Engineering Study of the Undulator Positron Target and Pulsed Coils as a Matching Devices for the ILC.

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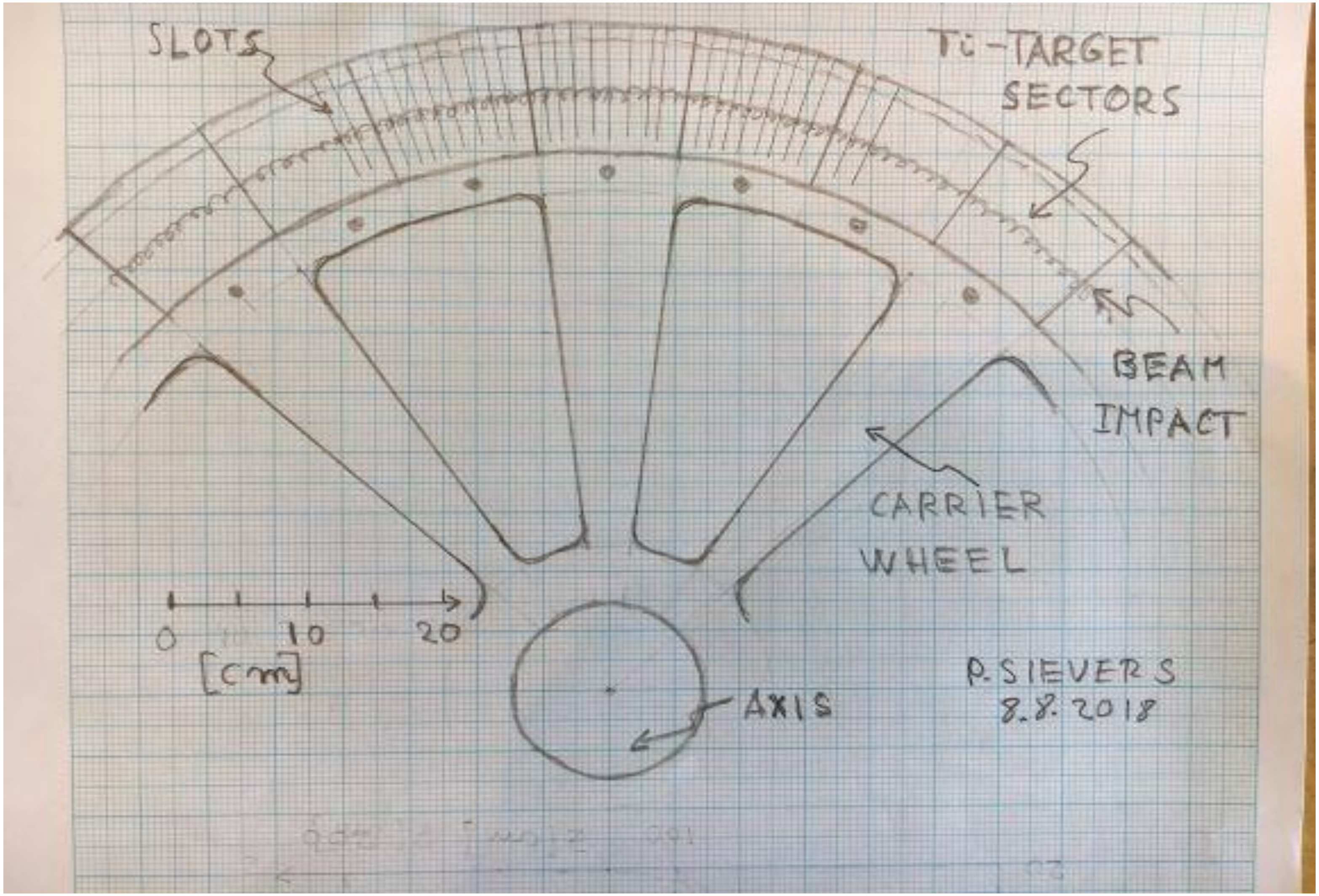
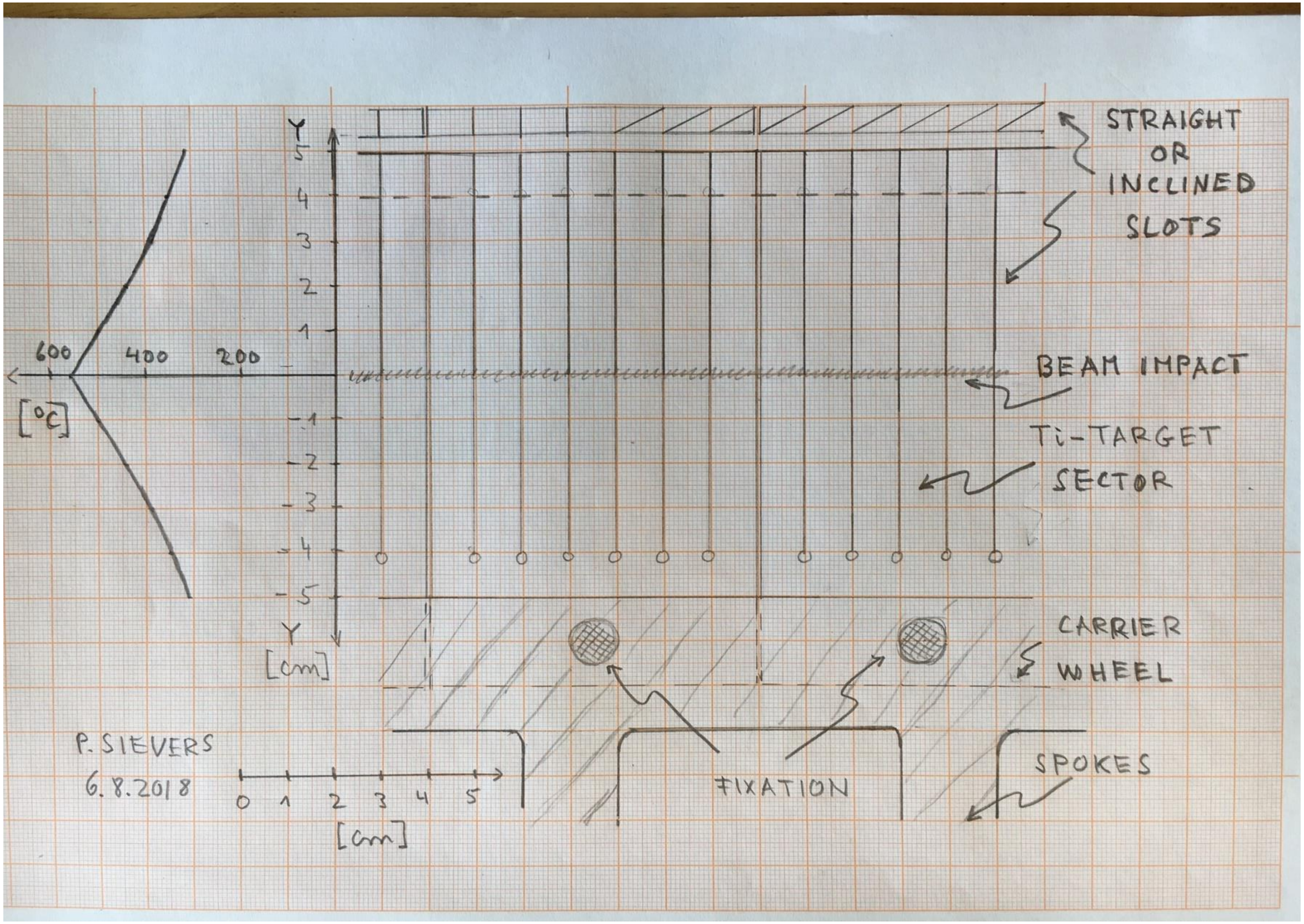
- 1.Review of the design of the wheel.
- 2. Validation by laboratory tests.
- 3. Study of a pulsed coils as a first matching device.
- 4. Induced currents in the rotating target.
- 5. Conclusion.

1. Design of the Wheel.
Positron WG: Editor: K. Yokoya-san.



Zoom of the Wheel.



