# Lawbreakers? Emission by superluminal* sources in the laboratory

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*faster than light *in vacuo.*

# Running order

- A brief history of superluminal emission.
- How do we make a practical source? Maxwell's equations.
- The prototype machine; a brief view.
- Some points about superluminal sources: emission from multiple source times *or even an extended period of source time* can arrive simultaneously at an observer!
- The emission cusp and $P \propto 1/r$; how to get around the inverse square law.
- More on the prototype machine: recent experimental data: $1/r$ and diffractionless beams.
- Future prospects.

*Note: No laws of physics were broken (or even harmed)*
*in the making of this production!*

## A brief history of superluminal emission.

- Emission from charged particle with $v > c$ studied by Sommerfeld in 1904.
- Work ignored, as Einstein's Special Relativity, forbidding $v > c$, published a few months later (1905).
- Several authors point out that no superluminal source can be point-like ($E = \infty$ on wavefronts from it).
- Ginzburg, Bykov and Bolotovskii (Soviet Union, 1979-1990); no physical principle forbids *extended*, massless superluminal sources.
- H. Ardavan publishes a model of pulsars based on superluminal emission.
- First practical device built in Oxford (UK) by Ardavan, Ardavan, Fopma, Halliday and Singleton (2002).

The "Lawbreakers?" in the title comes from a report on our being funded (approx. $500K) by the EPSRC (UK) to build the first practical device. This can be read in the *Economist* magazine (1 Sept, 2000). The article commences "You cannot break the laws of physics. But that is exactly what a group of… researchers is trying to do…"

Later in the article, an eminent astronomer refers to the project as "a waste of tax-payers' money!"

As we shall see, no laws of physics are broken by this experiment.

How do we make a superluminal source of electromagnetic radiation without breaking the laws of physics?

A good place to start is Maxwell's equations, which describe the whole of classical electromagnetism.

## Maxwell's equations.

The fundamental equations of electromagnetism, relating the fields **E**, **D**, **H** and **B**:

$$\nabla.\mathbf{D} = \rho_{\mathrm{free}}$$

$$\nabla.\mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J}_{\mathrm{free}} + \frac{\partial \mathbf{D}}{\partial t}$$

Use Maxwell III and IV:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J}_{\text{free}} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t}$$

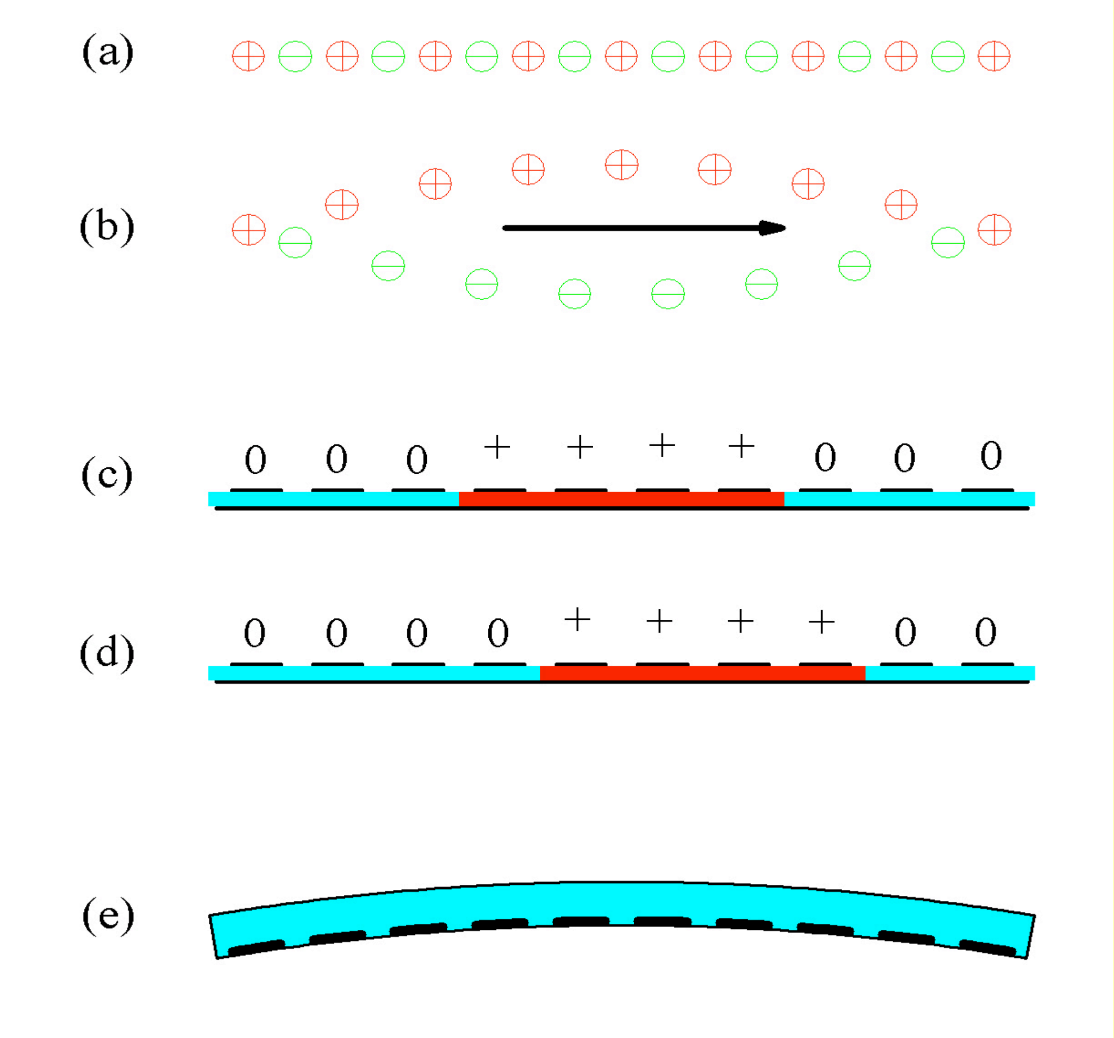
- Green terms describe waves of **E** and **H** that propagate in free space.
- In conventional radio transmitters and synchrotrons, an oscillating or accelerating current $\mathbf{J}_{\text{free}}$ of electrons is used to produce the waves.
- Our machine uses a polarization current $\partial \mathbf{P}/\partial t$ instead.....

To get around the "problem" of Special Relativity, one must use a source without rest mass.

A good choice is a polarization current.

# How do we make a practical superluminal source?

(a) Unpolarized solid containing ions.
(b) Turn on varying *E*-field => region of finite **P** that can be moved along arrow.
(c) Experimental realisation; electrodes above and below a strip of dielectric.
(d) Switch plates on and off; polarized region moves.
(e) Curvature of dielectric gives centripetal accel.

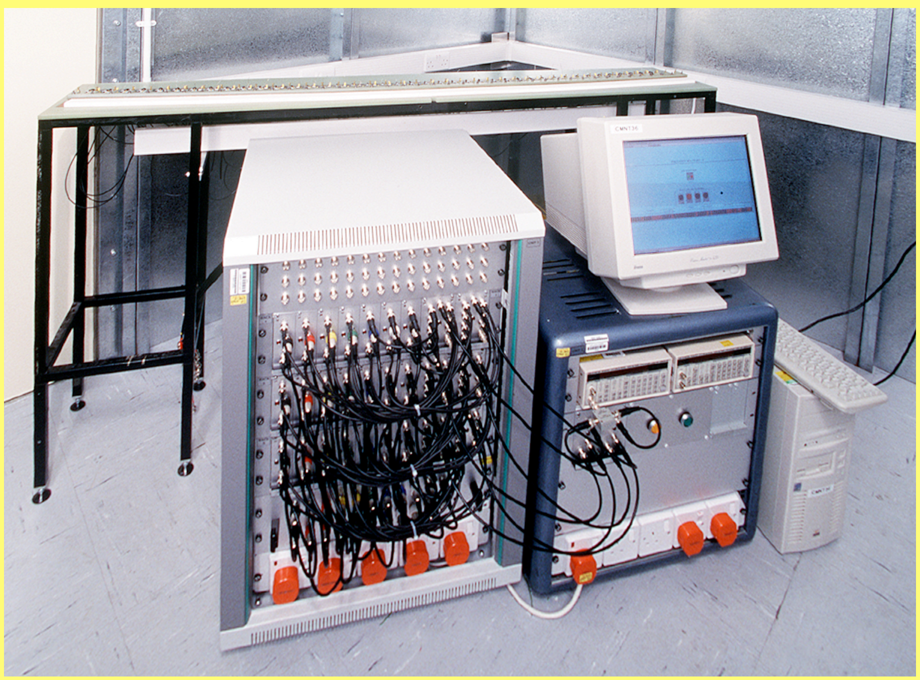


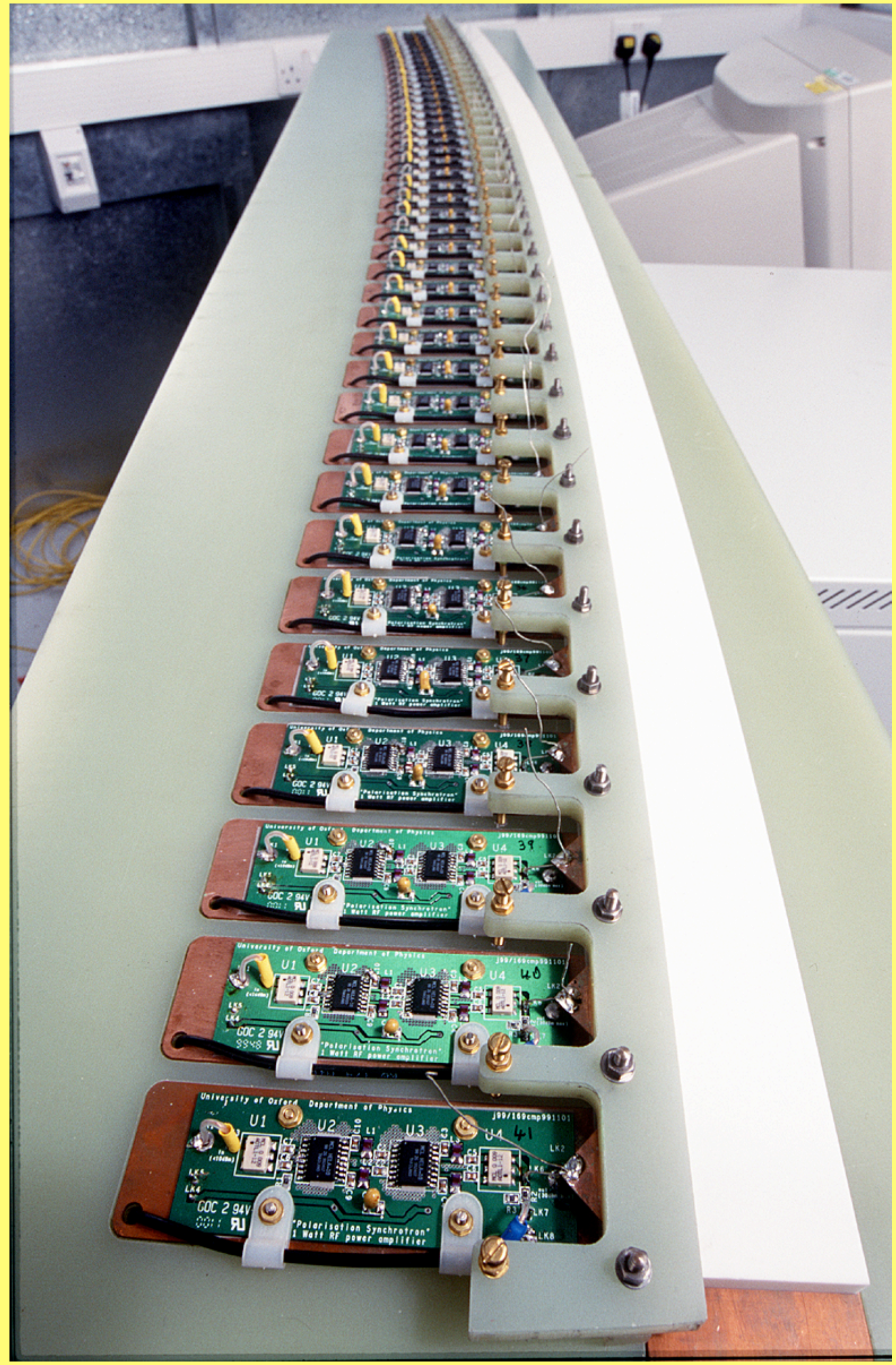
## The practical machine: “the Polarization Synchrotron”

The dielectric is a 10 degree arc of a 10.025 m radius circle of alumina (□ = 10).

