AA LONG TERM NOTE No. 21

Summary of the meeting of October 26, 1982

Present : B. Autin, R. Billinge, V. Chohan, T. Dorenbos, H. Haseroth, E. Jones, H. Koziol, F. Krienen, G. Nassibian, A. Poncet, K.H. Reich, R. Sherwood, P. Sievers, A. Tollestrup

Topic : Plasma Lens, by F. Krienen

PLASMA LENSES

Work on this subject started early '81 at Fermilab, $\bar{p}$ note 137.
A plasma lens can be a possible alternative to the lithium lens, now proposed for the Fermilab antiproton target train.
To make a fair comparison, only one parameter must be the same for both, i.e. the quantity k sin(kL), which controls the transformation of the upright ellipse in the centre of the target to another upright phase space ellipse in the image plane. k is the strength of the lens $k^2 = -ejZ/(2pc)$ m^{-2}, and L is the length of the lens. e is electronic charge, j is current density, Z is vac.imp. =377 ohm, p is momentum of the anti proton. The image plane is by definition located behind the lens at a distance $f = 1/(k\tan kL)$, the focal distance of the lens. So the distance between the two planes would be L + 2f.
It is shown that the shift of focus Δf vs $\Delta p/p$ is weakly dependent on the actual choice of the focal distance f. In a realistic design Δf would be ≤ 2 mm per percent momentum change.
Plasma lenses have been made for HEP . They developed from the linear Z-pinch, once a topic in fusion, according to which a strong longitudinal electric field is suddenly applied to a cylinder of low pressure gas. The gas is first weakly ionized with current flowing in a thin layer inside of the container wall (skin effect). The rapidly rising magnetic pressure drives the current layer inwards, according to Rosenbluth's snowplow model, compressing and ionizing fully the gas inside. Before the associated shock wave reflects at the axis and reverses the inward motion, a more or less uniform current density prevails across the arc column. A superimposed pulsed solenoidal magnetic field tends to control and to stabilize the pinch.
For lens application one crowbars the capacitor discharge at the right moment of plasma radius and current density. By maintaining a fairly high solenoidal magnetic field and having hollow electrodes one could alleviate the heat problem through the formation of a plasma jet axially projected into the adjacent compartments, where thermalization will be completed. The time scale of the peak current would be about 3 µsec, hence one should wish uniform pre-ionization, uniform starting electric field (using a shunted high turn solenoid, which acts as a voltage divider) and a capacitor bank of ringing frequency $\approx$ 100kHz

Fermilab Lithium Lens

diam	5 mm	20 mm
length	100 mm	150 mm
peak I	120 kA	350 kA
rate train	13 p 80 ms	} about the same
cycle time	4 sec	

Plasma Lenses in H.E.P

1950 Berkeley SC 184" 350 MeV
8 in^2 → 1 in^2

L = 48"
D = 4"
I = 4000 A

1964 BNL neutrino beamline

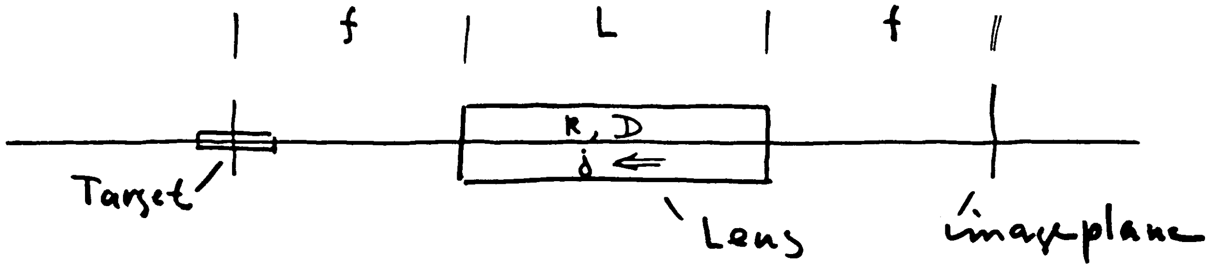
L = 150 cm
D = 20 cm
I = 150 kA

Rosenbluth's "Snowplow Model"

