Status: Undulator e^+ source WBS

G. Moortgat-Pick, S. Riemann,
Jim Clarke, Peter Sievers

Outline

- – Status TDR Baseline
- – Transfer 250 GeV
- – Open issues
- – Outlook: undulator collaboration

Status TDR lattice baseline

- Rather complete lattice exists for $\sqrt{s}$=500 GeV
  - source: OMD
  - pre-acceleration e+,e- to 125 MeV (NC)
  - pre-acceleration e+ to 400 MeV (NC)
  - 5 GeV booster (SC)
  - spin rotator+energy compression
  - DR
- Auxiliary source for commissioning (1% beam intensity)
  - uses microwave photo cathode gun
  - 500 MeV e- drive beam on same target
  - about 40 m long
- Lattice has been optimized from capture section up to DR injection
  - maximum transmission but minimum emittance growth

Status TDR lattice baseline

- Usual beamline instrumentation to measure orbit, emittance, energy spread.
  - Special diagnostics to ‘e+ unique systems’, e.g. target
  - BPM etc.
  - Performance specifications less demandind than for ML, RTML
- Positron source magnets
  - ~160 dipoles, ~500 quads, ~250 corrector magnets
  - Magnet designs ‘straight forward’
  - 27 DC solenoids (for focusing e+ at low energies)
  - 2 SC solenoids for spin rotation
- Dumps (electron and photon beam dump)
  - altogether 9 dumps (2 x tune-up dumps (400kW), 6 x based on solid-metal construction, 1xphoton dump), 16 var. ap. collimators, 1 fixed-ap. collimator, 5 stoppers

Required TDR lattice updates for Prelab

- Changes
  - instead of 150 GeV undulator drive-beam: 125 GeV drive-beam
  - slight undulator parameter changes (range of K~0.85 - 0.92)
  - photon energy (1st) ~8 MeV instead of ~10 MeV
- Maybe Inclusion of e+ source polarimeter
- Inclusion of final designs for undulator optimization (WP5), rotating wheel (WP6) and OMD (WP7)
  - not under WBS discussion

➡ Lattice updates: probably only small manpower efforts needed in prelab, since already a very detailed lattice exists (-> Benno)

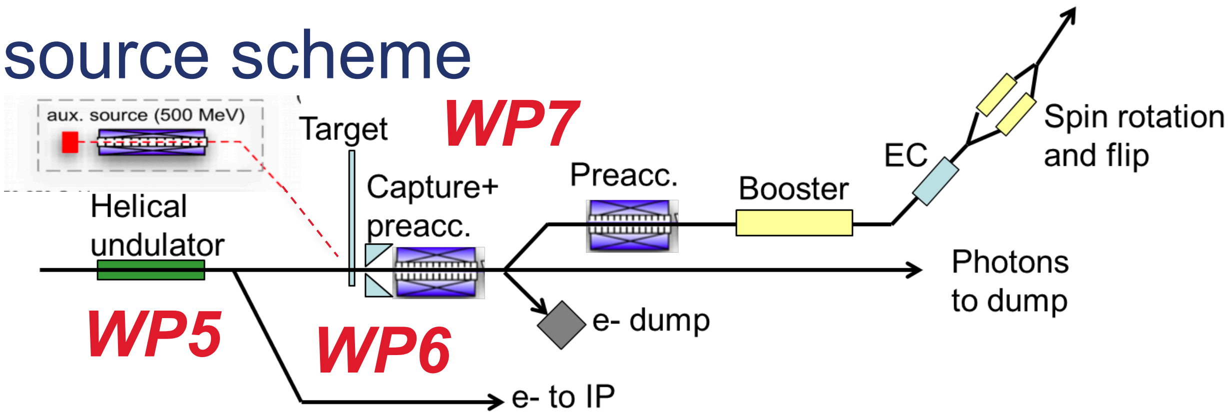
➡ R&D issues exactly following TDR

Started a list:
- *** TDR status**
- *** update**
- *** prelab**
- *** FTE**

Area	Sub-items	covered in TDR	updates required	Prelab Phase	FTE	
System						
	Lattice	✓	no			
Photon production						
Positron transport						
Booster Linac						
Linac-to-DR Line						
Optic parameter						
Accelerator components						
	Undulator parameters	✓				
	Target System WP6					
	OMD WP7					
	SW&TW structure	✓	no			
	Magnets:~160 di, ~500 quad, ~250 cor	✓	no			
	Diagnostics: BPM system	✓	no			
	Dumps:9					