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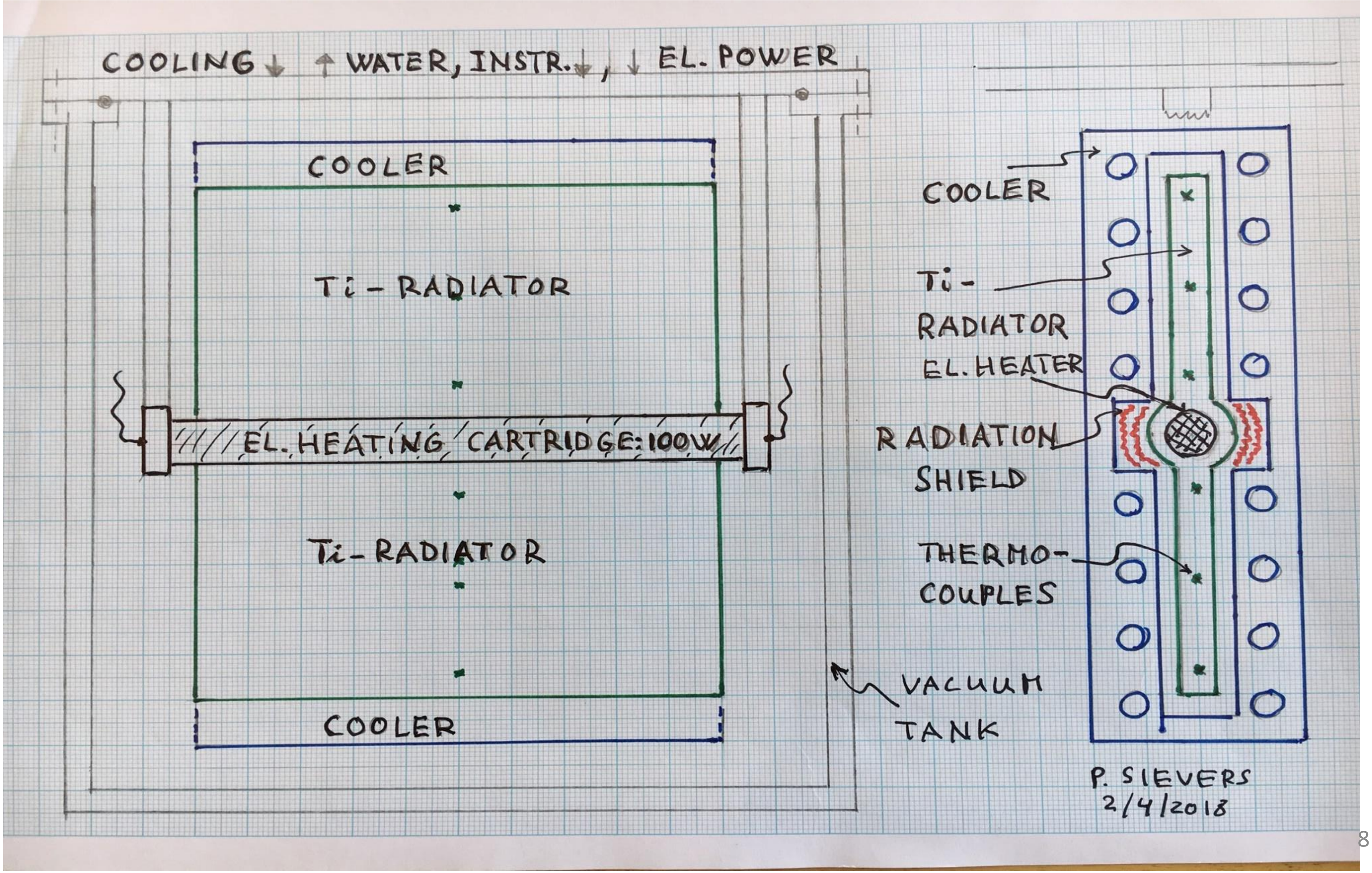
- Ti-target sectors are mounted around a wheel, the «Carrier Wheel».
- The target sectors have each a width of about 10 cm and a hight of also about 10 cm, providing a maximum surface for effective cooling by radiation. Peak temperatures of below 600 oC are expected.
- The sectors can be mounted onto the carrier wheel allowing for their free thermal expansion and thus low thermal stresses. Also, centrifugal forces are low, 9 MPa.

- To mount the actual Ti-target sectors onto a carrier wheel, allows for more freedom in the design and eases manufacture, assembly and quality control.
- The weight of the wheel, including its axis, can be below 50 kg.
- Slots of about 0.1 mm width and a pitch of 10 mm are cut into the Ti-sectors. This relaxes thermal tension and reduces Eddy Currents (see later).
- The slots cause an average reduction of target thickness of 1 % (straight) or 1.2 % (inclined). The yield depends only little on the target thickness.

2. Validation by Laboratory Tests to be funded and done within the next Two Years.

- The cooling by radiation can conveniently be tested and optimised on a small, stationary sector of the wheel, powered by an electrical heater.

Layout of Radiation Cooling Test.



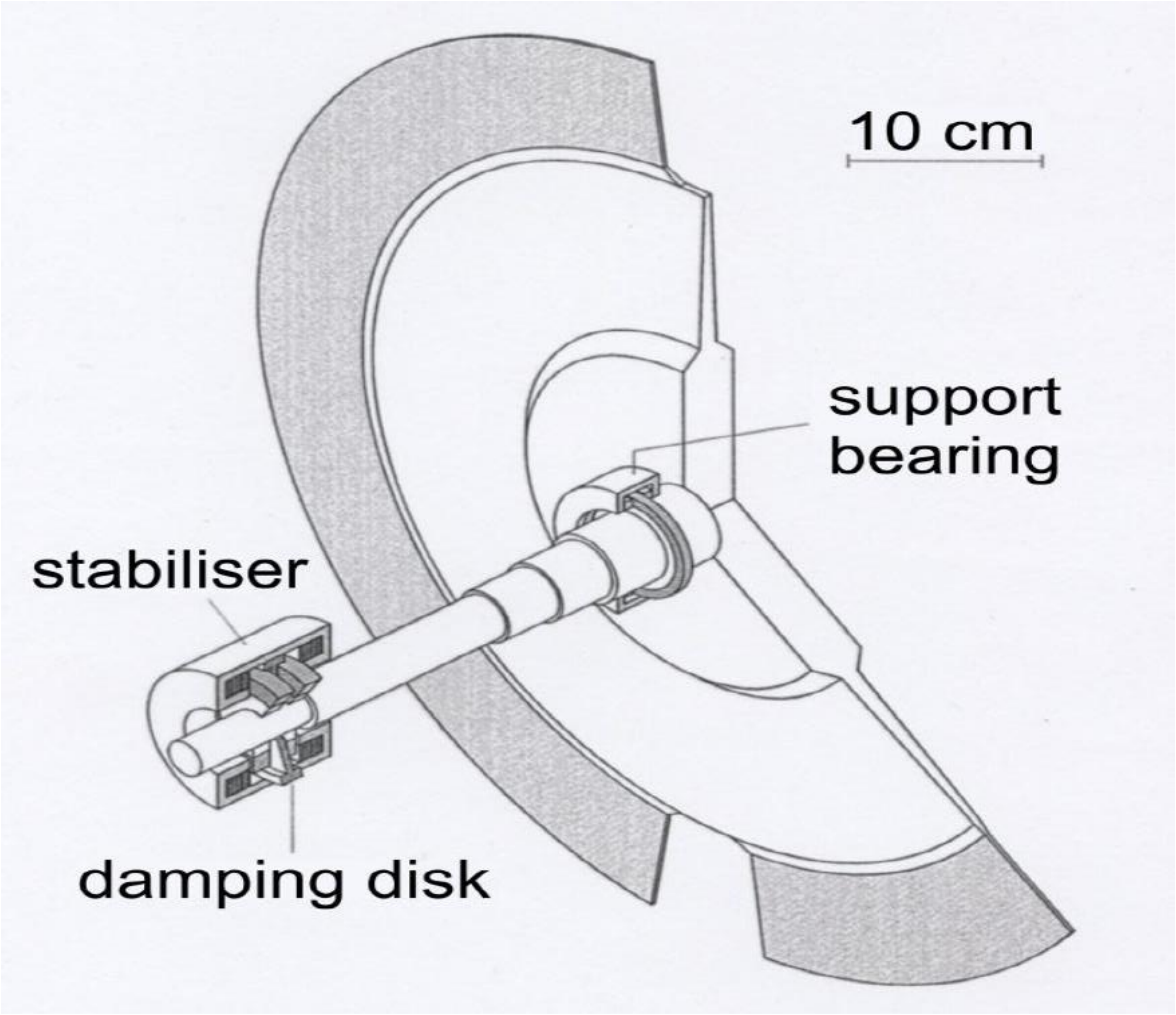
Test of the Resistance of the Ti-Alloy under Thermal Load.