Skin effect
magnetic pressure
Kinetic pressure
} pinch velocity

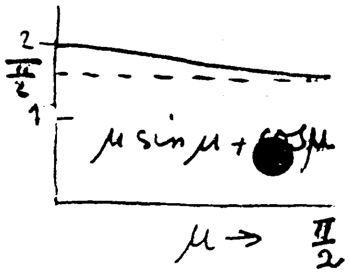
$$V^{1/2} I^{1/2} W^{1/2} \rho^{-1/4} \overset{\circ}{=} 10^{6} - 10^{7} \text{ cm/s}$$

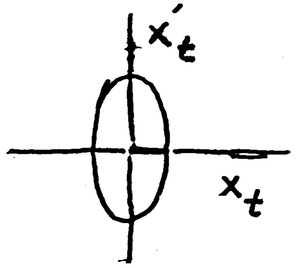
B_z solenoidal stabilising field!



$$\left.\begin{array}{l} k^2 = -\frac{1}{2} e j Z / H \\ \mu = kL \end{array}\right\} \quad M = \begin{vmatrix} \cos\mu & k^{-1}\sin\mu \\ -k\sin\mu & \cos\mu \end{vmatrix}$$

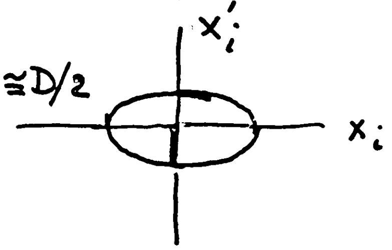
$$f = 1/(k \tan\mu) \Rightarrow \Delta f = \frac{\Delta p}{p} \, \frac{\mu \sin\mu + \cos\mu}{2k \sin\mu}$$





$$x_i = x'_t/(k \sin\mu) \cong D/2$$

$$x'_i = -x_t \, k \sin\mu$$



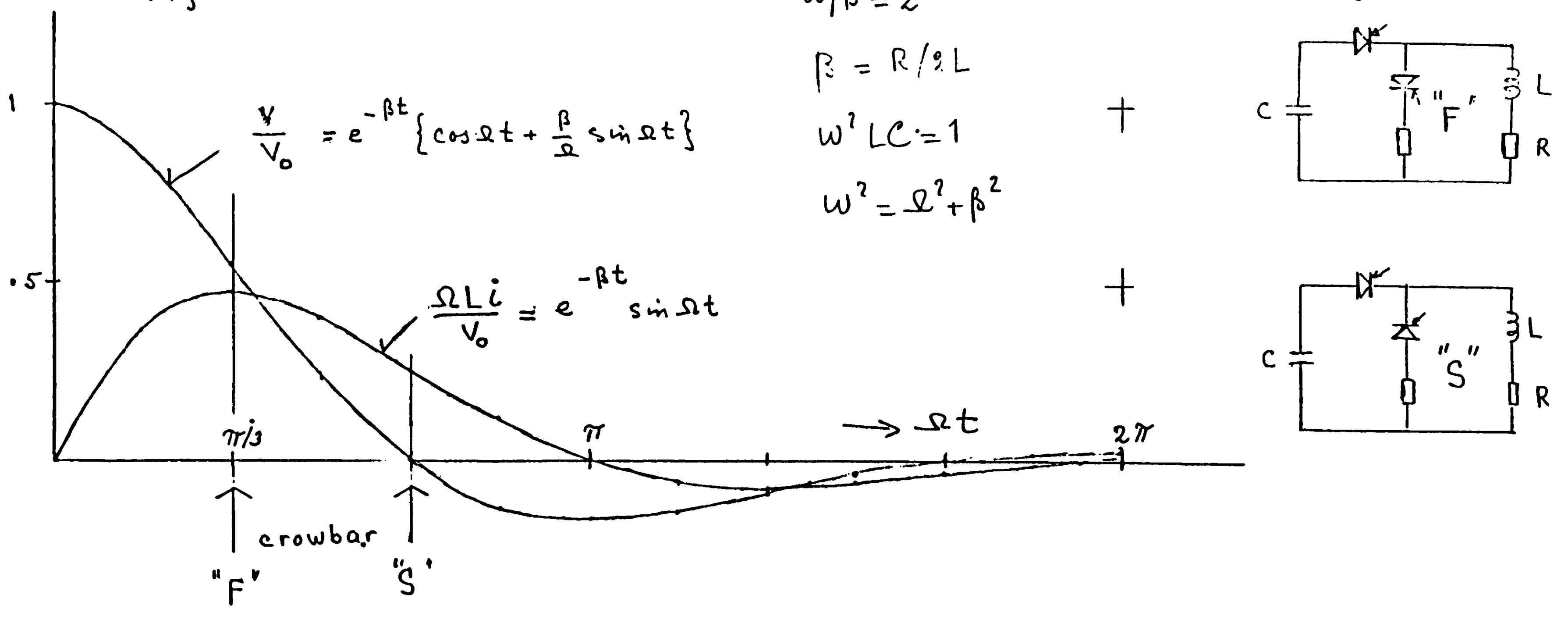
comparison of linear lenses } Distance target – image irrelevant. phase space is invariant transformation factor $\underline{\underline{k \sin\mu}}$