Open Issues:

The polarized e+ source scheme



Work package	Items
WP-5: Undulator	Simulation (field,errors, alignment, masks)
WP-6: Rotating target	Design finalization, partial laboratory test, mock-up design
	Magnetic bearings: performance, specification, test
	Full wheel validation, mock-up
WP-7: Magnetic focusing system	Design selection (FC, QWT, pulsed solenoid, plasma lens), with yield calculation
	OMD with fully assembled wheel

– Required WBS on these items: Benno's talk+update Peter

Open Issues for prelab

- Recommendation of Review panel: invest more manpower&money to demonstrate feasibility
  - should get highest priority
  - current activities: form/re-new undulator collaboration
  - strong interest and experience
  - lots of experience and mature undulator technology
  - regular meetings
  - involved so far: US labs, EU labs, CERN, Japan (?)

- Problem:
  - potential money in US: not before end 2023!

➡ not really a chance to have prototypes finished in 2024….

Further news and Conclusions

- Peter: already technical specifications and in contact with Jülich lab+industry
- Simulations for OMD ongoing
- ‘Old’ and ‘new’ collaborations fostered

- BUT: we have to get the money
- Labs can only contribute ‘parasatically’ to their ongoing work (as soon as it is not a ‘project’)
- High international prioritization would be desired…

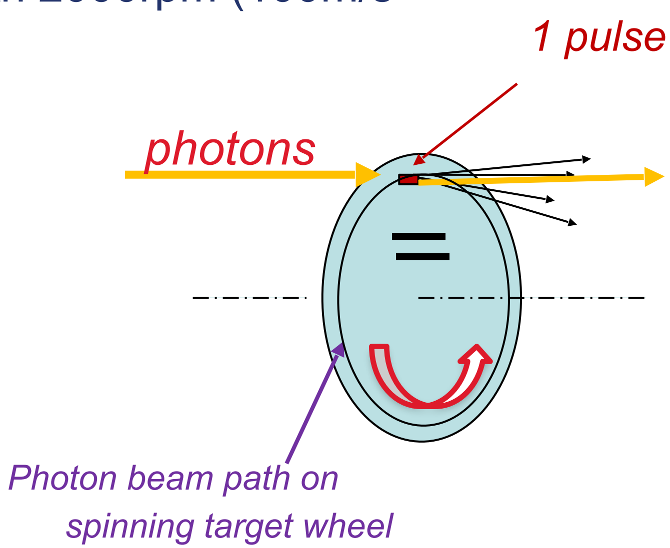
Back-up

The conversion target

- Located ~240m downstream the undulator exit
- Undulator photon beam, few 10^{16} γ/sec, ~60-70kW
- Only few % of the photon beam power is deposited in the target

- Target design:
  - Wheel (~1m diameter) spinning in vacuum with 2000rpm (100m/s tangential speed) to distribute heat load
  - material: Ti6Al4V

- Target thickness:
  - ILC250:
    - Av. photon energy is O(7.5 MeV);
    - target thickness of 7mm ($0.2X_0$)
    - Power deposition ~2kW (nominal Lumi)
  - ILC500:
    - Av. photon energy is O(27 MeV);
    - target thickness of 14.8mm ($0.4X_0$)
    - Power deposition ~2kW (nominal L)



- Photon beam hits wheel at r=0.5m
  - One pulse with1312 (2625) bunches occupies ~7 (~10)cm
  - Every ~7-8sec load at same target position
  - in 5000h roughly 2.5×10^6 load cycles at same spot