There are 41 electrodes, driven by 41 individual amplifiers.

The speed of light is exceeded very easily using frequencies in the MHz range.





There is a very important way in which superluminal sources differ from subluminal ones.

Superluminal sources can make *more than one* contribution to the electromagnetic fields received at an instant by an observer. We show two examples.

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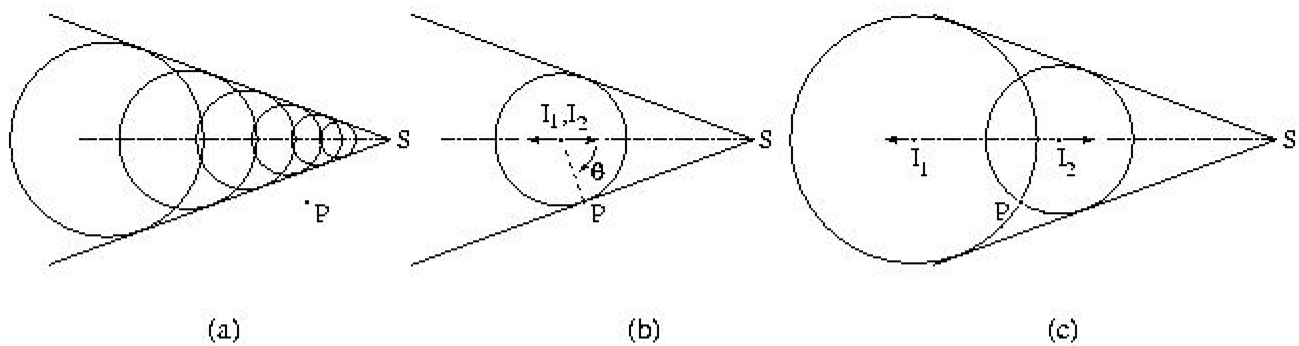
## Example 1: linear motion

**Source time versus reception time; Picard's manoeuvre and multiple images.**

Envelope of spherical wavefronts from superluminal ($v > c$) source



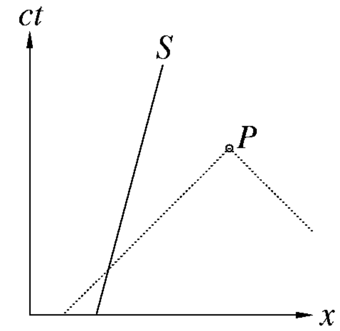

- (a) Nothing observed at P.
- (b) Two coincident images observed at P.
- (c) Two distinct images observed at P.

# To emphasize this point, we use space-time diagrams

An observer is represented at a particular time $t$ and position $x$ by the point $P$. (S)he can observe the source $S$ if its path intersects the light cone of $P$, *i.e.*the lines defined by $dx/dt = \pm c$.

A **subluminal** source ($v < c$) □ makes only one contribution.

A space-time picture:




A point source makes a single instantaneous contribution to the field at space-time point $P$.

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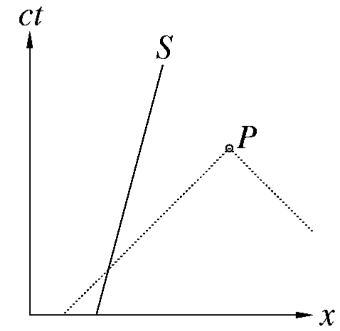
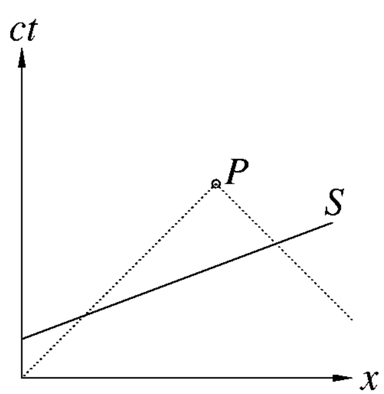



A point source makes a single instantaneous contribution to the field at space-time point $P$.

In a space-time diagram, the source crosses the light-cone of $P$ twice:

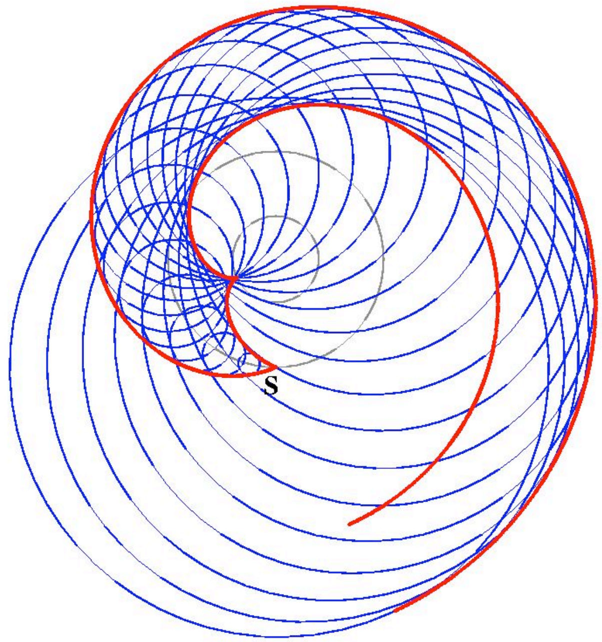



However, a **superluminal** □ source has a shallower trajectory on the space-time diagram ($v > c$).
It crosses the light cone twice, *i.e.* it makes two contributions to the field at $x,t$.

We have seen that a superluminal source moving in a straight line contributes *twice* to the electromagnetic fields received at an instant by an observer.

Now consider a superluminal source moving on a *circular* path; this is like a pulsar or our experimental machine. We shall see that this can contribute $2n+1$ times to the fields reaching an observer.

## Example 2: circular motion




- Spherical wavelets from rotating source.
- Cross-section of envelope in orbit plane.
- Orbit and light cylinder ($r = c/\omega$).

Source: $r = \text{const}, \quad z = \text{const.}, \quad \varphi = \hat{\varphi} + \omega t$

Observer: $r_{\mathrm{P}},\ z_{\mathrm{P}},\ \varphi_{\mathrm{P}}$

Separation, source to observer:

$$R(t) = [(z_P - z)^2 + {r_P}^2 + r^2 - 2 r_P r \cos(\varphi_P - \hat{\varphi} - \omega t)]^{\frac{1}{2}}$$

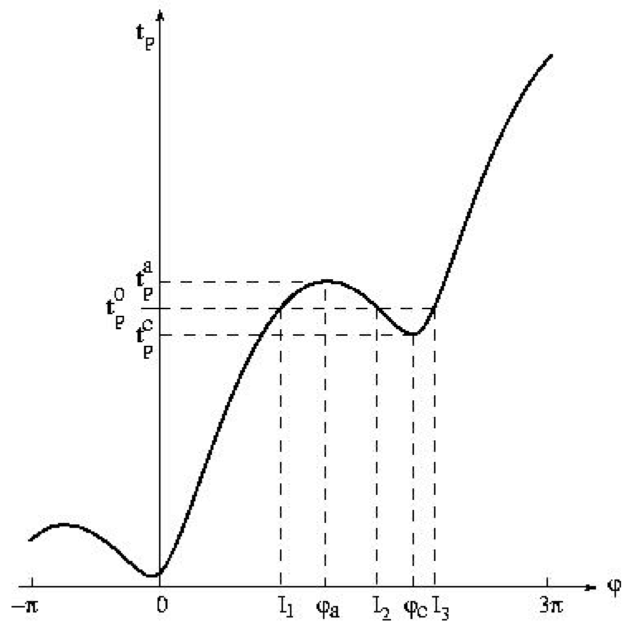
# Multiple images from a rotating superluminal source.

There are three ways of showing that a superluminal source on circular path contributes $2n+1$ times to the fields reaching an observer.

Method 1: consider the time that it takes light to get from the source to the observer.

## Observation and emission times.

Obs. time $t_{\rm P}$ = source $t + {\rm dist}/c = t + R_{\rm P}/c =$
$t+[(z_P-z)^2+{r_P}^2+r^2-2r_P r\cos(\varphi_P-\hat{\varphi}-\omega t)]^{\frac{1}{2}}/c$



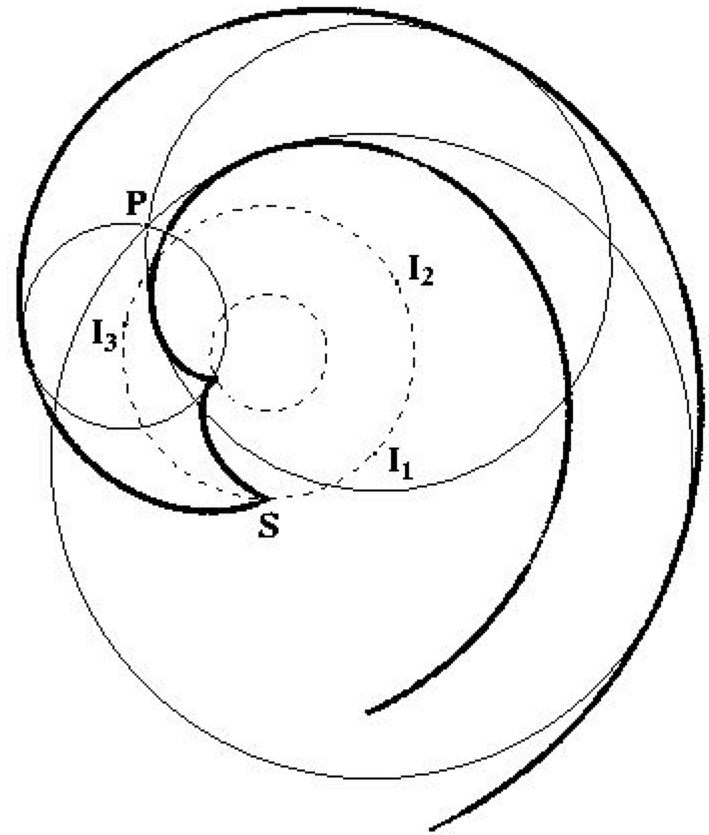

Obs. time versus azimuthal position of S; source at $r = 2c/\omega$; obs. at $r_{\rm P} = 3c/\omega$.