		Plasma	Lithium
GeV/c	p	5.36	5.36
m^{-1}	$k \sin kL$	5	5
rad	kL	1.4	.9333
m	L	.2795	.15
m^{-1}	k	5.0738	6.222
m	f	.034	.1190
mm	r	10	10
$A\ m^{-2}$	$j\ 10^{-9}$	.7320	1.1007
kA	i	229.96	345.80
T	B_{max}	4.5993	6.9159

FK July 8, 1981

3

Fig 1



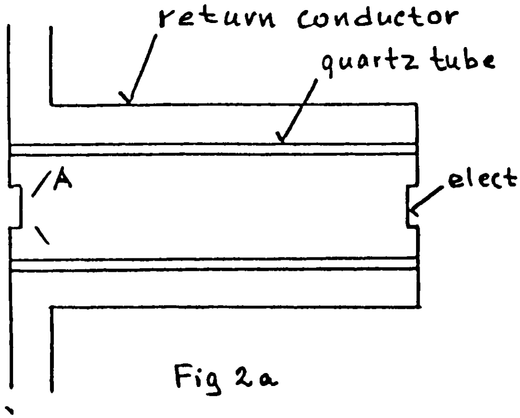


Fig 2a

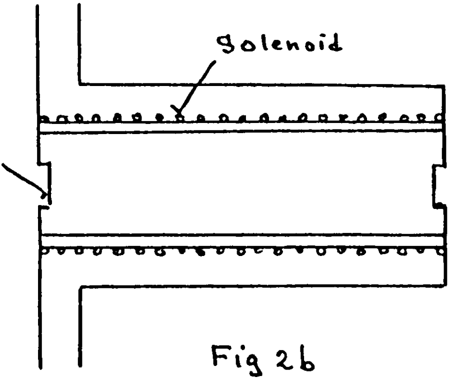


Fig 2b

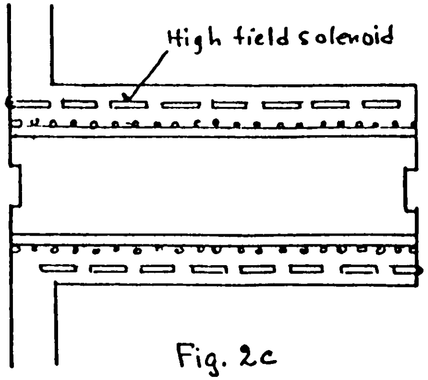
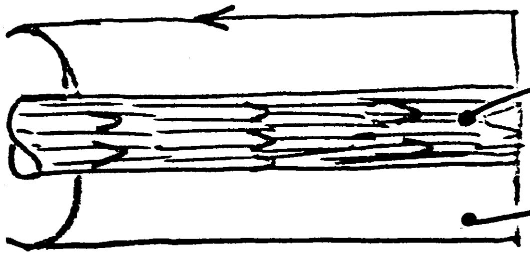


