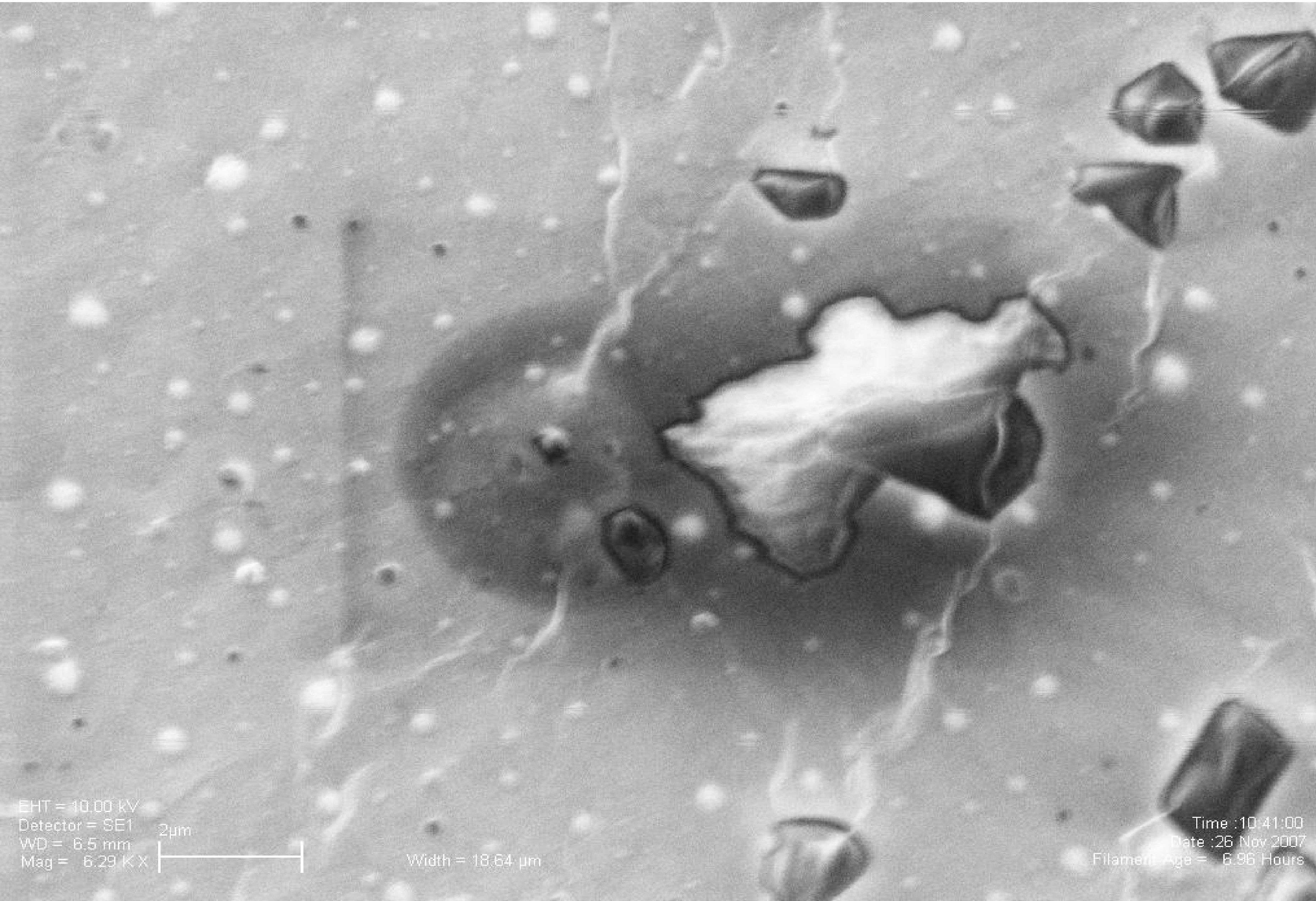
600 keV, $2\mu A$, beam ~ 1mm, wobbling ~ 1Hz