- Submit Ti-specimens to mechanically applied static and cyclic stresses at elevated temperatures at around 400-600 oC and record the failure rates.
- Observe structure changes, plastic deformations and creep.
- These tests can readily be done by specialised material tests laboratories.
- Material tests and radiation damage under or after electron or photon irradiation are very difficult, time consuming and costly.

R+D for the Magnetic Bearings with Permanent or Electro Magnets.

- Write up a performance specification:
- Weight of the wheel, dimensions, rotation velocity, geometric and dynamic stability, external mechanical and thermal loads, vaccum compatibility, radiation resistance, operational environment, reliability, ……
- Submit this to specialised manufacturers, to make a feasibility study, draw up a R+D plan and make a cost estimate.
- Prototype tests should follow soon.

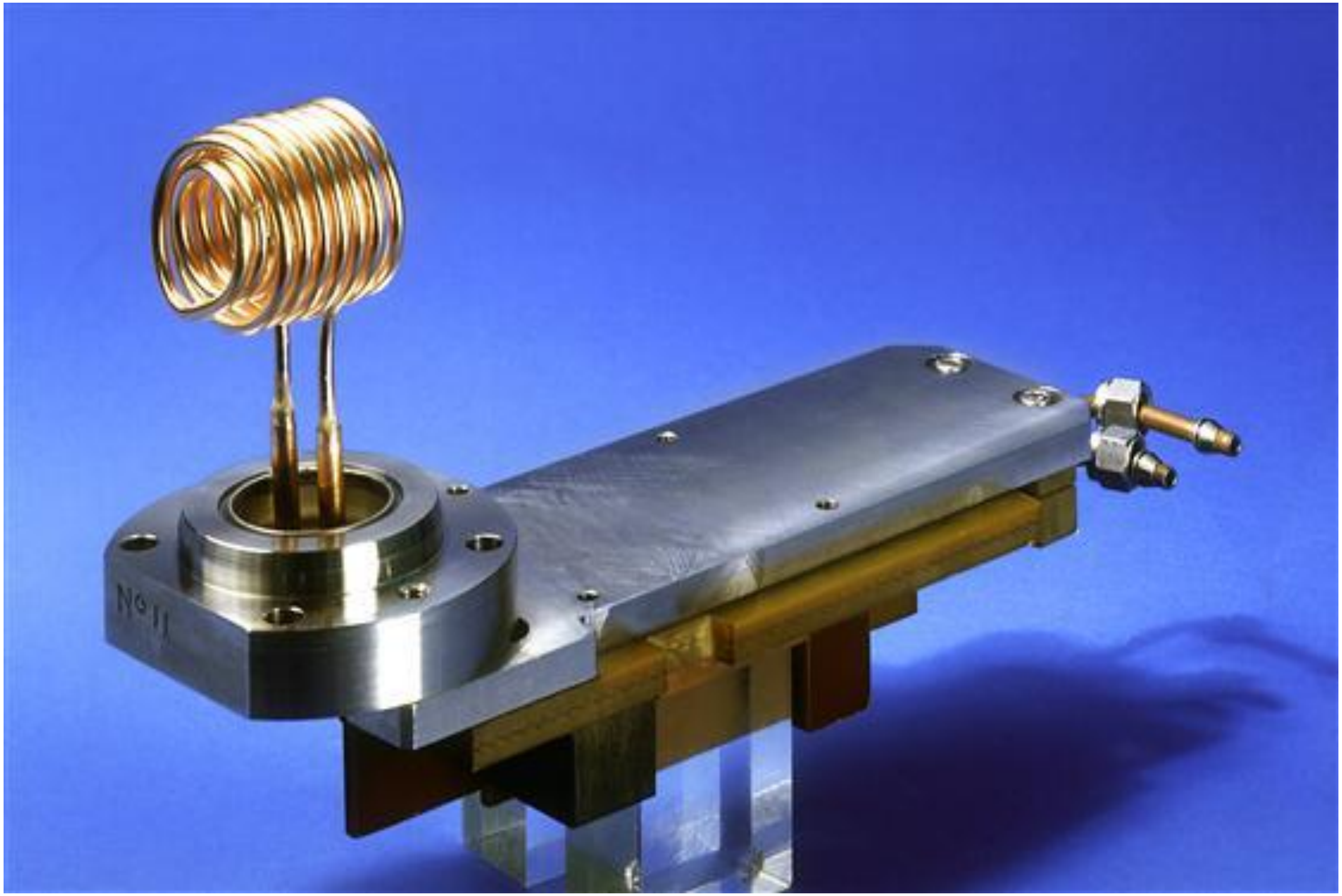
Magnetic Bearing. Cortesy Juelich-ZEA-Germany.



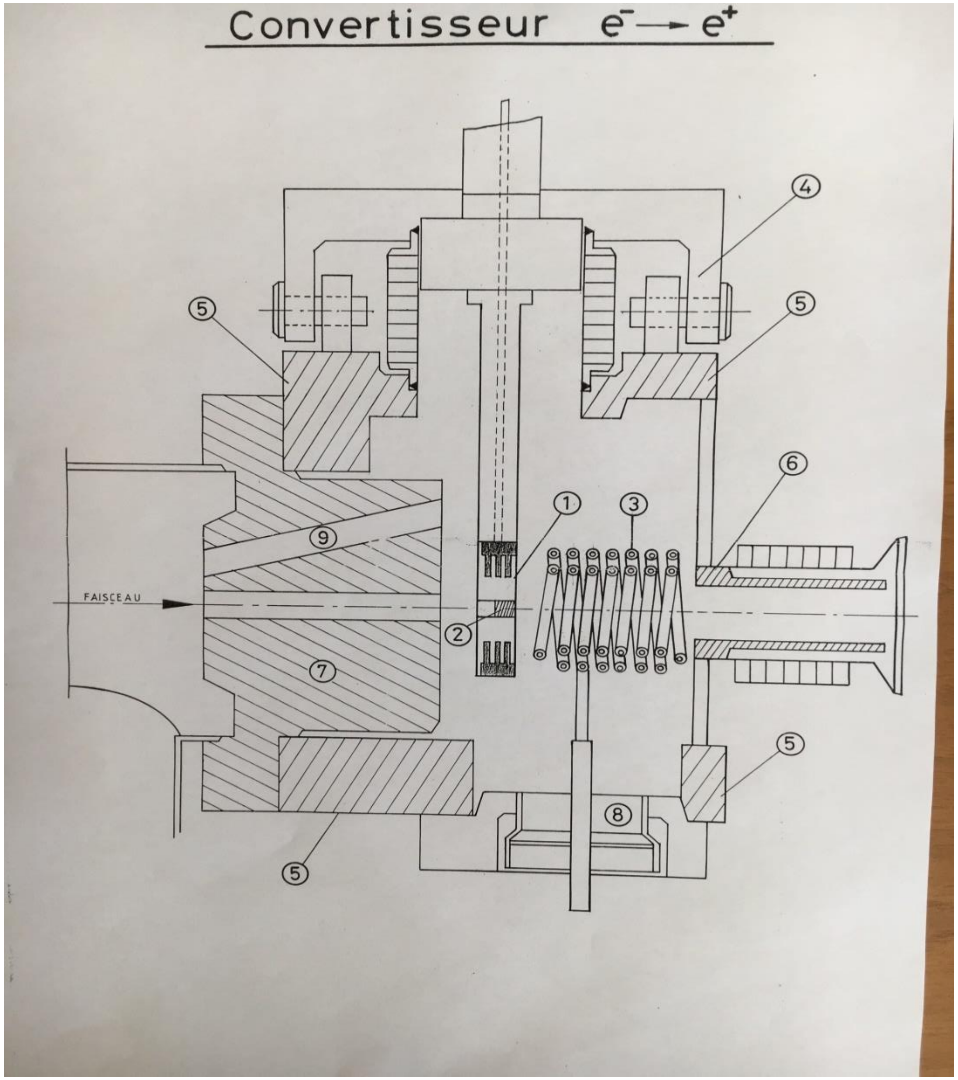
3. Pulsed Coils as a Matching Device for the Positron Target.