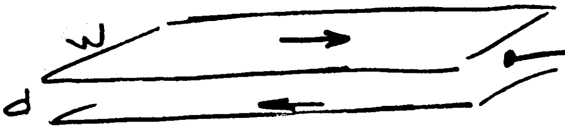
Fig. 2c



$L_{wire} = \frac{\mu_0}{8\pi} = 50\, nH/m$

$L_{coax} = \frac{\mu_0}{2\pi} \ln \frac{r_0}{r} =$

additive! $200 \ln \frac{r_0}{r}$ nH/m



$L_{strip} = \mu_0 \frac{d}{w}$ nH/m

L_{total} 50 nH ⇒ 110 nH

$\omega^2 LC = 1$

$\beta = R/2L$

ω/β	1	2	4	
"F"	2.39	1.35	.725	$\frac{\text{heatloss up to } \tau}{\text{max magn. energy}}$
"S"	e^2	3.05	1.20	
C	1100	275	69	μF
V_0	6.24	8.42	12.91	kV
τ	5.56	3.36	1.89	μs

GE 14F 1277: 20 kV 15 μF 20 nH

3000 J 150 10^3 disch at 200 kA

14" × 7¼" × 24", 150 lb

Derating: 50% voltage ⇒ 1800 disch/hour

24 hr service, 9000 hr life time

16 10^6 disch life expectancy

"Voltage divider" = Uniformity

$$B_z = \frac{\int v\,dt}{\pi r_0^2 n} \quad \text{and} \quad L_{sol} = \mu_0 \frac{\pi r_0^2 n^2}{l}$$

$$\tau_{sol} = L_{sol}/R_{sol} = \tfrac{1}{2}\mu_0 \sigma r_0 \underset{\uparrow \text{ skin depth}}{s} \gg \tau_{\text{peak current}}$$

Stabilizing
high field solenoid } in parallel fig 2c
separately programmed
watch eddies in return
conductor/end-caps

Quartz

Cooling

8 kJ in capacitor

3 kJ peak magn. field

3 kJ diss. heat at peaking time

→ 50/50 crowbar

4.5 kJ total diss.