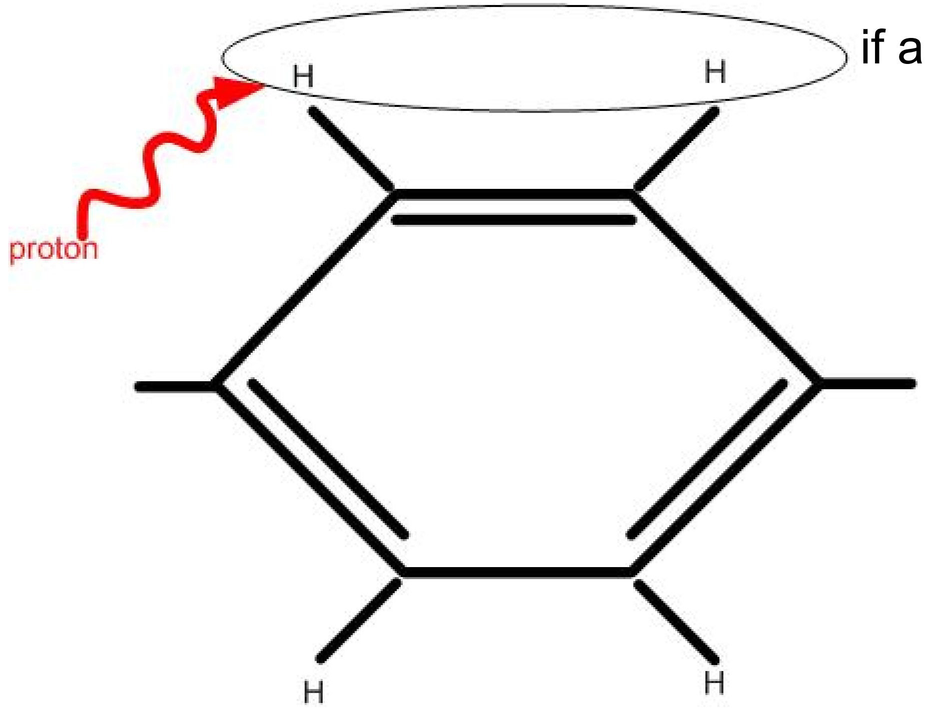

Beam Defocused, No Wobbling
$2\mu A$
300 keV,

300 keV , $2\mu A$, Defocused Beam, Magnification: 24



300 keV , 2μA , Defocused Beam, Magnification: 6290





if abstracted → they cleave H + H → H_2

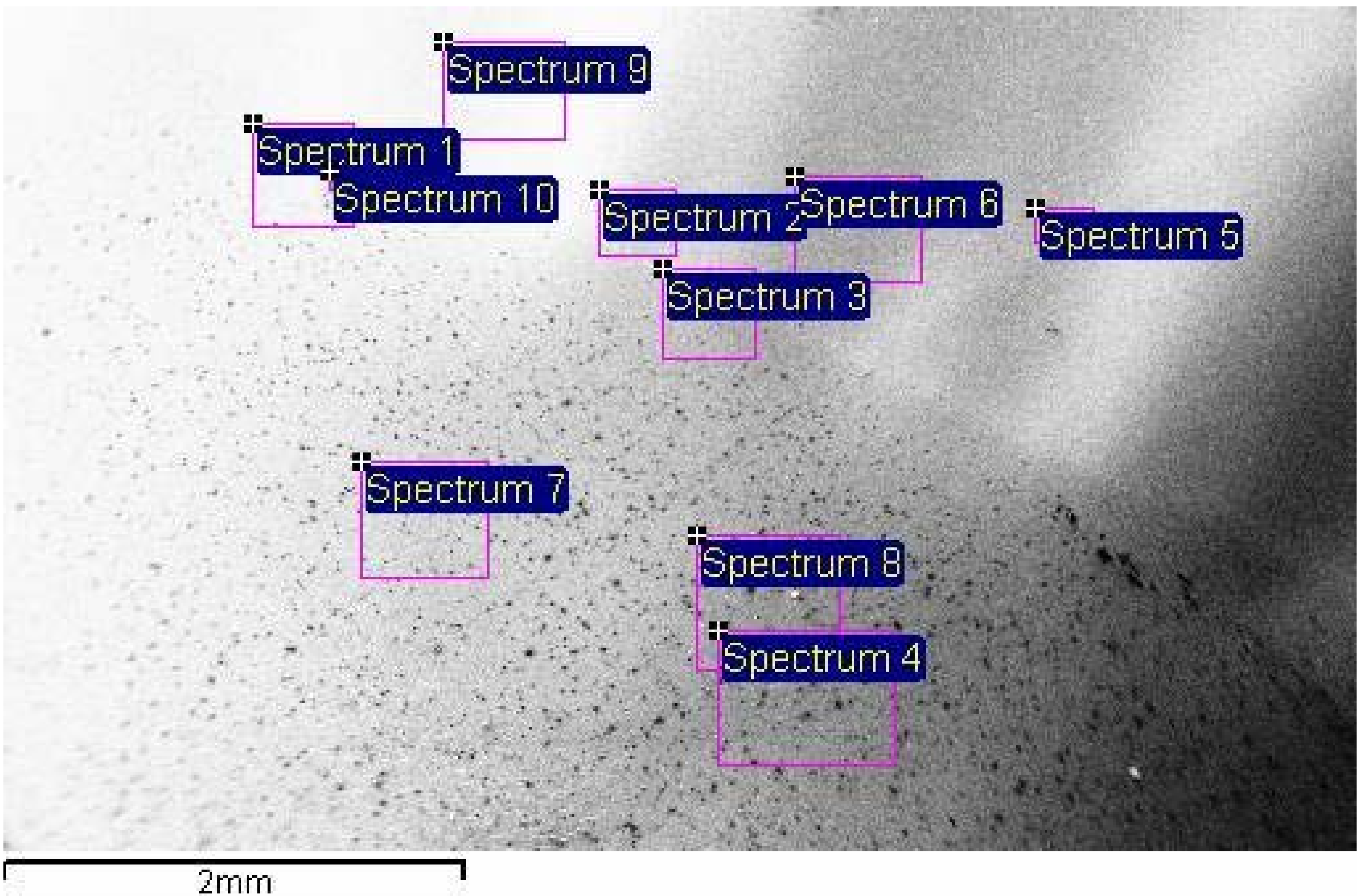
G = 3, i.e. 3 H_2 molecules / 100 eV, i.e. for one 600 keV proton 18000 H_2 molecules,