- Using Flux Concentrators, powered by long and stable 1 ms pulses of about 3.5 T seems to be difficult.
- D.C. powered Quarter Wave Transformers with maximum fields of about 1 T are envisaged, with however limited yield.
- Motivated by discussions with Wanming Liu, Fukuda-san, Louis Rinolfi and Rober Chehab:
  Pulsed Solenoids as a matching device could be a valid option.
- Such solenoids have been widely used or studied in the past: LEP, LAL, DESY, KEKB,…..

The LEP-Pulsed Solenoid- L. Rinolfi.
I=2.5 kA, Bo=0.83 T, 100 Hz with 20 µs.



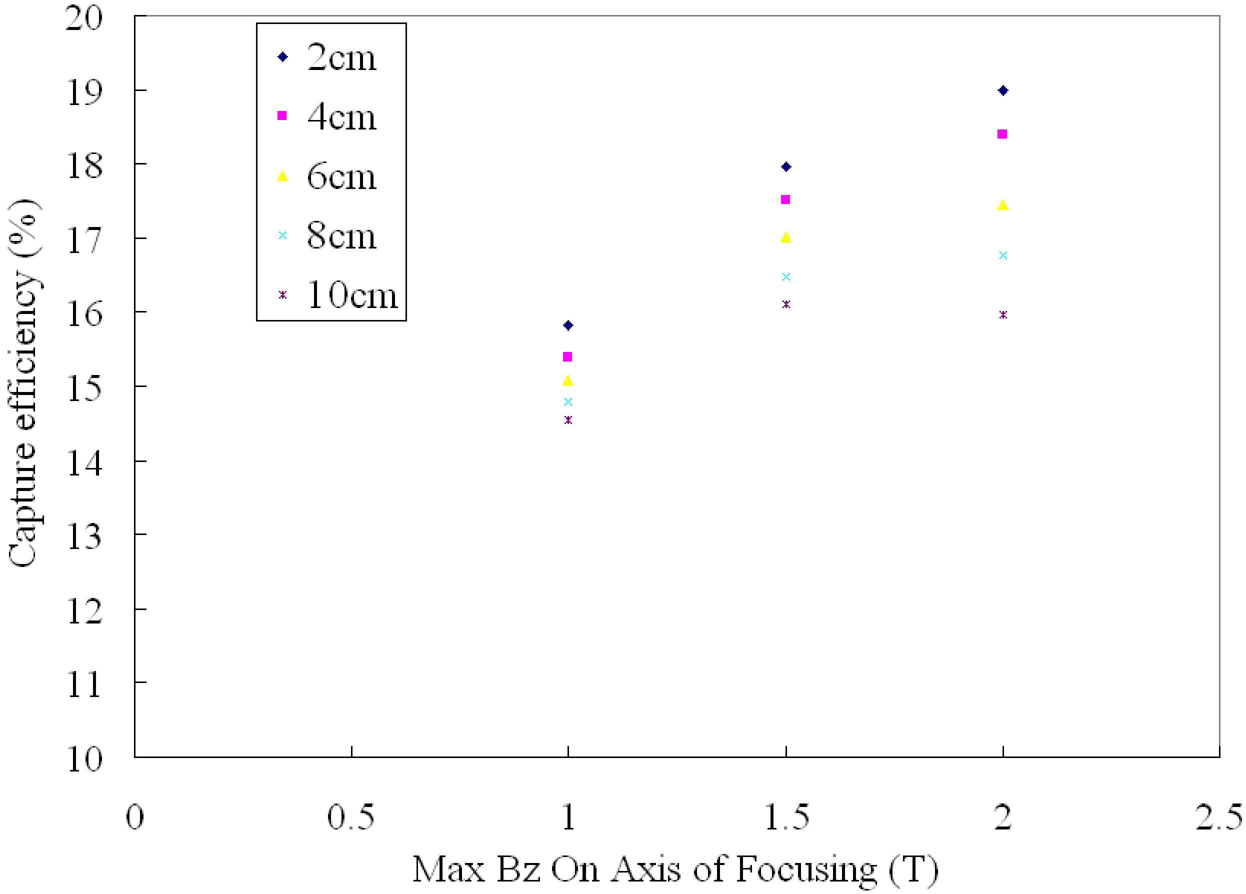
The LEP Positron Source- Cortesy L. Rinolfi.



Pulsed Coils for the ILC- Undulator Driven Positron Source.

- This is a purely technical study to investigate the maximum fields which can be reached with such a device.
- The coil can be configured either with a constant aperture, solenoid, or a conical aperture, similar to a Flux Concentrator.
- To correlate the achieved magnetic fields to the resulting positron yield, is outside of the scope of this study.

Yield versus Bz: Cortesy Wanming Liu.



The Conductor.

- Use high quality, oxygen free Copper with high electrical conductivity: σ=5.85 10^5 (1/Ωm).
- Square cross section of 10 x 10 mm^2 with a central cooling channel with a diameter of 6 mm.
- With a half sine current pulse with a duration of 4 ms, one can achieve an about uniform current density at its peak during 1 ms. This eliminates the problem with time varying fields in Flux Concentrators.
- There remains a residual current variation of +/- 3% over 1 ms. This can be further improved by appropriate shaping of the pulse profile.

Powering of the Cu-Conductor.

- Consider a conductor with a length l=1 m, pulsed with half sine pulses of 4 ms, 50 kA peak at 5 Hz.
- Av. Ohmic resistance: 2.38 10^-4 Ω. Av. d.c.Voltage: 12. V. Av. Pulsed power: 5.95 kW.
- PEDD(el): 1.86 J/g pulse, well below the accepted limit of 10 J/g.
- ΔT=4.66 K/pulse.
- Av. Power density: 83 W/cm^3.

Cooling of the Conductor.

- Water flow with a velocity of 6 m/s through the conductor gives a mass flow of 0.17 l/s.
- Pressure drop ΔP=6 Bar/meter.
- ΔT in water over the conductor length of 1 m: 8.35 K. Water inlet at 20 oC.
- Peak temperature rise in the coil above the water temperature just after a pulse, during steady state cycling: 18.3 K.
- Peak temperature in the conductor: at the inlet 38.3 oC, at the outlet 46.7 oC.

Parameters for the Cu-Conductor per unit length of 1 m.