- Three images at time $t_{\rm P}^0$ ($t_{\rm P}^{\rm c} \leq t_{\rm P}^0 \leq t_{\rm P}^{\rm a}$);
- $I_2$ and $I_3$ created at $\varphi_{\rm c}, t_{\rm P}^{\rm c}$
- $I_1$ and $I_2$ annihilated at $\varphi_{\rm a}, t_{\rm P}^{\rm a}$
- Only one image seen at other times

# Multiple images from a rotating superluminal source.

Method 2: consider the Huyghens wavelets emitted by the source at various times. At the instant depicted in the picture, three reach the observer at P, who sees images of S at $I_1$ , $I_2$ and $I_3$.

The images represent three separate emission times in the source's frame of reference.

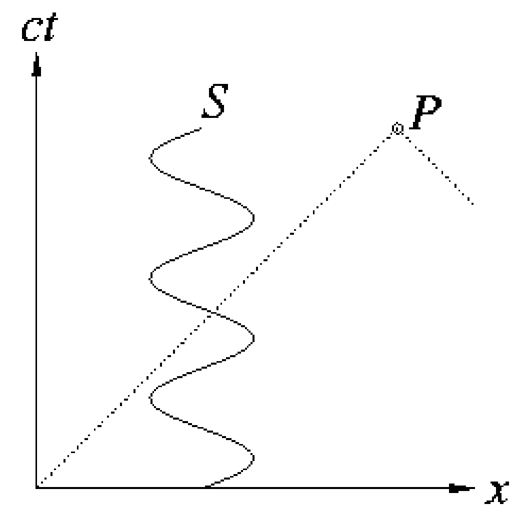



- Observer at P sees three images of S.
- Images lie on trajectory of S.

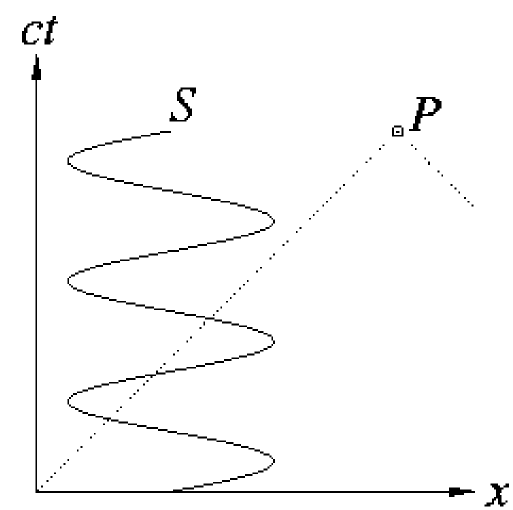
## Multiple images from a rotating superluminal source.

<u>Method 3</u>: use space-time diagrams. If the source rotates in the *xy* plane, the projection of its motion on the *x* direction is sinusoidal.

Depending on the speed of the source, the time *t* and P's position *x,* the observer at P sees one image =====>




or three images. ===============>



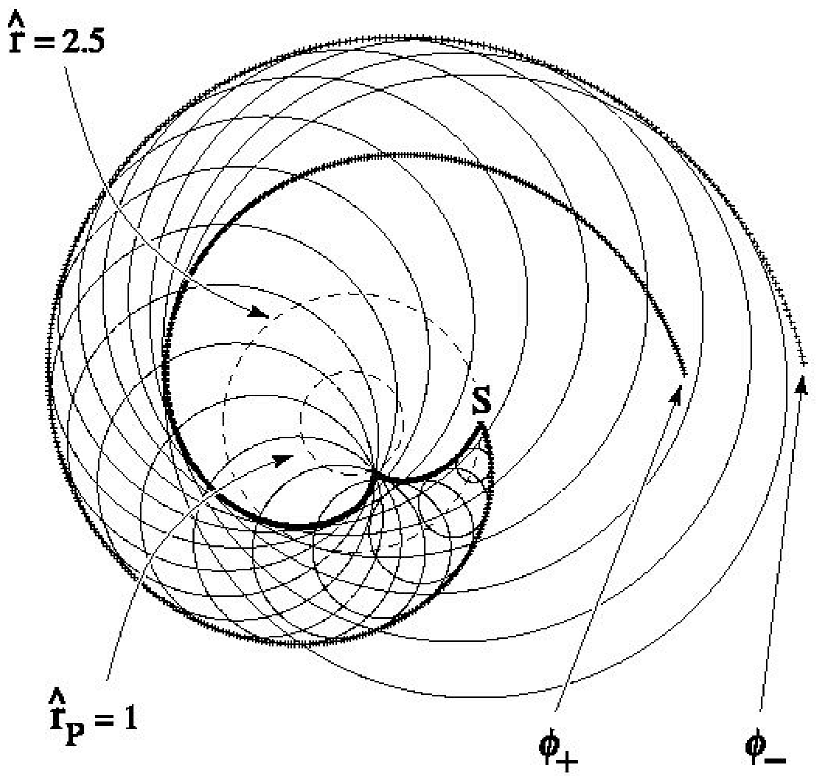

If the source speed is high enough, there will be $(2n+1)$ images.

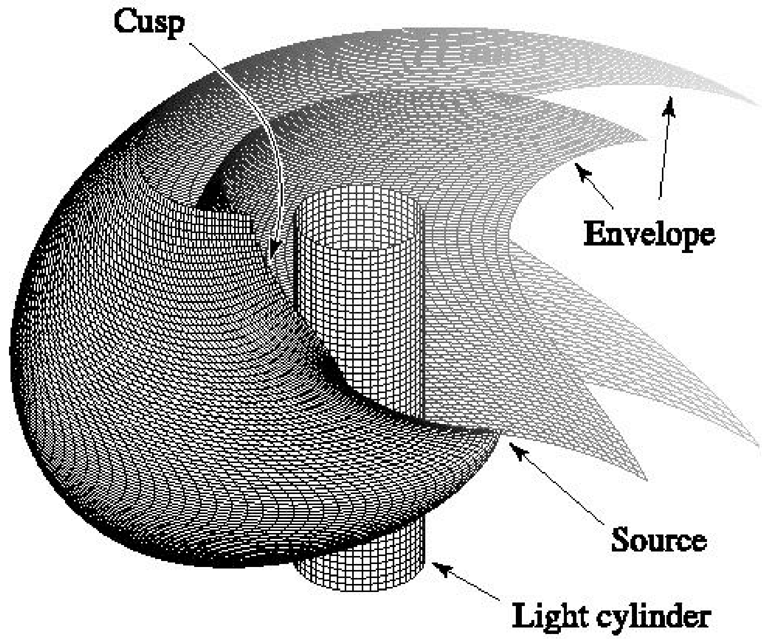
# Multiple images from pulsars

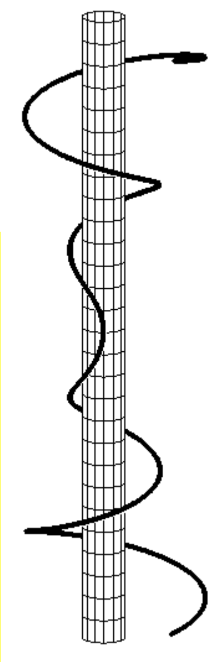
- Sallmen et al. (1999)
- Backer et al. (2000)
- Graham-Smith et al. (2000)
- Moffett et al. (1999)
- Corder and Wolszczam (1986,1987)

e.g. Crab Pulsar: 3 closely-spaced images whose splitting is frequency-independent over *five orders of magnitude* of frequency; "A multiplicity of components is intrinsic to emission from pulsars..." (Sallman).

# The cusp- a unique property of an accelerated source that travels faster than its emitted waves



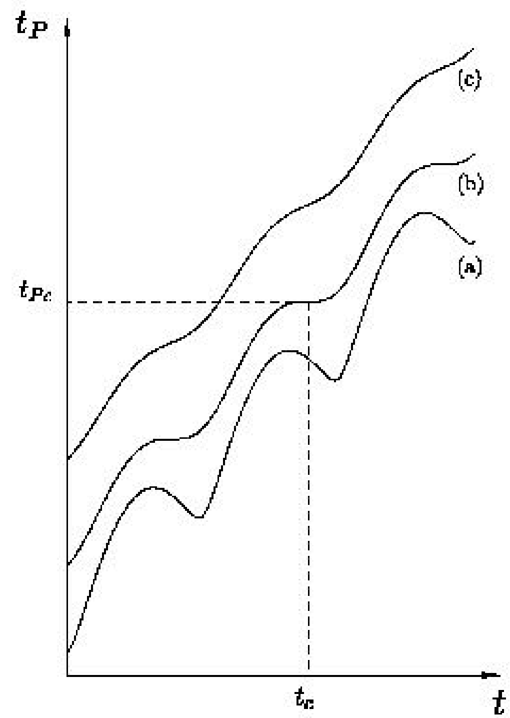



The envelope of the spherical wavefronts from the source has two sheets that meet in a *cusp.* In the plane of the source's rotation, this touches the light cylinder (above left); it spirals away from the rotation axis above and below the plane (above right). Its locus looks something like an old-fashioned bedspring.=>

# Why is the cusp important?

Obs. time $t_P$ vs. emis. time $t$ for an obs. point that lies (a) inside or on, (b) on the cusp of, and (c) outside the envelope of the wave fronts.




The cusp is the locus of source points which approach the observer at $c$ *and* with zero acceleration along the radiation direction.

There are two important points.

On the cusp (b), the observer receives radiation in a very short time period that was emitted *over a considerably longer period of source time.* => There is a concentration of energy on the cusp.

The cusp is due to source points approaching the observer at *c* and at zero acceleration => on the cusp, *the source is effectively coherent.*

# The cusp for a volume source

Thus far, we have been discussing the emission of a single volume element of a superluminal source.

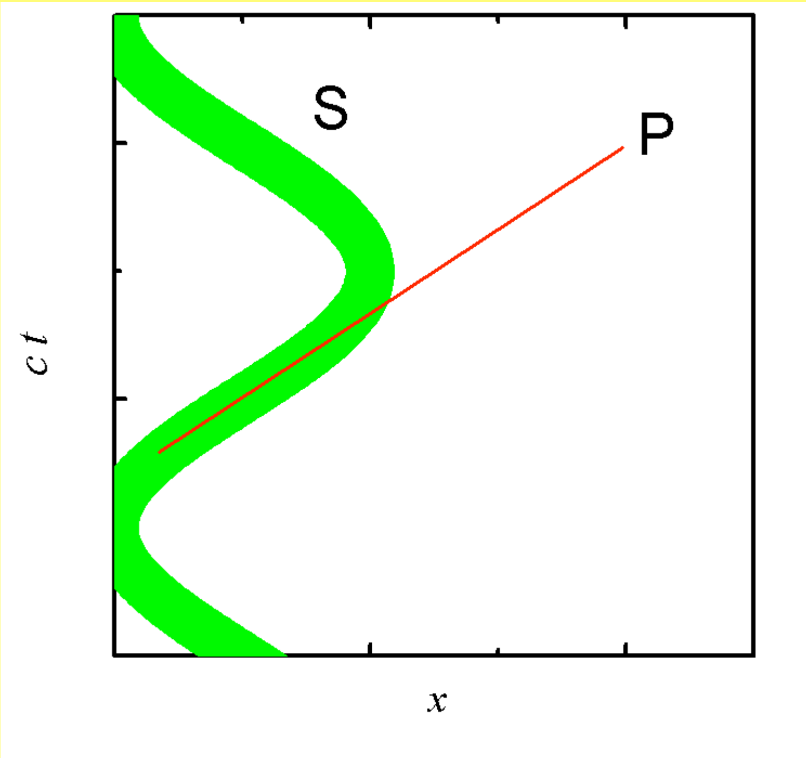
But our experimental machine is a *volume (extended) source.*

In the case of the cusps from the elements of an *extended* source, a *volume* of source space-time can contribute to the instantaneous signal at P. =================>

The contribution corresponds to a region of the source that approaches P at *c* and with zero acceleration.