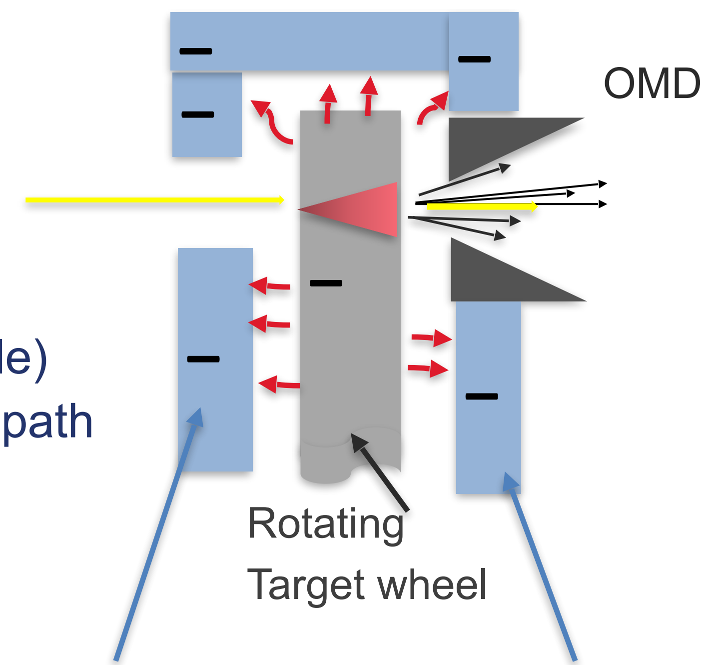
Cooling of the target wheel

- Water cooling (TDR design) does not work
- Few kW heat deposition can be removed with thermal radiation:
  - heat radiates from spinning target to a stationary water-cooled cooler

$$P \sim \sigma \varepsilon A \left(T_{radiator}^4 - T_{cool}^4\right)$$

ε = effective emissivity

Side view cutout e+ target

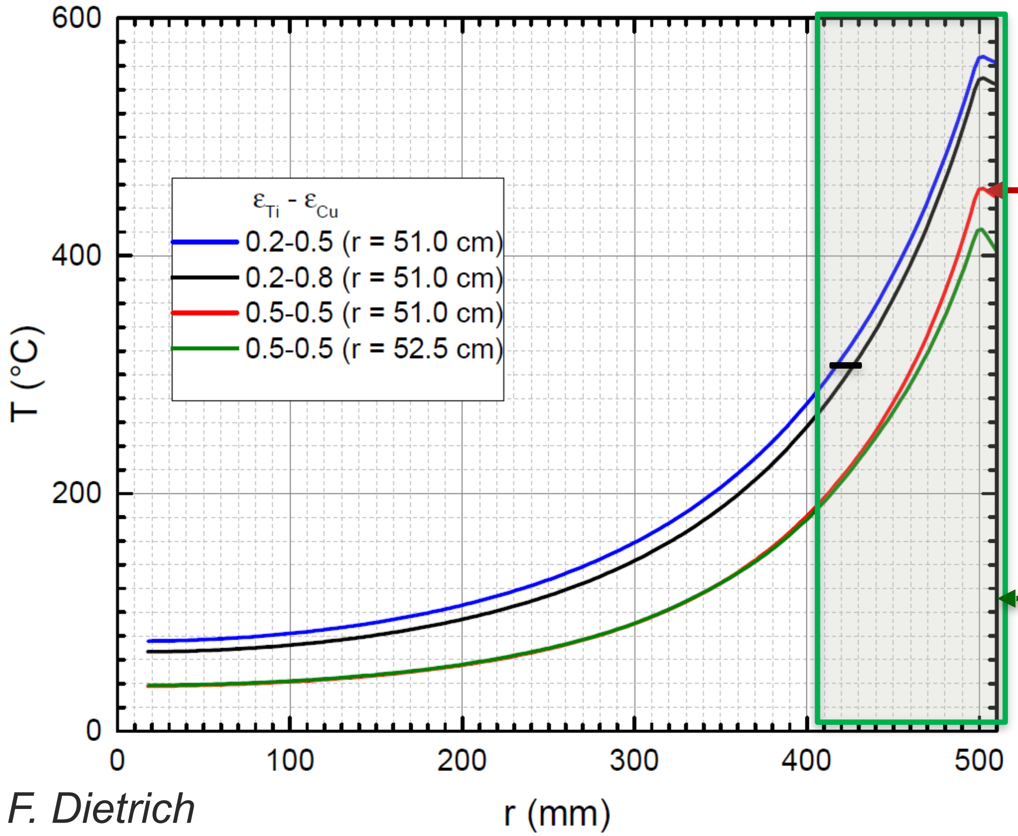


stationary water-cooled cooler, T_{cool}

- Ti alloys have low thermal conductivity
  (λ = 0.06 – 0.15 K/cm/s)
  - heat propagation ~ 0.5cm in 7sec (load cycle)
  - heat accumulates in the rim near to beam path