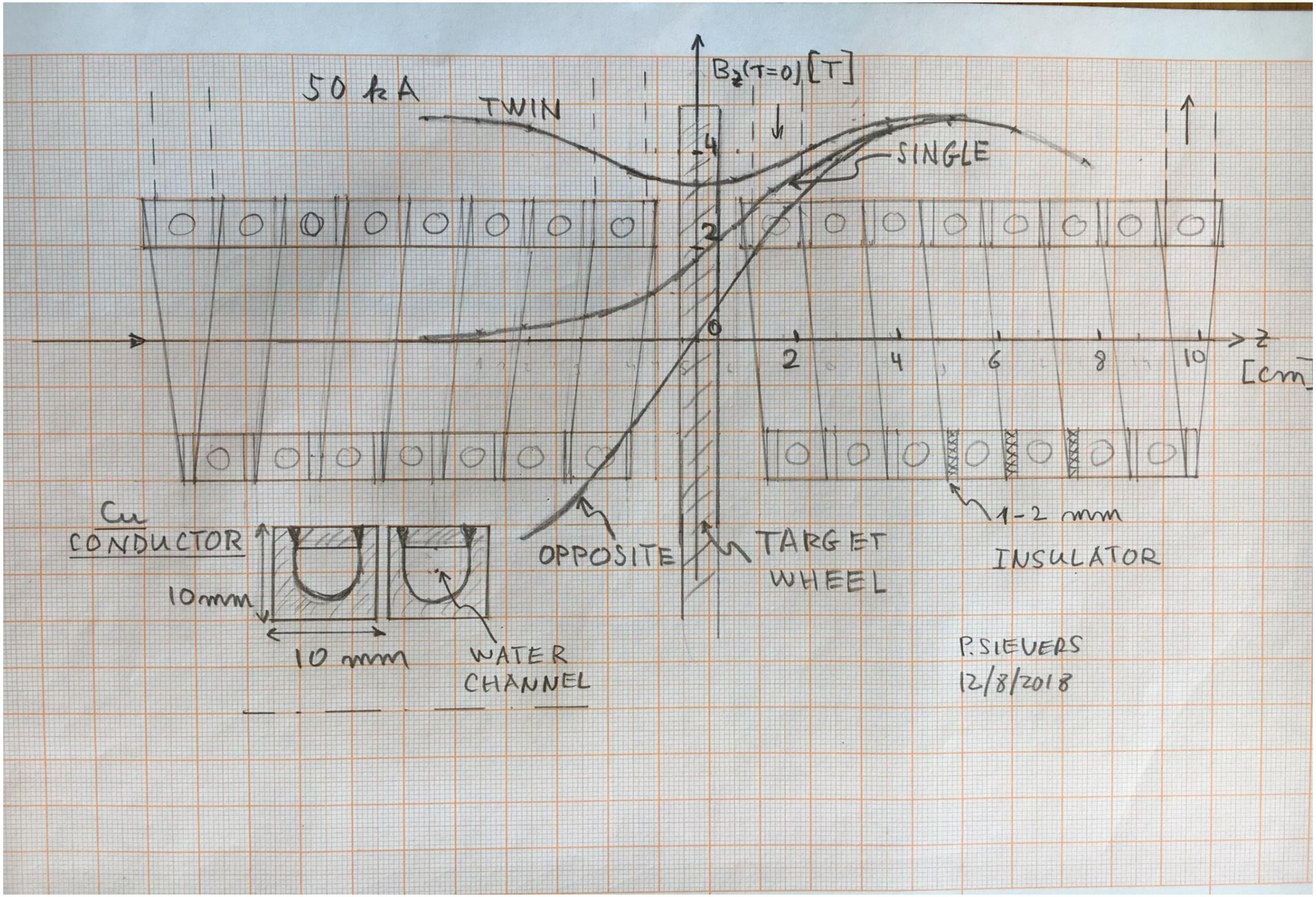
Powering	Duration of Half-sine Pulses	Frequency	Peak Current	Av. Resistance	Av. Power
	4 ms	5 Hz	50 kA	2.4 10^-4 Ω	5.95 kW

Pulsing	El. PEDD/Pulse	ΔT/Pulse	Water Cooling	Peak Temp. in Cu	Peak Temp. in Cu
	1.86 J/g (83W/cm^3)	8.35 K/pulse	6 m/s 0.17 kg/s	At inlet 38.3 oC	At outlet 46.7 oC

Parameters for the Coils.

- With the 1 m long conductor, a coil with 7 turns, with an inside uniform diameter of 4 cm and an insulating gap of 2 mm between turns, an effective length of 7 x 1.2 = 8.4 cm can be built.
- The diameter of 4 cm is important to place the Cu-conductor beyond the radiation emerging from the target. There the PEED(beam) is next to zero (Takahashi-san).
- With a peak current of 50 kA a peak field of 4.83 T is achieved inside the coil.
- Option: a coil with an inside diameter of 2 cm, with 16 turns over 19.2 cm would give a field of 6.25 T.
- With 2 cm aperture, the PEDD from the beam is about 13 J/g. Adding the ohmic PEDD, would result in 15 J/g (700W/cm^3), above the limit of about 10-12 J/g.

Aperture 4 cm, 50 kA, 7 Turns.



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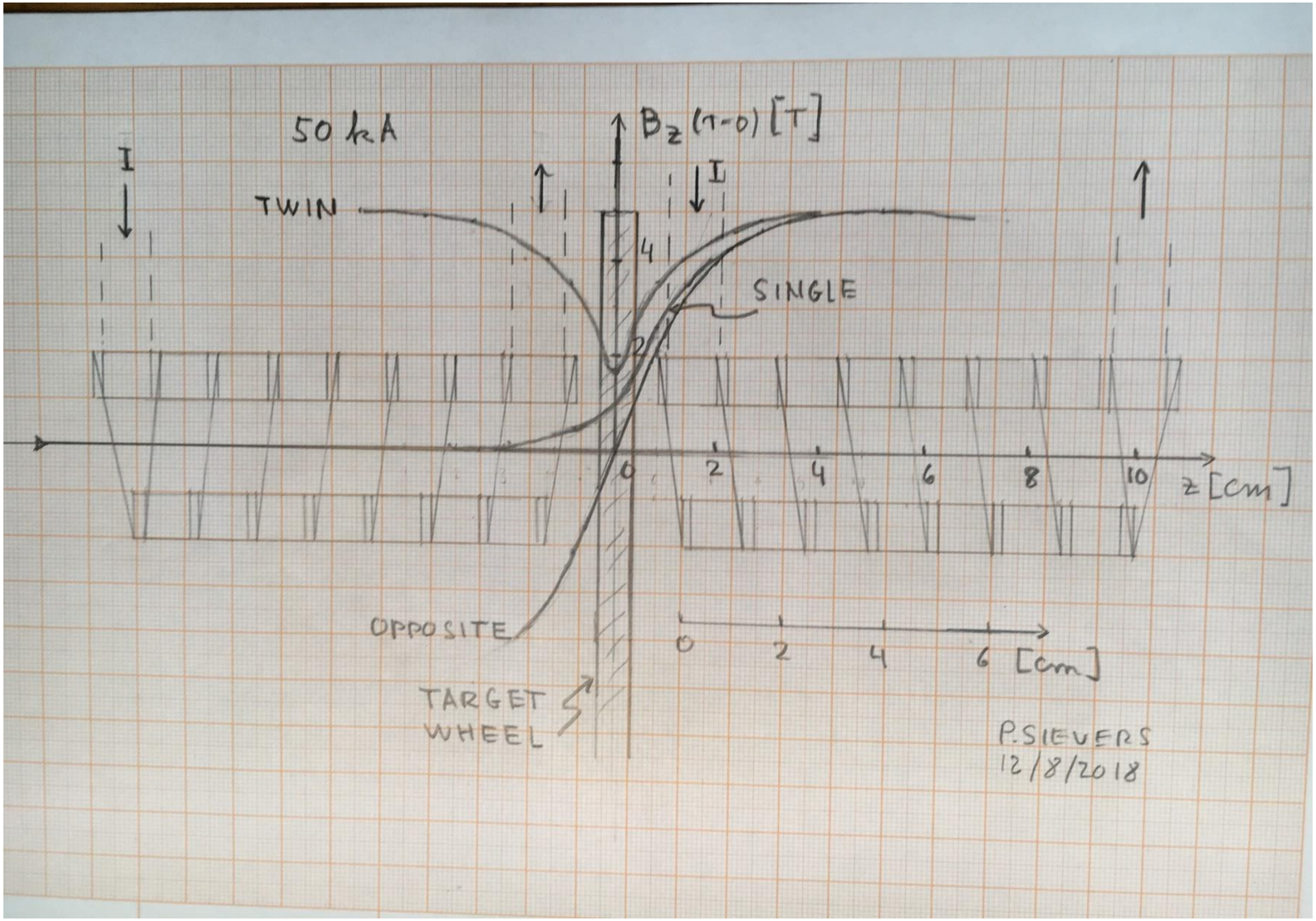
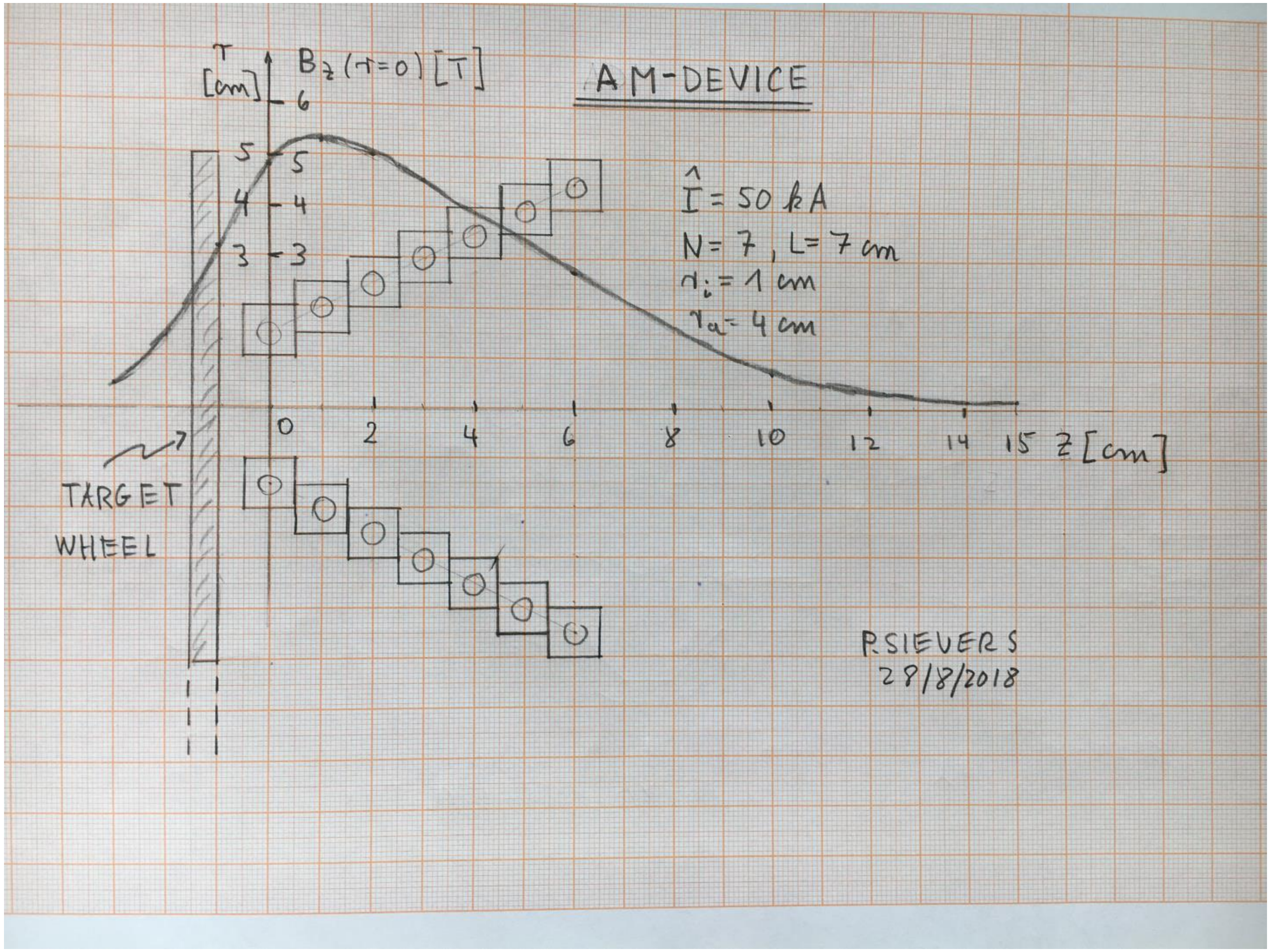
Aperture 2 cm, 50 kA, 7 Turns.