The *oscillation* inherent in the synthesis of the source results in a contribution from this region that will be effectively *coherent.*

Space-time diagram for P on the cusps of a volume source



# Solving for the radiation on the cusp

Liénard-Wiechert fields are divergent:
=> use Hadamard's regularization technique (i.e. reverse the order of differentiation and integration): singularity in Liénard-Wiechert potentials is integrable.

Asymptotic expansion of Green's functions in time domain, followed by evaluation of Hadamard's finite part of the integral representing the radiation field. See J. Optical Soc. Of America A **21**, 858 (2004). =>

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**Spectral and polarization characteristics of the nonspherically decaying radiation generated by polarization currents with superluminally rotating distribution patterns**

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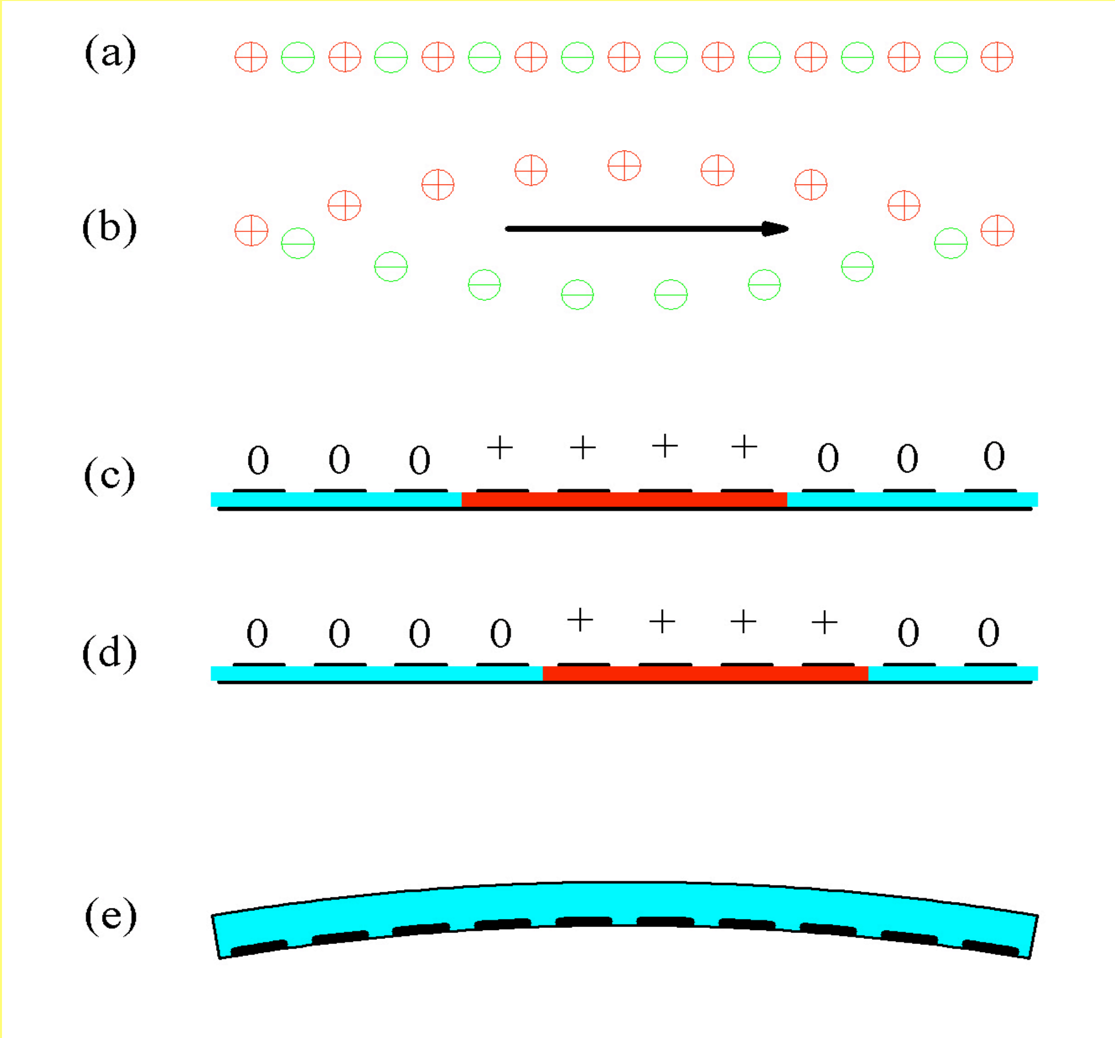
Final result: =>
E-field of radiation varies as $1/R_{-}$,
i.e. the power varies as $1/R$.
(c.f. conventional transmitters: power varies as $1/R^2$.)

$$\mathbf{E}^{\rm ns} \sim \tfrac{4}{3}(2\pi)^{\frac{1}{2}}\hat{R}_P^{-\frac{1}{2}}|\sin 2\theta_P|^{-1}\exp(\mathrm{i}\Omega\varphi_C/\omega)\times \sum_{\mu=\mu_\pm}|\mu|^{\frac{1}{2}}\,\mathrm{sgn}(\mu)\exp(\mathrm{i}\tfrac{\pi}{4}\,\mathrm{sgn}\,\mu)$$
$$\times\exp[-\mathrm{i}\mu(\hat{R}_P-\omega t_P+\varphi_C)]\{(\mathrm{i}\bar{s}_\varphi+\Omega\bar{s}_r/\omega)\hat{\mathbf{e}}_\parallel$$
$$-[(\mathrm{i}\bar{s}_r-\Omega\bar{s}_\varphi/\omega)\cos\theta_P+\Omega\bar{s}_z\sin\theta_P/\omega]\hat{\mathbf{e}}_\perp\} \qquad (57)$$

# Back to the experimental machine; a reminder of how it works

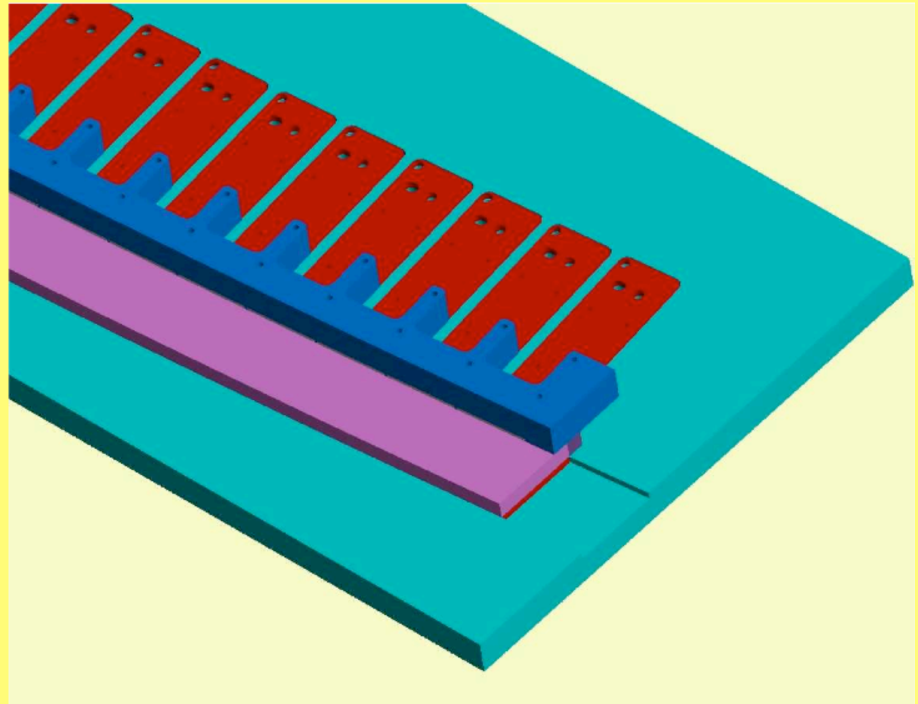
(a) Unpolarized solid containing ions.
(b) Turn on varying *E*-field => region of finite **P** that can be moved along arrow.
(c) Experimental realisation; electrodes above and below a strip of dielectric.
(d) Switch plates on and off; polarized region moves.
(e) Curvature of dielectric gives centripetal accel.



# A practical superluminal source

Experimental machine is a 10° arc of an $a$ = 10.025 m radius circle of alumina (□≈10), 5 mm across and 10 mm thick.

41 electrodes, mean width 42.6 mm, centre separation 44.6 mm covering the inner 10 mm of the alumina.



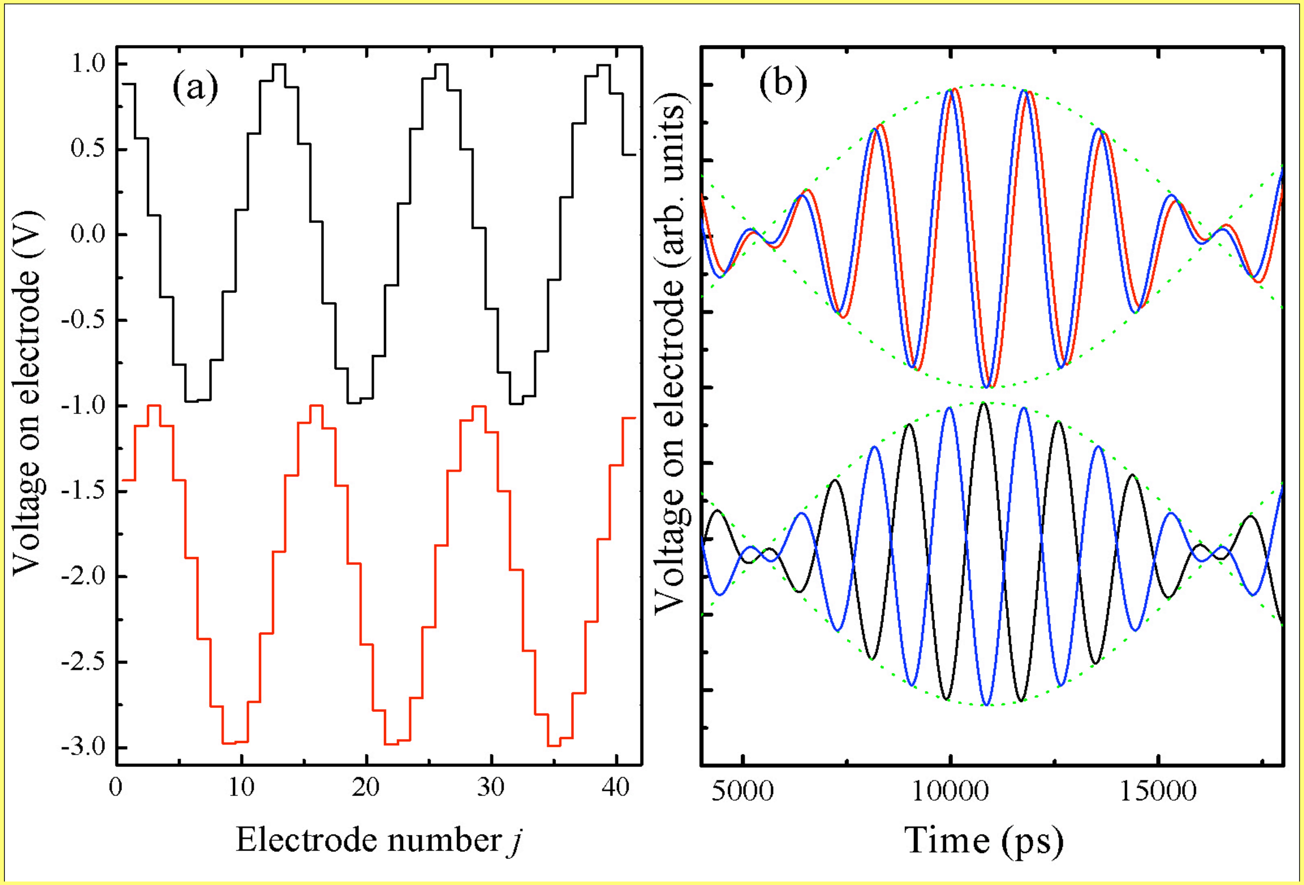
*To animate the polarization current, apply voltages to the electrodes:*

$j^{th}$ electrode voltage: $V_j = V_0 \cos[□(j□t\text{-}t)] \cos □ t$

Speed $v = a□□/□t$ ; $v > c$ achieved for $□t$ < 149 ps

# Animating the polarization current

Voltage on each electrode at times t = 0 and t = 420 ps (offset for clarity). Note that the cos □ $t$ term hardly changes in this time.