for 1μA of 600 keV protons: ~ 3×10^{16} H_2 molecules per second,

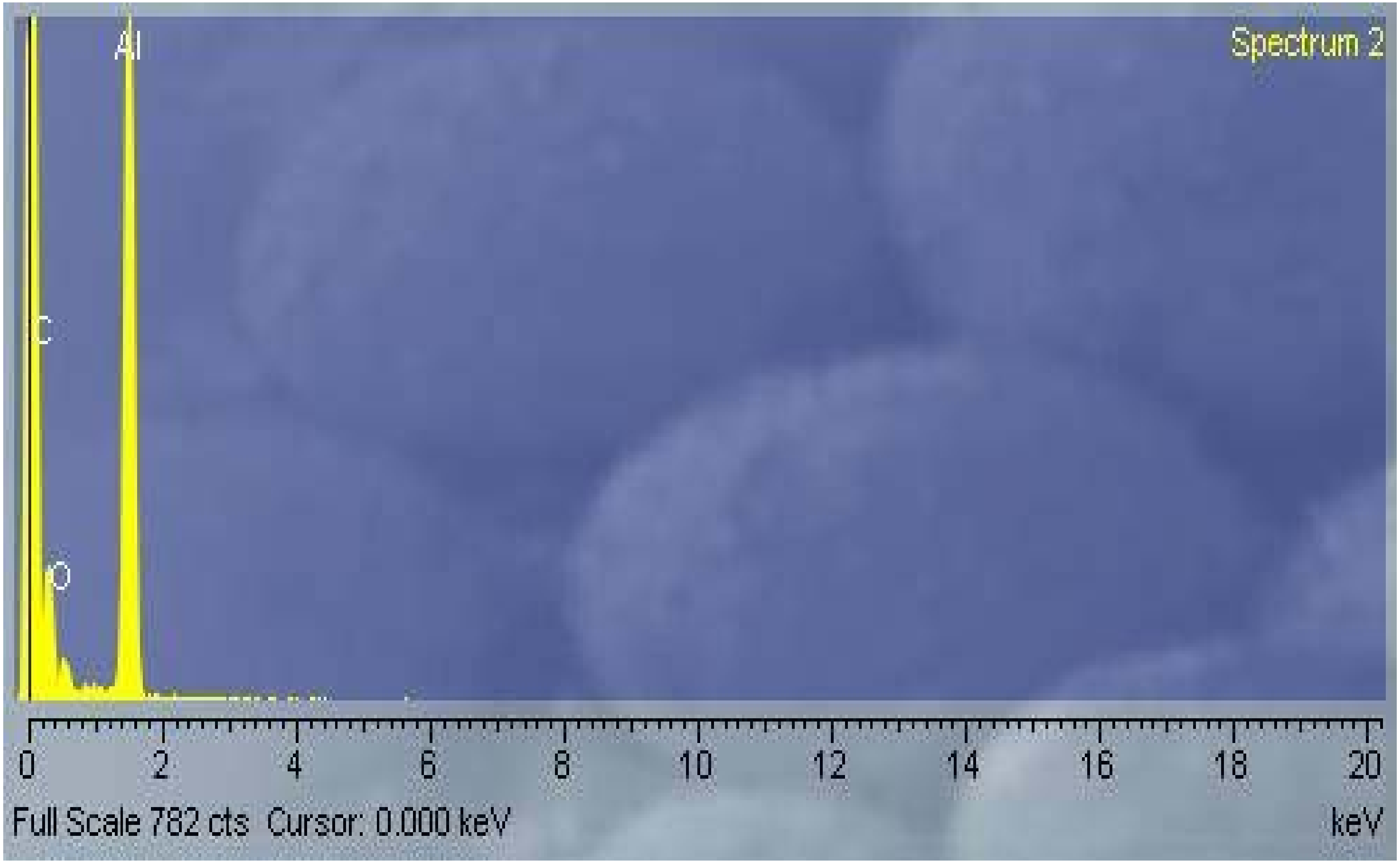
H_2 molecules try to escape through the weakest sites of the foil.