Adiabatic Matching Device



- Induced voltage with an inductance of ~1 µH: 39 V.
- Magnetic radial pressure at the inside of the turns: 18.6 MPa.
- Magnetic azimuthal stress in the turns: 37.2 MPa $\leq$ limit of 60 MPa .
- Still, some solid engineering is necessary to firmly constrain the turns mechanically to resist to these pulsed loads.
- DPA in the Cu-conductor: >0.15 dpa/5000 h (A.Ushakov).
- Radiation resistant insulation in the gaps of < 2 mm betweeen the conductors must be foreseen.

Field Quality

- Have only considered the Axial Field Bz(r=0) along the axis.
- As in all magnetic matching devices, FC, QWT and Solenoids, transverse field components Br appear in the fringe fields:
- $\partial Bz/\partial z = -1/r \cdot \partial(r \cdot Br)/\partial r.$
- It may be necessary to reduce substantially the insulating gaps between the coil turns from 2 mm to 0.1-0.2 mm, similar to a spiral slit FC.
- Also the current inlet and outlet may disturb the field. Like for the LEP-coil, use a two-layer solenoid with both the current connections at the downstream end.

Parameters for the ILC-Solenoidal Coils.

- Consider coils at 50 kA, number of turns N=7, effective length 7 x 1.2 cm = 8.4 cm.

Free Coil Aperture	Inductive Voltage	Peak Field inside the coil	PEDD	Radial magn. Stress	Tangential magn. Stress
4 cm	~ 40 V	4.67 T	1.86 J/g	17.4 MPa	37.2 MPa
2 cm	~ 40 V	5.0 T	15. J/g, incl. Beam!	20. MPa	~ 20. MPa
ADM Ri=2 cm; Ra=4 cm	~40 V (?)	5.3 T	15. J/g, incl. Beam!	22. MPa	~22. MPa

4. Induced Currents in the Rotating Wheel by the Fringe Field of the Solenoid.

Magnetic Fields in the Coil and at the Wheel for Single, Twin and Opposite Coils.

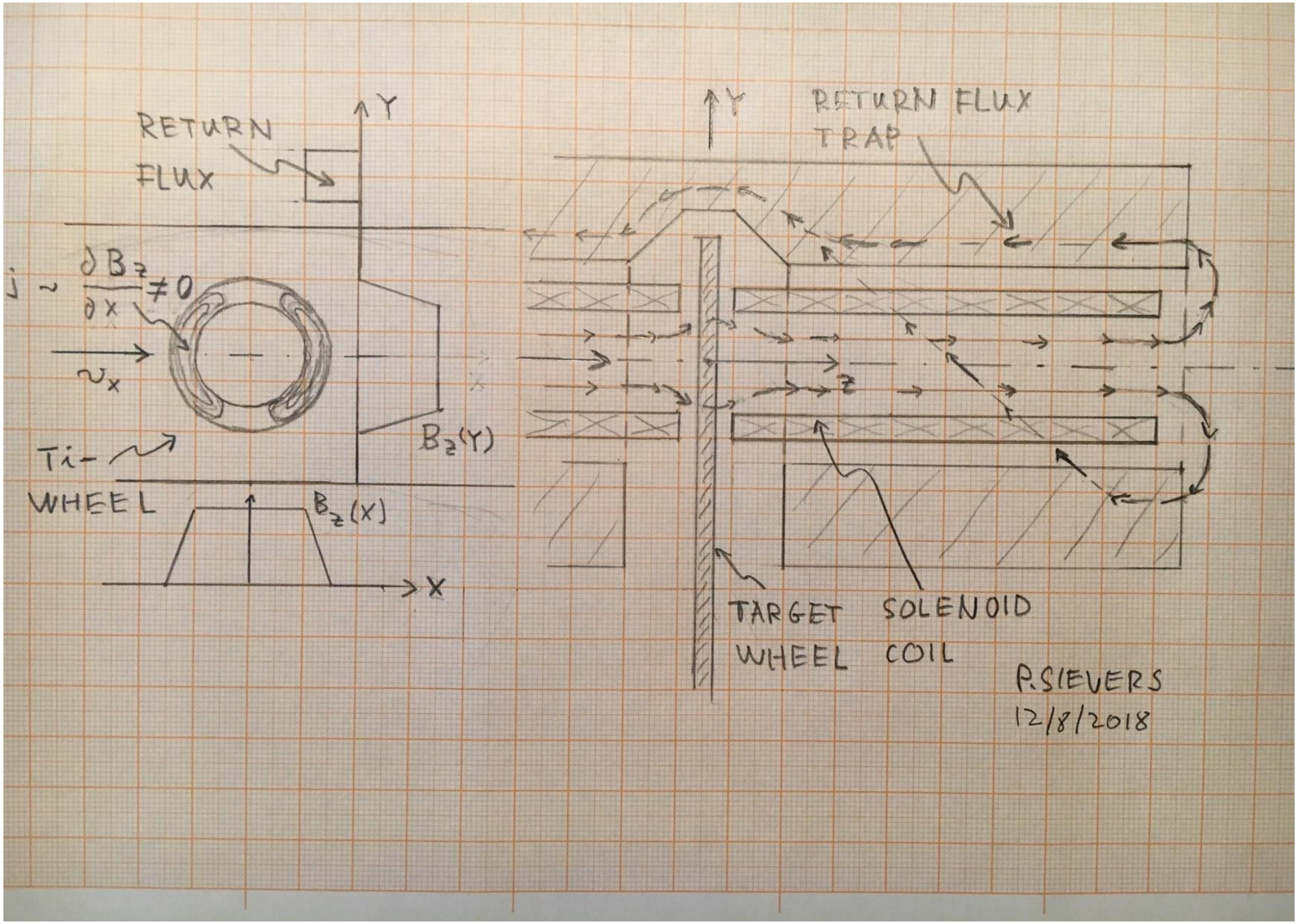
- Gap between twin coils: target width 7 mm plus 2 times 5 mm distance to coil: 17 mm.