Comparison of voltages for $j = 20$ and $j = 21$.

Comparison of voltages for $j = 20$ and $j = 26$.

$j^{th}$ electrode: $V_j = V_0 \cos[\square(j\square t\text{-}t)] \cos \square t$

First term => propagation [see (a)]; speed set using □$t$ [see (b)].

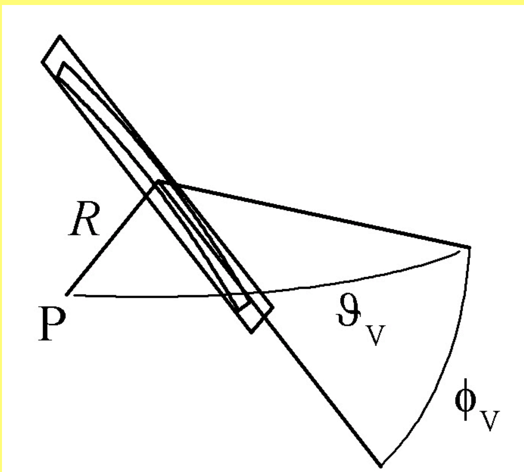
Second term = modulation of all electrodes [(b); dotted line].

Emission at two frequencies $f_{\pm} = |\square \pm \square|/2\square$.

# Experimental geometry

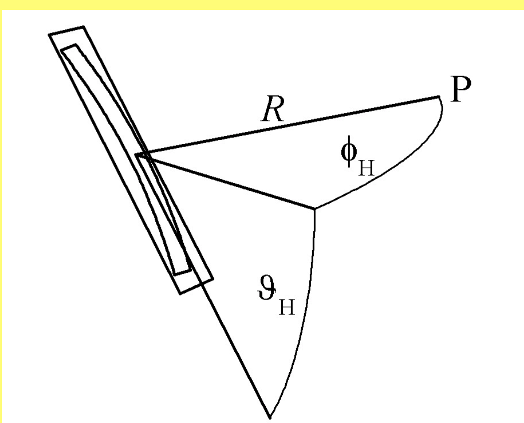
It is necessary to map out the 3D angular distribution of the radiation emitted by the array. The array is mounted on a pivot allowing it to be raised. This is on a turntable, for rotation. The whole assembly is on a scissor lift.

The detector (P) is at a distance *R* away from the array, which can be mounted in two ways:




(V) array on its side; turntable varies angle $\square_V$ , pivot varies angle $\square_V$

and




(H) array initially horizontal; turntable varies angle $\square_H$, pivot varies angle $\square_H$ .

Experiments are carried out on an active airfield (Turweston Aerodrome, near Brackley, Northants); this provides 900 m of well-characterized surface (the runway) over which to do experiments.
Measurements are performed at night to avoid aircraft; the detector (dipole aerial plus spectrum analyser) is moved to various distances along the runway centre.

# Interference from the ground

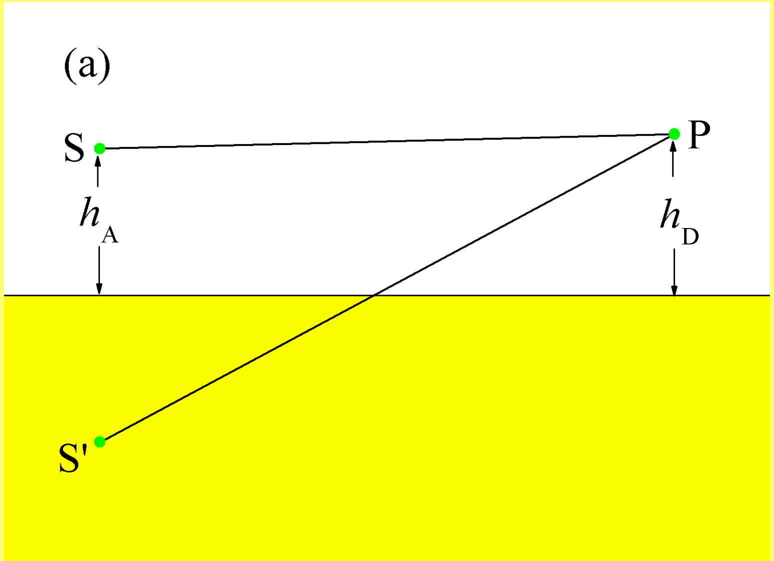
We deal not just with the real source S, but also with its image S’ (a).

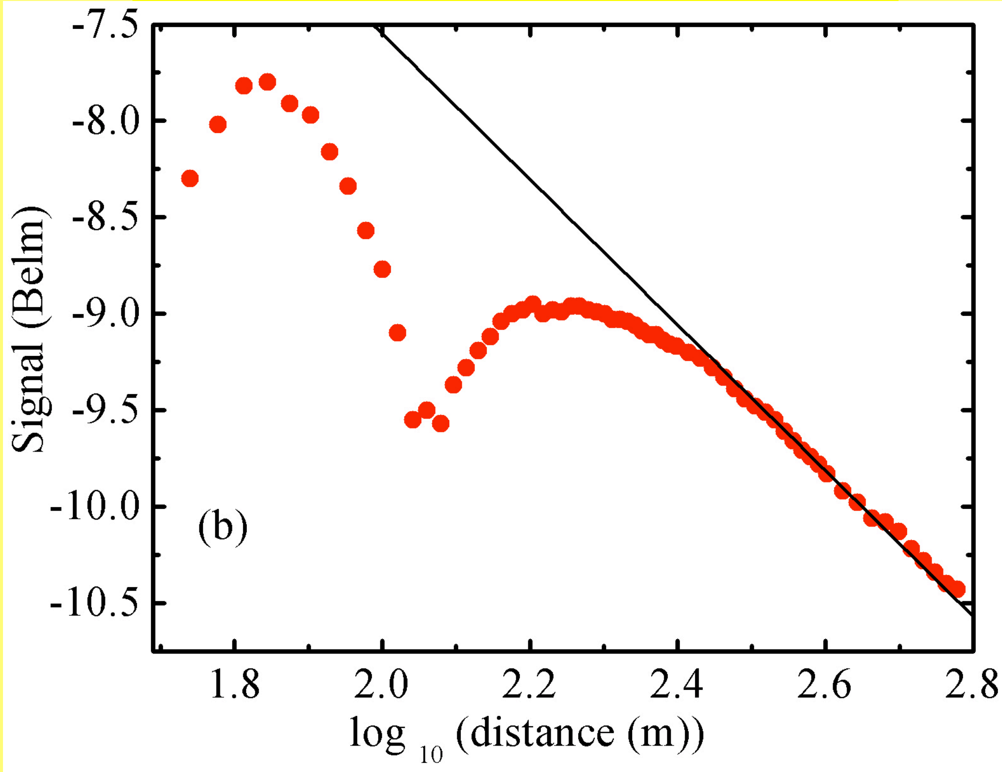
Even with a dipole aerial (b), we get

- fringes
- long distance variation

$P \propto 1/R^{4}$ (!)

The latter is well known to radio engineers as the “Egli” path loss.



# The theoretical model used to fit the data

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## Frequency spectrum of focused broadband pulses of electromagnetic radiation generated by polarization currents with superluminally rotating distribution patterns

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## Spectral and polarization characteristics of the nonspherically decaying radiation generated by polarization currents with superluminally rotating distribution patterns



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## Experimental demonstration of a new radiation mechanism: emission by an oscillating, accelerated, superluminal polarization current

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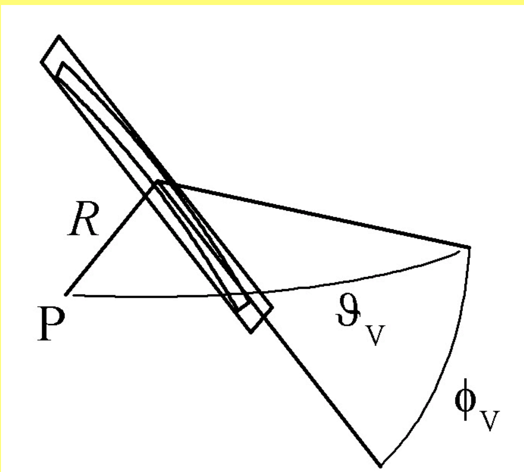
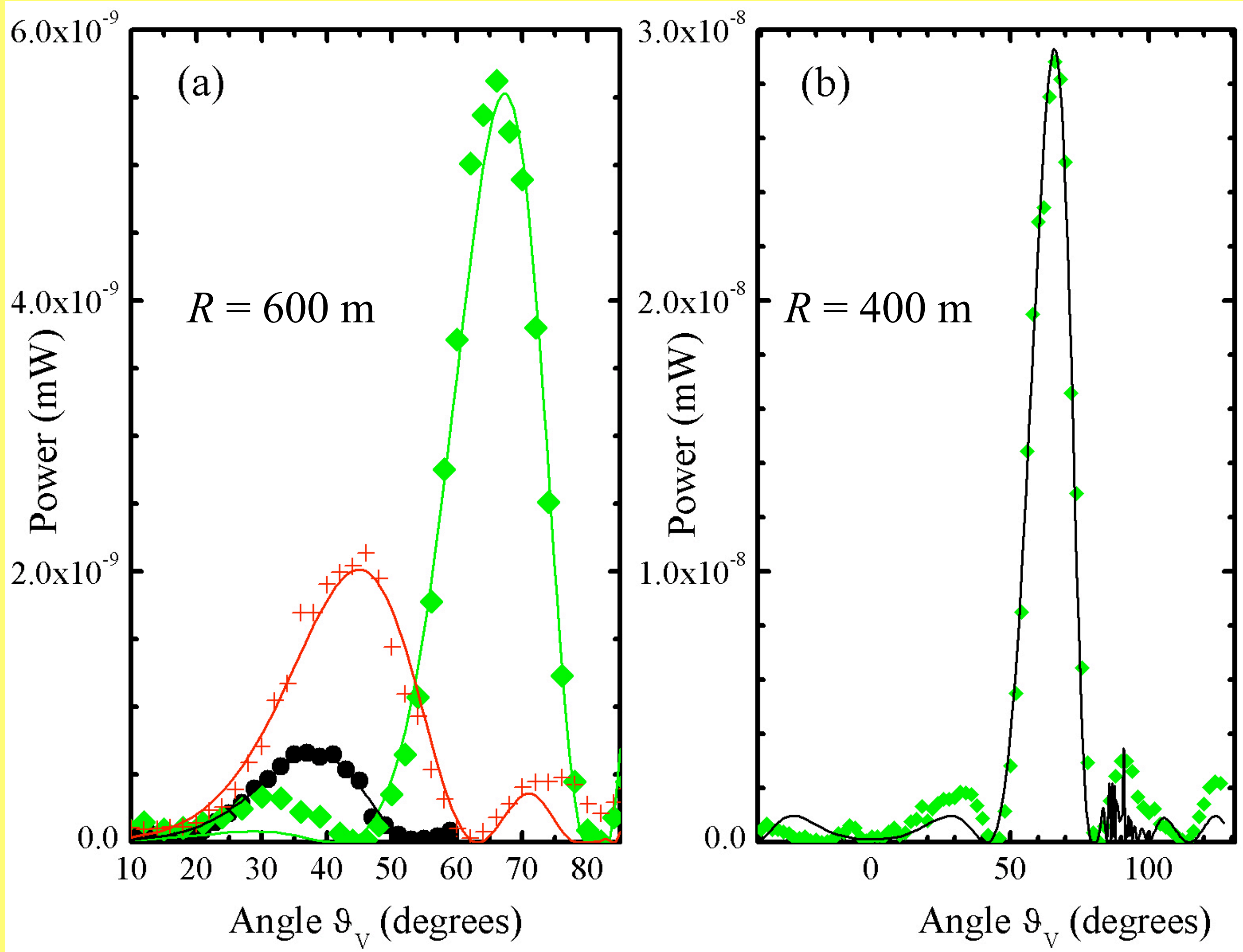
The theory of accelerated, oscillating, superluminal sources is given in the first two articles (J. Optical Soc. Of America A **20**, 2137 (2003), and A **21**, 858 (2004)).
The inclusion of interference from the ground is given in the third (experimental) paper (arXiv:physics/0405062 - submitted to J. Applied Physics).
There are essentially no adjustable parameters in the model fits following.