Kapton structure will be destroyed!

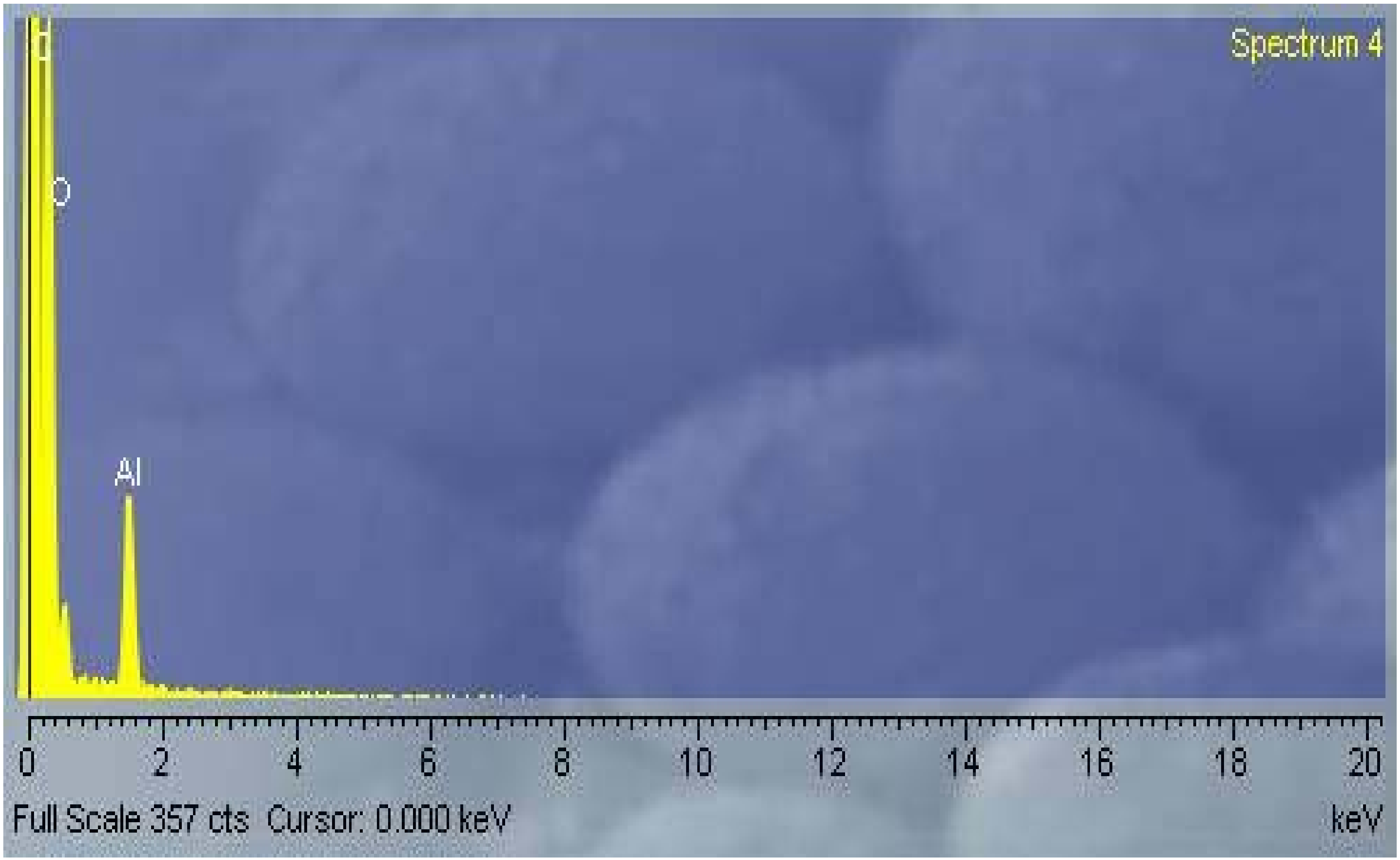
Fringe Area Irradiated/Blank foil, 300 keV, Defocused Beam + Wobbling