Free Coil Aperture	Coil Layout	Peak Field in Coil Bz(r=0)	Bz at Target Centre/ Target Exit	dBz/dz at Target Centre
r=4cm	Single coil	4.7 T	1.7. T/2.2 T	80 T/m
	Twin coil	4.7 T	3.4 T/3.5 T	~ zero
	Opposite coil	4.7 T	Zero/0.7 T	160 T/m
r=2 cm	Single coil	5.0 T	1.0 T/1.6 T	140 T/m
	Twin coil	5.0 T	1.6 T/2.6 T	~ zero, ?
	Opposite coil	5.0 T	Zero/1.0 T	280 T/m

Induced Currents in the Ti-Wheel.

- Only very approximative estimates are made:
- Currents induced by a stationary axial field Bz or flux Φz in a material moving in x-direction with a velocity v:
- $d\emptyset/dt = d\emptyset/dx \cdot dx/dt = d\emptyset/dx$ ·v. For a dx=1 cm the time increment dt= 0.1 ms, causing a skin depth in Ti of about 1 cm> 0.7 cm of target thickness, ignore skin effect.
- dϕ$/dx \cdot v = 1/\sigma \cdot \oint j$ds. Find j by integration over convenient current loop where j is constant.
- D.c.-Power deposited in the moving material:
- W=1/$\sigma \int j^2$dV $\sim(\partial\emptyset/\partial \mathrm{x})^2 \cdot v^2 \cdot$ V $\sim B^2$.
- Duty Cycle: Pulsing: 4 ms/200 ms= 2%; Factor 2 for entering and exiting the dΦ/dx-zone; Factor ½ due to half sine pulse: Total 2 %. This helps a lot!

Induced Currents and Flux around the Target.



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Minimise Magnetic Effects on the Rotating Wheel.

- Produce axial field profiles Bz with small radial extension and small dΦ/dx.
- However, even with small Bz the gradients dBz/dx can be high (see opposit coils). These cause transverse fields Br which contribute to magnetic effects in the target.
- Avoid return flux penetrating through the target.
- Place beam impact closer to the rim of the wheel?
- Av. Power and Torque: Shorten pulse duration $\tau < 4$ ms. 2 ms may still be possible?

Average Power and Torque in the Wheel at 50 kA(very preliminary!)

- Consider only an axial field Bz at the wheel from a pair of Twin-Coils with small dBz/dx.
- Laminating the target widths from 1.0 cm to 0.5 cm reduces the power by a factor ~3.

Free Coil Aperture	Av. Bz	Av. Power. Lamination 1 cm.	Av. Torque. Lamination 1 cm.	Av. Power. Lamination 0.5 cm.	Av. Torque. Lamination 0.5 cm.
2 cm	2.5 T	250-380 W	1.25-1.9 Nm	85-125 W	0.4-0.6 Nm
4 cm	3.3 T	400-600 W	2.0 -3.0 Nm	130-200 W	0.65-1.0 Nm

Comments

- The magnetically induced power should be kept below 200 W, 10 % of the beam power of 2 kW. This would increase the wheel temperature of 550-600 oC by about 25 K.
- Not all of the induced currents, as assumed above, contribute to the torque. Possibly only half?
- Still, the position and velocity of the wheel must be tightly controled.
- Example: An average torque of 0.25 Nm would cause a drift of rotation velocity of $\Delta\omega/\omega$=2 10^-4 over 1 s. Therefore, the impact pattern of the beam around the target rim would shift over this time by 2 cm. A fast control loop is required!

Laboratory Test of Eddy Current Effects in the Ti-Wheel.

- Instead of inducing currents by a stationary flux in a rotating wheel:
- Use a pulsed magnetic flux on a stationary sector of the wheel: dϕ(eq)/dt .
- This is much simpler and, by scaling, should produce reliable results.
- The pulse duration applied to the stationary sector should be equivalent to the transition time of the rotating wheel through the quasi stationary zone where dϕ/dx is non zero. Here a width of this zone of 1 cm is assumed.
- Thus, the transition time is of the order of 0.1 ms, requiring an a.c.-magnet of some 5 kHz. Such devices are used in industry for induction heaters.

What to measure?

- Measure the rate of temperature rise and thus the deposited average power in a thermally isolated Ti-strip.
- The width of the strip should be about the same as the width of the solenoidal field, where the dB/dx is non zero and which only contributes to the induced currents.
- With a coil conductor size of the solenoid of 1 cm, this zone will also extend over a width of about 1 cm.
- The effect of lamination can readily be measured by heating simultaneously two strips, each with half the width of 0.5 cm.
- Some estimates of the upper limits of the braking Lorentz force should be possible.
- Clearly, these tests must be backed up by computer simulations.

5. Conclusions.

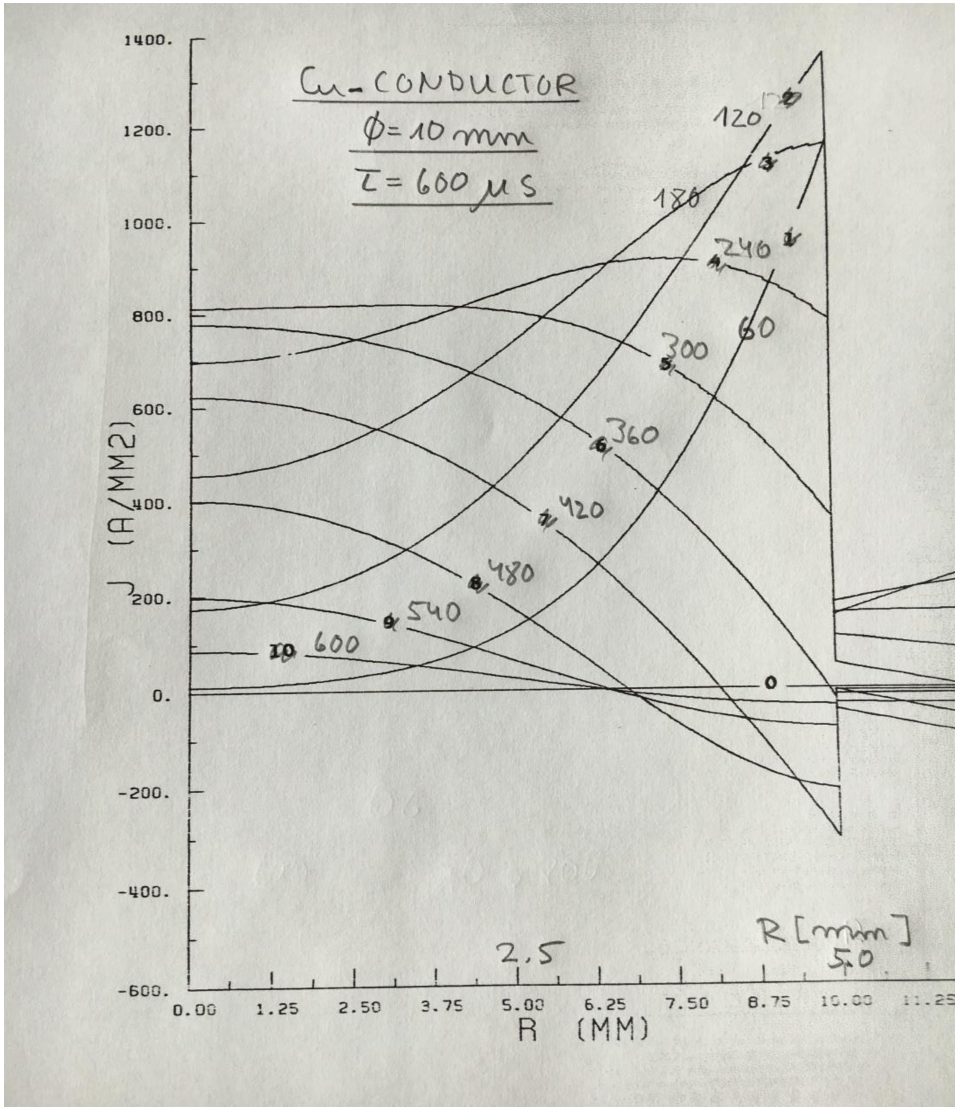
- Mature engineering designs have been evaluated for the target wheel, its cooling by radiation and its rotation in vacuum using magnetic bearings.
- As a next step, these issues must be validated by small scale loboratory tests and should be funded in the next future.
- Pulsed coils as a matching device can provide high fields of several Tesla, near to or even inside the target and are stable in time over 1 ms.
- Their strength is, however, limited by the power in the coils as well as by parasitic heating of the rotating wheel by eddy currnets.
- The pulser for the coils must still be designed.