# Does it work? Yes!

Beaming tests with the array plane vertical.



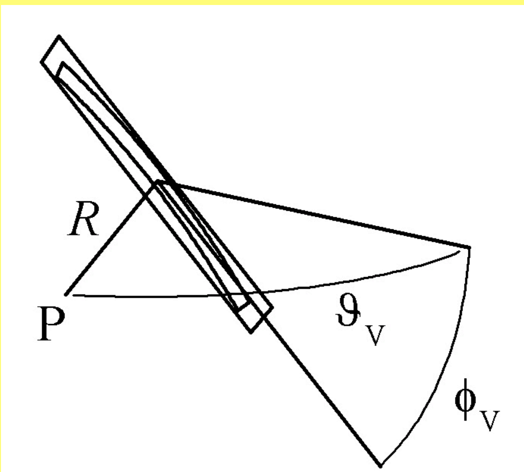

Expect Çerenkov-like emission peaked at □$_V$ = arcsin{$R/R_P$ [1-$(mc/nv)^2$]–} with $n$ = 2□$f$/□ ; $m$ = □/□. Data are for □/ 2□ = 552.654 MHz, □ / 2□ = 46.042 MHz and $f$ = |□ +□|/ 2□ : speed $v/c$ = 1.06 (dots), 1.25 (crosses), 2.00 (diamonds).

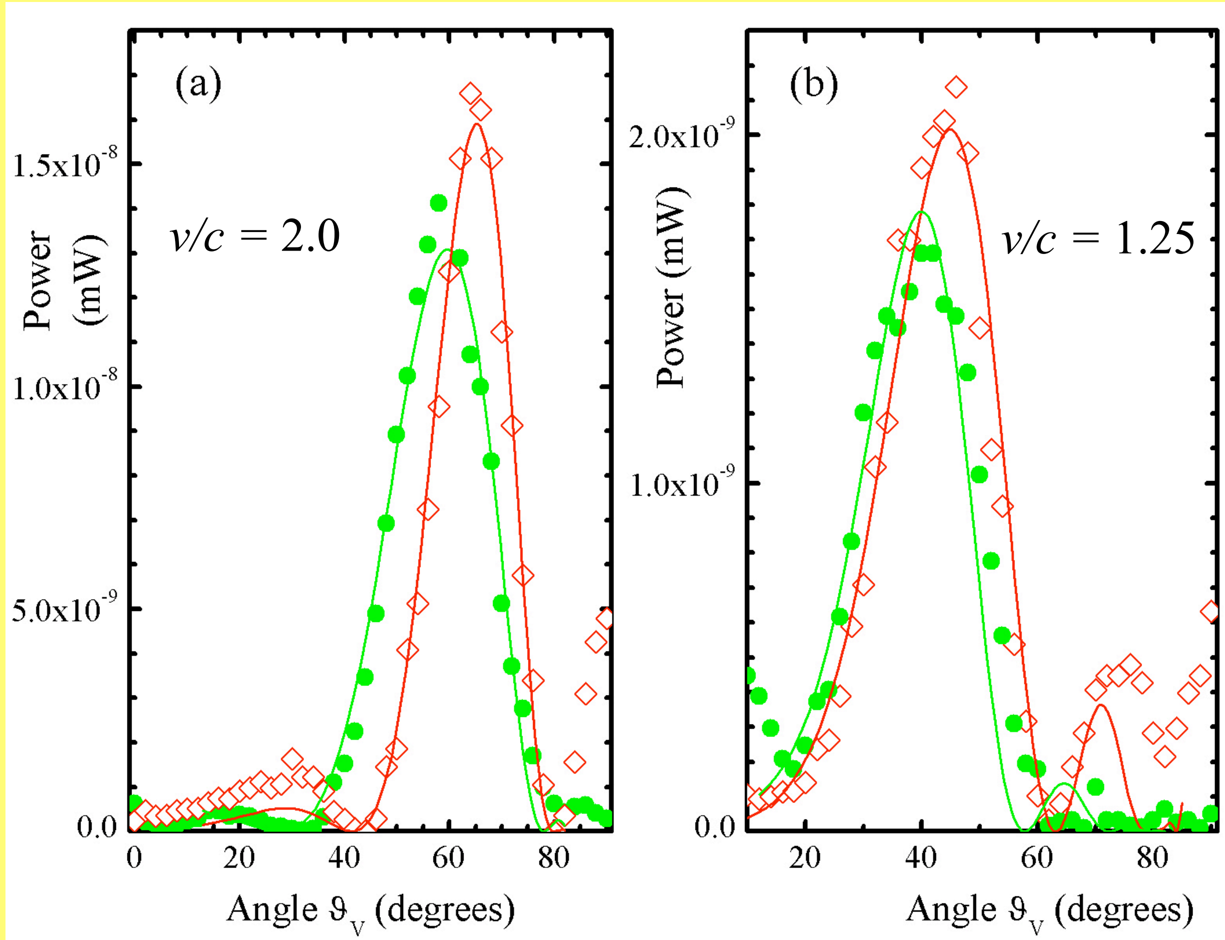
Emission moves to higher angles as $v$ increases. *Curves are model with source speed as input.*

Note narrow beam, even though the measurement is at several 100 hundred Fresnel distances.

# Does it work?
# Yes (II)!

Beaming tests with the array plane vertical: the effect of frequency.



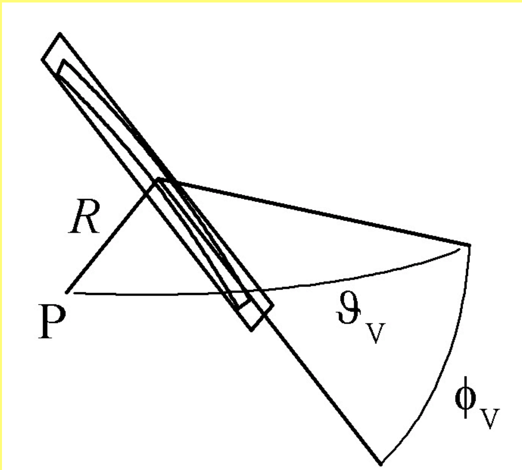




Expect Çerenkov-like emission peaked at $□_V$ = arcsin{$R/R_P$ [1-$(mc/nv)^2$]$^{-}$} with $n = 2□f/□$ ; $m = □/□$. Data are for $□$/ 2□ = 552.654 MHz, □ / 2□ = 46.042 MHz;

$f_+$ = |□+□| 2□ (red) and $f_-$ = |□ - □|/2□ (green); $R$ = 600 m.

Emission moves to higher angles as *n* increases. *Curves are model with source speed as input.*

# Narrow beams are preserved well out into the far-field




Frequencies: □/ 2□ = 552.654 MHz,

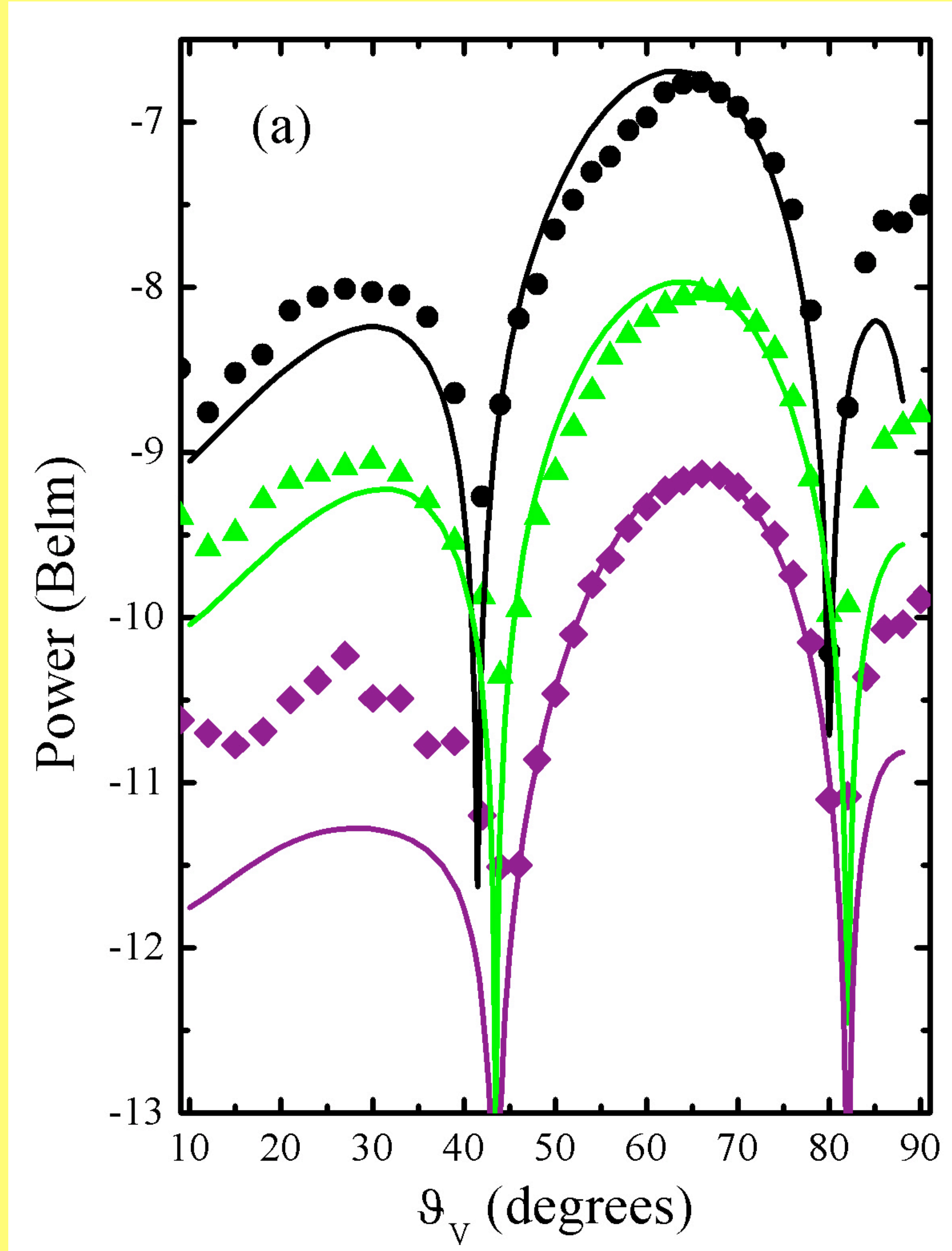
□/ 2□ = 46.042 MHz;

*f* = |□+□| / 2□, speed *v*/*c* = 2.0.