Spectrum of Region 2 (Blank Foil): Al Dominates



Spectrum of Region 4 (Irr. Foil): Kapton Constituents Dominates



Conclusions of ND-Experiments

- best choice for uniform irradiation: defocused beam & wobbling
- alternative: wobbling at high frequencies
- stopping power in Kapton: no energies larger than ~ 500 keV necessary
- avoid burn through: intensities < 200 nA/cm^2
- optical properties determined by C, O, and Al chunks of ~ few 100 nm sputtered on the surface

Final Remarks

- we have got some experience to work with KOBE

- sail foil quality suffers from
  - reduced reflectivity
  - destruction of the Kapton substrate (heat release and $H + H \rightarrow H_2$)

- we recommend to deploy any sail only above the outer radiation belt (18000km)

But First of All:

WE NEED A PROJECT WHICH DEMONSTRATES FOR THE FIRST TIME THE FEASIBILITY OF SOLAR SAIL TECHNOLOGY!

We should very actively campaign for the extremely promising solar sail technology!

1st Cosmic Velocity

Velocity which a body must have to move on a circular orbit around the earth.

Condition: centripetal force = gravitational force

$$\frac{mv_1}{r} = G\frac{mM_{\mathrm{Earth}}}{r^2}$$

$$\Rightarrow for\, r = r_{\mathrm{Earth}} : v_1 = \sqrt{\frac{GM_{\mathrm{Earth}}}{r_{\mathrm{Earth}}}} \approx 28400 \mathrm{km/h} = 7.91 \mathrm{km/s}$$

2nd Cosmic Velocity

To remove a body from the Earth's gravitational attraction it has to get so much kinetic energy $E_{kin,2}$, that this energy is ≥ difference between final and initial energy.

In the limit (=): $E_{kin,2}$ = final energy –initial energy

$$E_{\text{kin},2} = 0 - \left(-G\frac{mM_{\text{Earth}}}{r} \right) \Rightarrow \frac{1}{2} m v_2^2 = G\frac{mM_{\text{Earth}}}{r_{\text{Earth}}} \Rightarrow$$

$$v_2 = \sqrt{\frac{2GM_{\text{Earth}}}{r_{\text{Earth}}}} = \sqrt{2}\, v_1 \approx 40300\ \text{km/h} = 11{,}2\ \text{km/s}$$

Maximum Gravitational Caused Velocity

The largest velocity aquired by gravitational acceleration in our solar system is the free-fall velocity of a body at the solar surface.

$$v_{\mathrm{ff}} = \sqrt{\frac{2GM_{\mathrm{sun}}}{R_{\mathrm{sun}}}} \approx 620\,\mathrm{km/s}$$