- The e+ yield must now be evaluated and optimised by using appropriate combinations of coil geometries and peak currents while minimising the magnetically induced power and friction in the rotating target.

- This should bring the Undulator driven e+ source very close to reality and hopefully to increased yields!

Thank You For Your Attention.

Backups



Cu-CONDUCTOR
ϕ=10 mm
τ=600 μs
J (A/MM2)
1400.
1200.
1000.
800.
600.
400.
200.
0.
-200.
-400.
-600.
0.00
1.25
2.50
3.75
5.00
6.25
7.50
8.75
10.00
11.25
R (MM)
R [mm]
2,5
5,0
120
180
240
60
300
360
420
480
540
600
0
1
2
3
4
5
6
7
8
9
10

Magnetic Field in a Singel Current Loop.

- Bz(z,r=0)$= \mu \cdot I \cdot r^2/\sqrt{}(z^2+r^2)^3$
- For z=0: 1/r
- For z$\gg r$: r^2/z^3

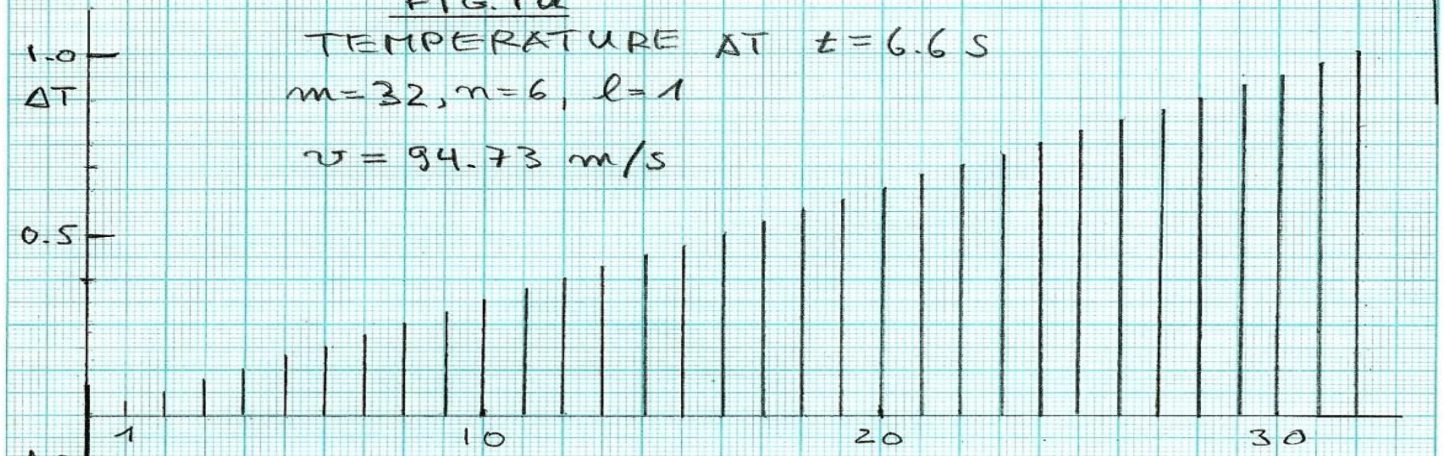


FIG. 1a

TEMPERATURE ΔT $t = 6.6$ S

$m = 32, n = 6, l = 1$

$v = 94.73$ m/s

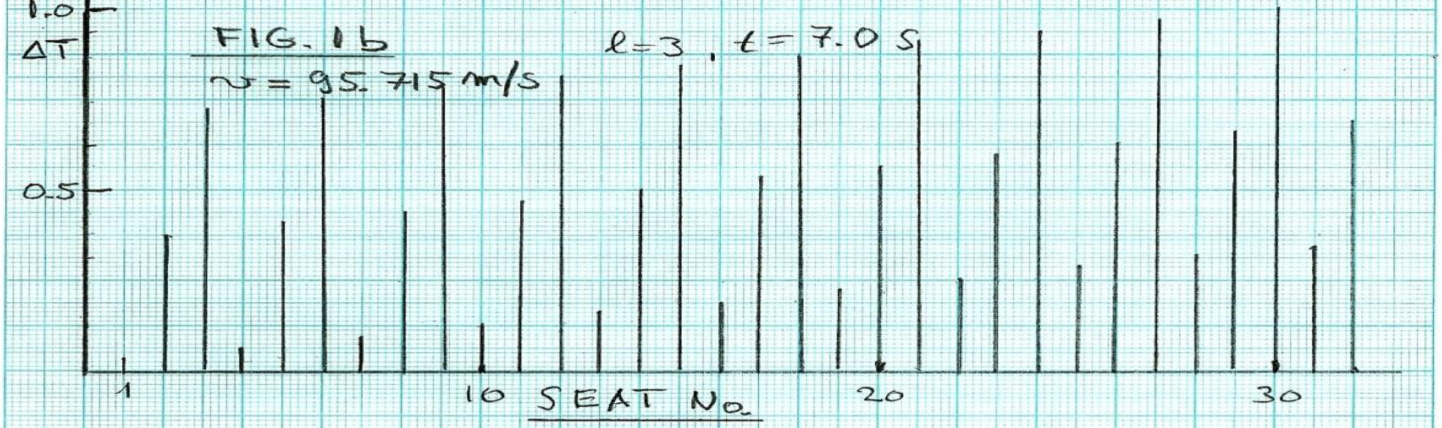


FIG. 1b

$v = 95.715$ m/s

$l = 3, t = 7.0$ S

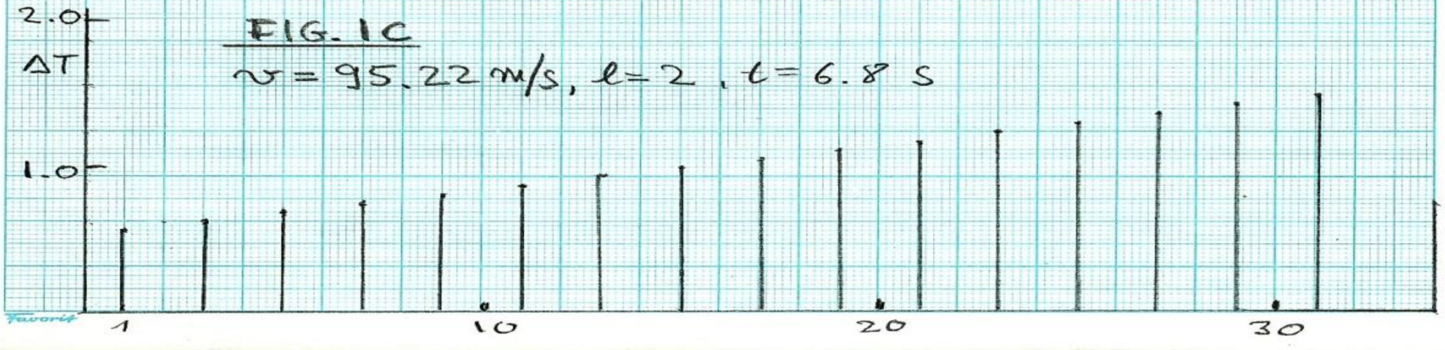


FIG. 1C

$v = 95.22$ m/s, $l = 2$, $t = 6.8$ S