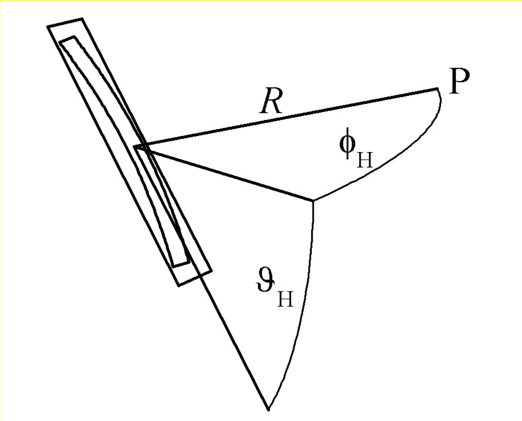
Data are shown for *R* = 200 m, 500 m, and 900 m (points); curves are model predictions.

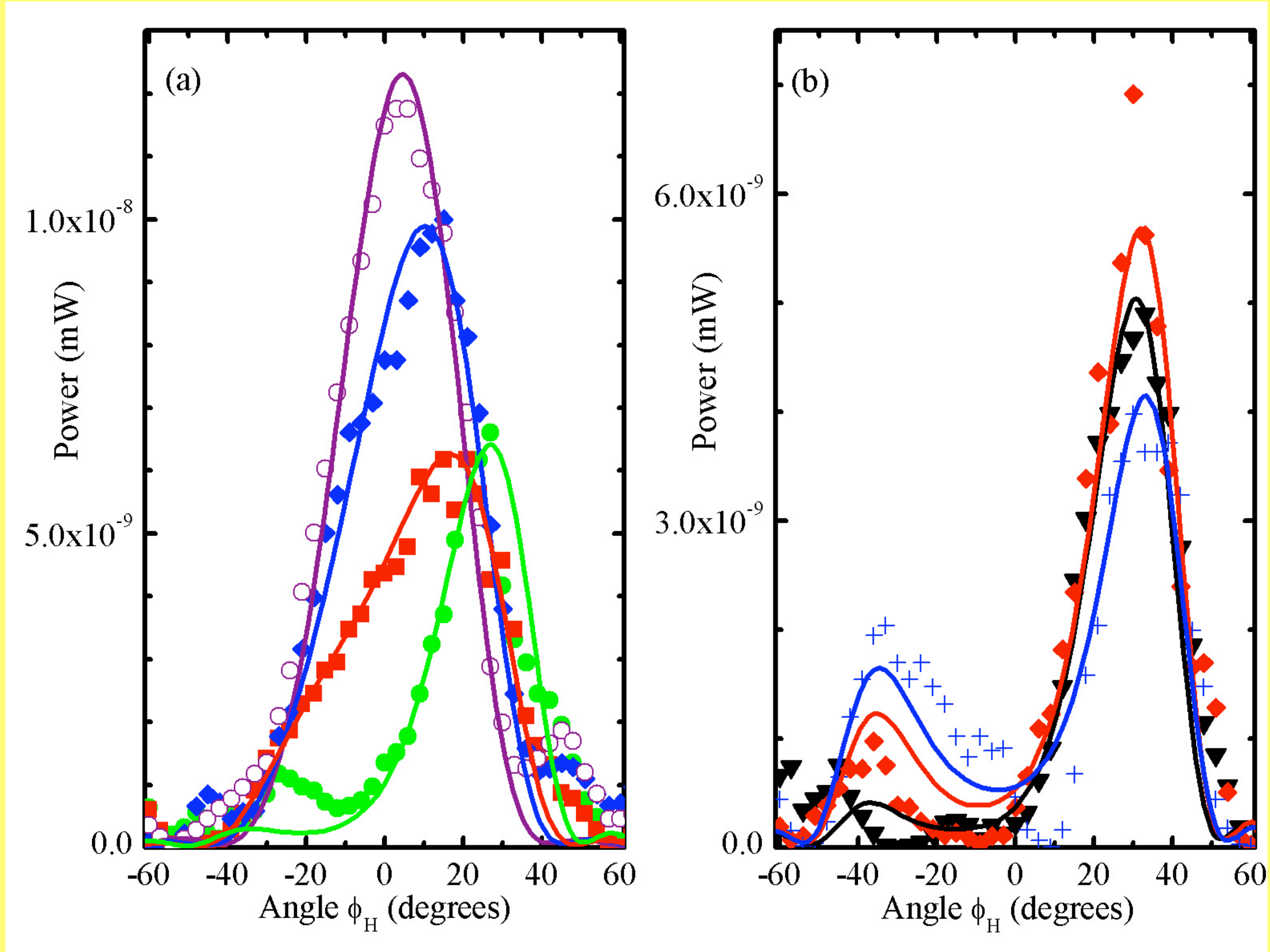
Note nicely defined beam, even at several hundred Fresnel distances.

A conventional antenna would have to be many times larger to provide such tight beams.



# Beaming in the orthogonal plane




Frequencies:
$\omega / 2\pi$ = 552.654 MHz,
$\Omega / 2\pi$ = 46.042 MHz;
$f = |\omega + \Omega| / 2\pi$,
speed $v/c$ = 1.06.

Data are shown at $R$ = 400 m for $\vartheta_H$ = 40 (circles), 35 (diamonds), 30 (squares), 25 (dots), 20 (triangles), 15 (red diamonds) and 10 degrees (crosses). The curves are model predictions.

The beam is well defined in both planes of rotation, even at hundreds of Fresnel distances.

A conventional antenna would have to be many times larger to provide such tight beams.

# Locating the cusp

Parameters:
□/ 2□ = 552.654 MHz, □ / 2□ = 46.042 MHz;
*f* = |□+□| / 2□. Data are shown for □ = 20° and □ = -5°, close to predicted cusp direction.

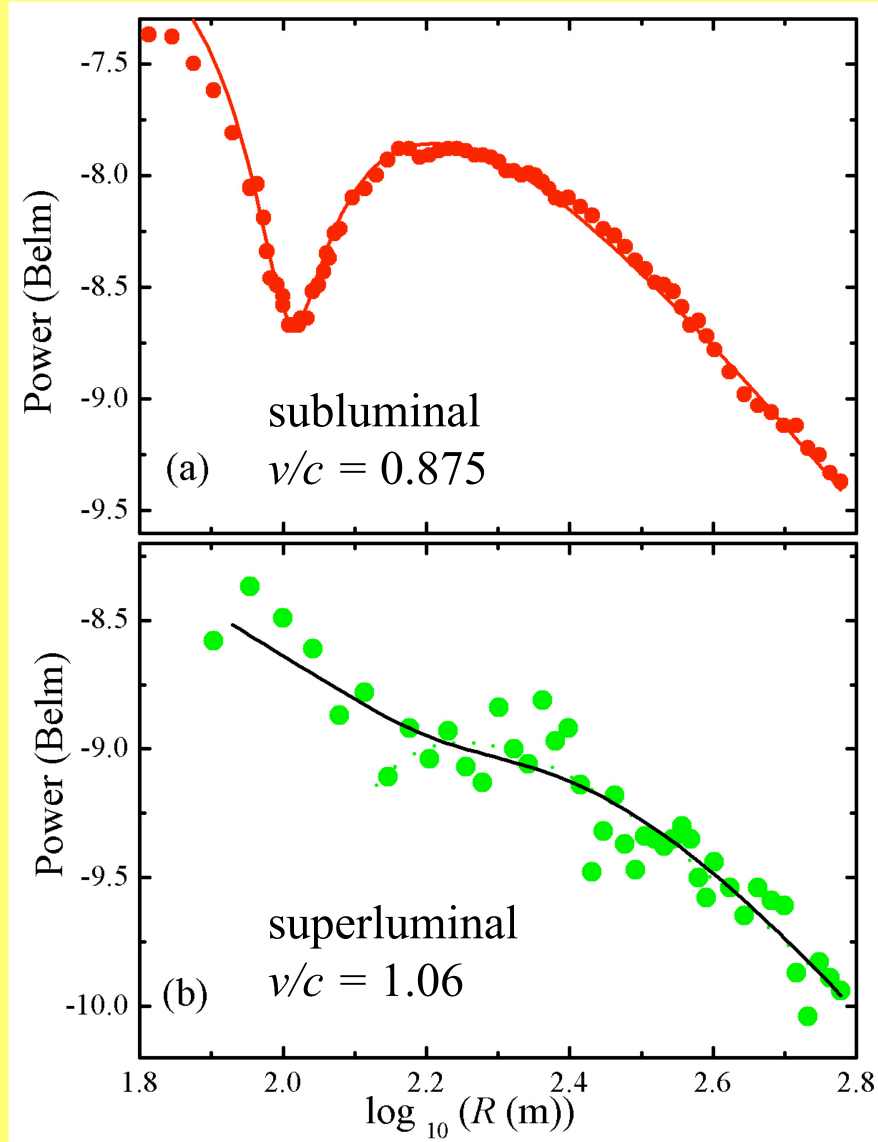
Subluminal experiment looks entirely conventional (c.f. dipole shown earlier).

For superluminal case, note:

- Scatter, c.f. laser speckle (coherent source);
- slow decrease of power with *R*;
- absence of fringes => tight beam.

In (a), model assumes power varies as $1/R^2$;
in (b), model assumes power varies as $1/R$.