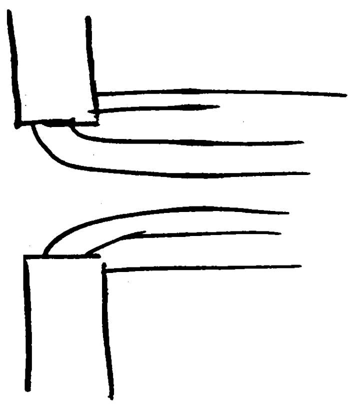
50/50 plasma # 2¼ kJ in plasma

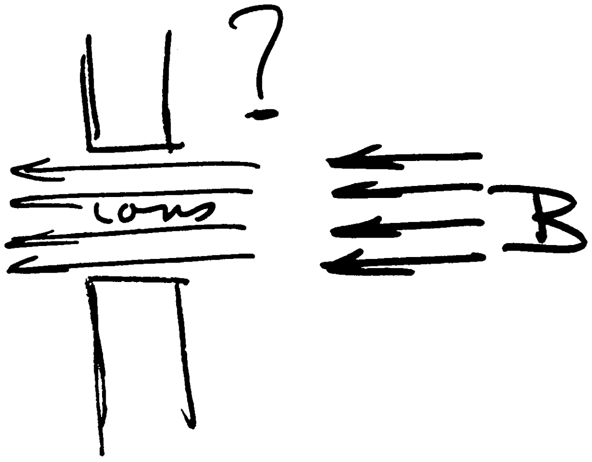
radiation

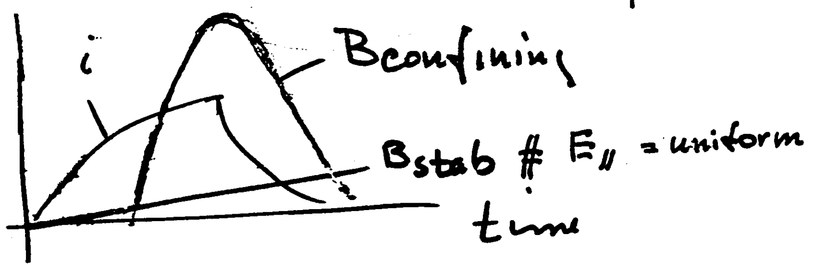
impact ≅ 1 Coulomb

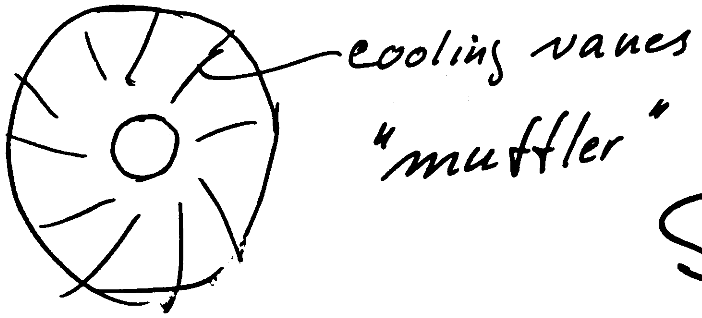
thermalization

Endcaps









Summary

1 Pre-ionisation
2 Uniform E_Z
3 programmed B_Z (avoid eddy currents)
4 Hollow Electrodes
5 Plasma jets & external cooling

Jan 26, 1984

<u>Critical</u> $L = 100\,nH$, $R = 40\,m\Omega$ $\Big\}$ $\beta = \frac{40m}{200n} = 0.2\,M\ sec^{-1}$

$$\omega = \beta = 0.2\,MHz$$

$$C = \frac{1}{\omega^2 L} = \frac{1}{4\,10^{10}\ 100n} = \frac{1}{4000} = 250\,\mu F$$

$$Z = \sqrt{L/C} = \sqrt{\frac{100n}{250\mu}} = 20\,m\Omega$$

$$V = i Z e^1 = 168k \cdot 20m\ 2.73 = 9.3\,kV$$

$$\text{Stored energy} = \frac{1}{2}\,250\mu\ 9.3^2\,10^6 = 11.3\,kJ.$$

$$\text{peaking time}\quad \tau = \frac{1}{\beta} = 5\,\mu s$$

Same problem but a bit less than critical i.e. by factor $\sqrt{2}$

$$\omega = 0.2\sqrt{2}\ MHz$$

$$C = 125\,\mu F$$

$$Z = 20\sqrt{2}\ m\Omega$$

$$\Omega = \sqrt{\omega^2 - \beta^2} = 0.2\,MHz\ (=\beta)$$

peaking time $\tan \Omega t = \Omega/\beta = 1$ or $\Omega t = \pi/4$ or

$$\tau = \frac{5\pi}{4} = 3.93\,\mu s$$

$$e^{-\beta t} = e^{-\pi/4} = \frac{1}{2.19}$$

$$V = i Z\ 2.19 = 168k\ 20\sqrt{2}\ 2.19 = 10.8\,kV$$

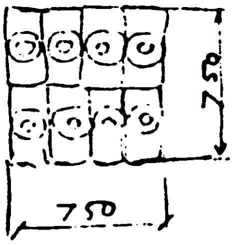
$$\text{Stored energy}\ \frac{1}{2}\,125\mu\ 10.8^2\,10^6 = 7.3\,kJ$$

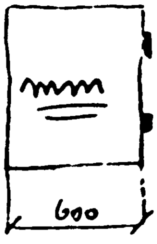
Capacitor bank. 50% derating in the 20 kV model

20 kV 15 μF 20 nH 3000 J 155 kaised 200 kA 14" x 7¼" x 23⅞" 150 lb type 14F 1277

about 8 of them needed for the subcritical device x ½ ton affair

Capacitor inductance $\frac{20}{8} = 2.5\,nH$





Source charge
.. 50% rated voltage
1500 discharge per hour
24 hr service
9000 total in volume
[illegible]