*The fit to (b) is in good agreement with theoretical expectations for the cusp.*

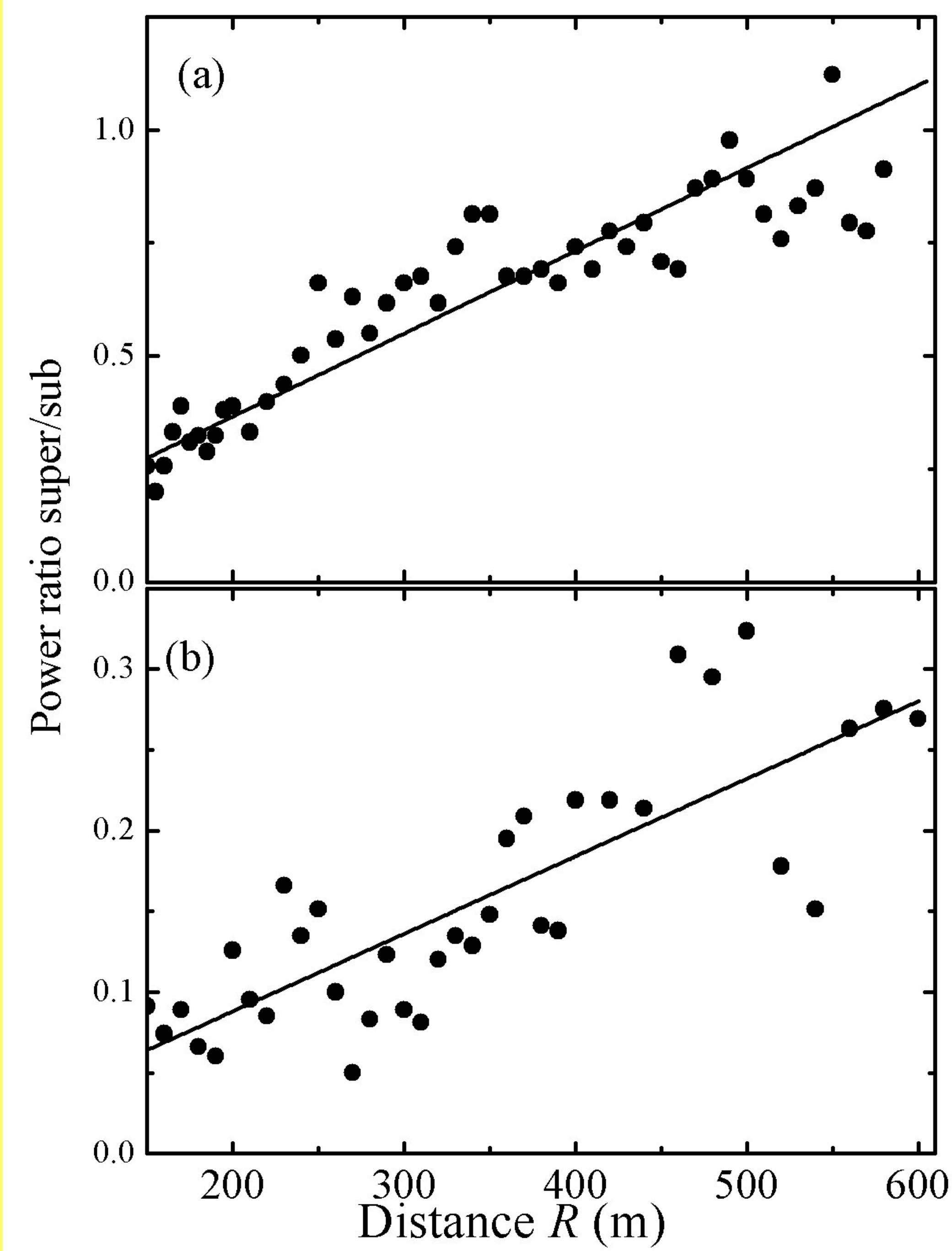


# Characterizing the cusp: another method

Both figures show data recorded along the expected cusp direction. (The weather conditions differed between (a) and (b).)
Data are plotted as the ratio of the power with the machine running superluminally ($v/c$ = 1.06) to that with it running subluminally ($v/c$ = 0.875). (Frequencies as previous figure.)

The line is a fit to the function (power ratio) = *CR*□ with □= 1.

This implies that the power on the cusp falls off as 1/*R as predicted by the theory papers.*



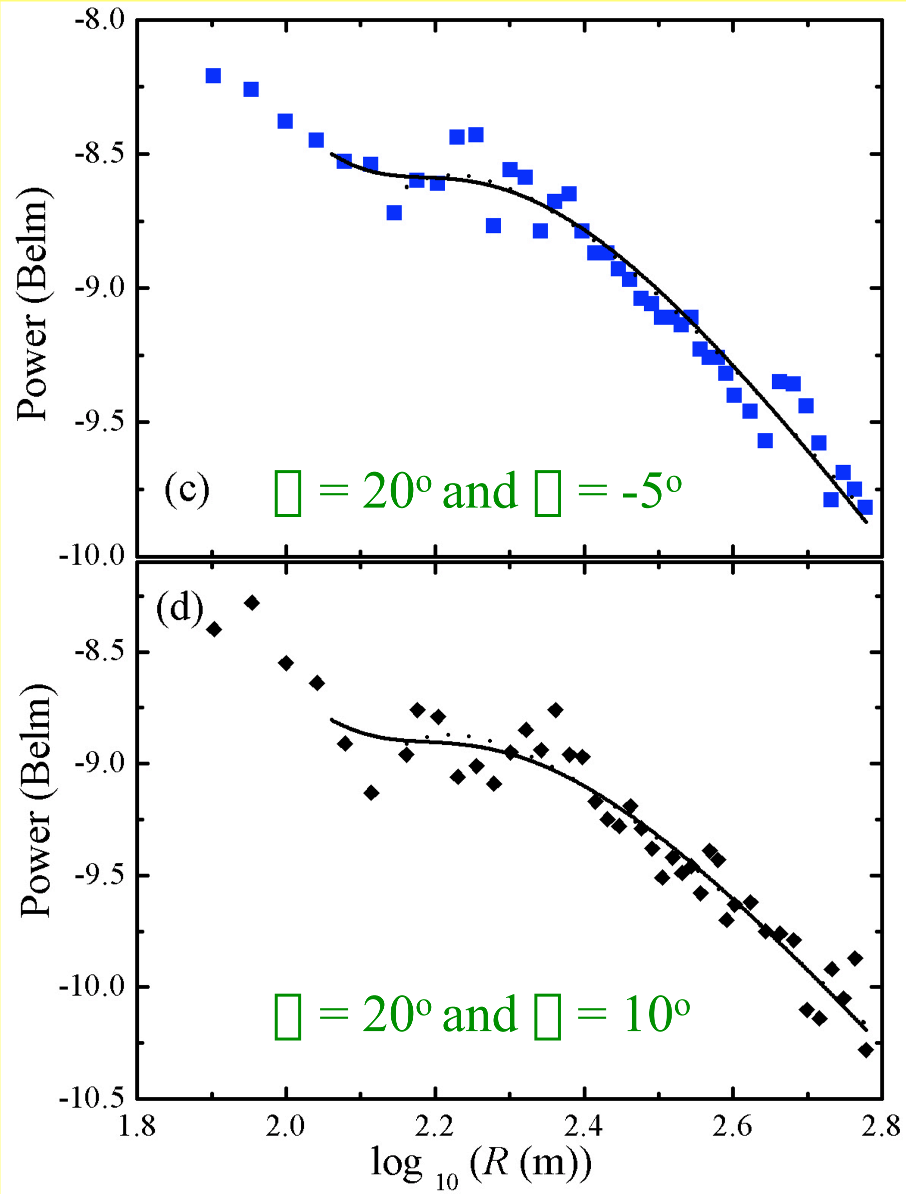
# The cusp is predicted to be narrow

Move to -5 degrees (c) and +5 degrees (d) either side of the predicted cusp direction.

(□/ 2□ = 552.654 MHz,
□/ 2□ = 46.042 MHz; $v/c$ = 1.06).

Note:
- less "speckle" (the machine is not so coherent a source in this direction);
- faster decrease of power with *R:* models (curves) assume power varies as $1/R^{1.5}$.

- Data are in good qualitative agreement with theoretical predictions.

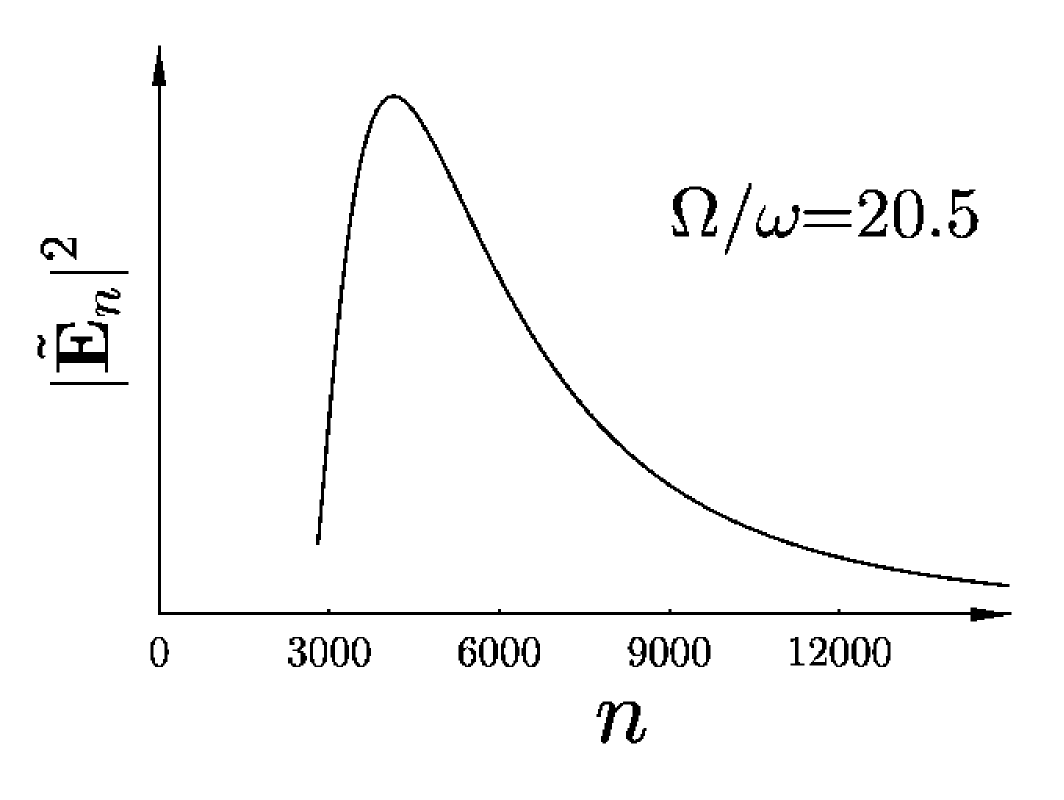


## High-frequency emission

In addition to the tightly-beamed radiation, an accelerated superluminal source is predicted to emit broad-band, higher frequency radiation.

For excitation frequencies in the 10s of MHz, this emission will be in the THz region of the spectrum.

=> A new type of solid-state source for the "THz gap".




($n$ is the harmonic number of the radiation)

See *J. Optical Society of America A* **20,** p2137 (2003); many experiments remain to be done on this aspect of our machine's behaviour.

# Summary

•We have built a practical superluminal source- *a Polarization Synchrotron*- and are using it to explore the physics of the emission and propagation mechanisms.

•The machine demonstrates that $P$ □ $1/r$ around the cusp; applications in low-power, long-range transmission.

•Beaming is unusual- diffractionless, curved beams; applications in radar, medicine etc..

•The high-frequency emission has yet to be explored

Huge, new, unexplored field of research…..

# Future prospects for the Polarization Synchrotron

- A completely new type of solid-state light-source:
- emits GHz and THz radiation by animating a superluminal (faster than light *in vacuo*) polarization current;
- produces tightly-focused wavepackets (“beams”);
- some emission declines as $1/R$, rather than $1/R^2$.
- => obvious applications in radar, secure, low-power communication etc., etc.;
- principles outlined in *J. Optical Society of America A* **20,** p2137 (2003), A **21**, p858 (2004) and in arXiv:physics/0405062.

# Potential medical applications of Polarization Synchrotrons

Mark II version will provide

- monochromatic, tightly focused GHz “beams”;
- broad-band THz radiation.

Medical applications:

- THz imaging and absorption spectroscopy;
- dumping of energy at very precise point in body; *e.g. activation of chemotherapy, selective irradiation of deep tumours without harming normal tissue, thermocautory removal of thrombotic and embolic vascular lesions without invasive surgery.*