Temperature distribution in target

Average temperature in Ti6Al4V wheel as function of radius r for different surface emissivity of target and cooler (Cu); Target wheel assumed as disk



F. Dietrich

Photon beam impact at r=50cm

Deposited power = 2kW

ε_{eff}= 0.33 for ε_{Ti} = ε_{Cu}=0.5

T_{ave} ≤ 460˚C

max average temperatures can be decreased for larger wheel radius

Main cooling power from area with r_0 ±5cm

Studies (FLUKA, ANSYS) show that such spinning disk stands heat and stress load

WP6: wheel design (1)

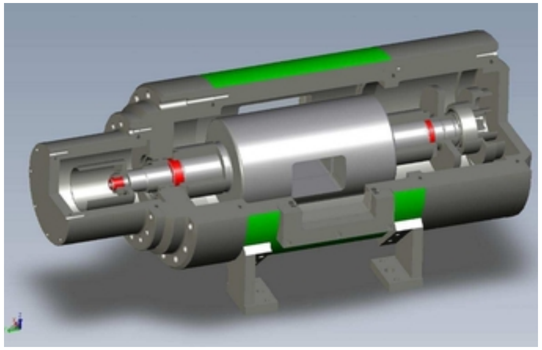
- Material:
  - material tests with load similar as expected at ILC were done using the e- beam at Microtron in Mainz → Ti alloy will survive load cycles for ≥1 year
  - To be continued to study strength against high cyclic peak load at high T (luminosity upgrade)
  - Include alternative alloys with high T and high strength
- Target geometry
  - Optimize temperatures, stresses, thickness etc. while maintaining the required e+ yield
  - Study influence of eddy currents (heating, drag forces) caused by B field at target from OMD
  - Studies to be done with ANSYS, COMSOL,…
- Lab test of target sector to confirm cooling performance
- Drive and bearing
  - Magnetic bearing for vacuum-tight spinning wheel

WP6: wheel design (2)

JÜLICH
FORSCHUNGSZENTRUM

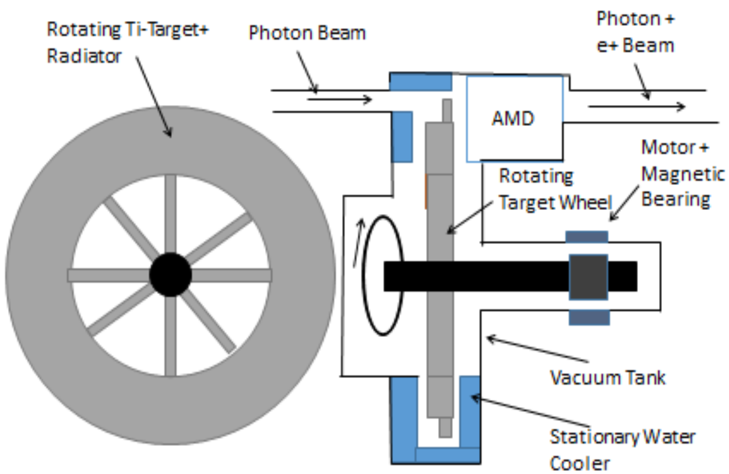
Drive and bearings

- Radiation cooling allows magnetic bearings
  - A standard component to support elements rotating in vacuum.
  - The axis is «floating» in a magnetic field, provided by permanent or electro magnets
  - Allows long time operation at high rotation speed without maintenance
  - Among other things,magnetic bearings are used as Fermi-choppers in Neutron Physics and Spallation Sources.
  - Breidenbach et al. (SLAC) presented at ICHEP2016 a design proposal using magnetic bearing (see backup) for the undulator target
- For the specific ILC-application, a technical specification of the required performance and boundary conditions has to be negotiated with the supplier.
  - Specification to be done based on simulation studies

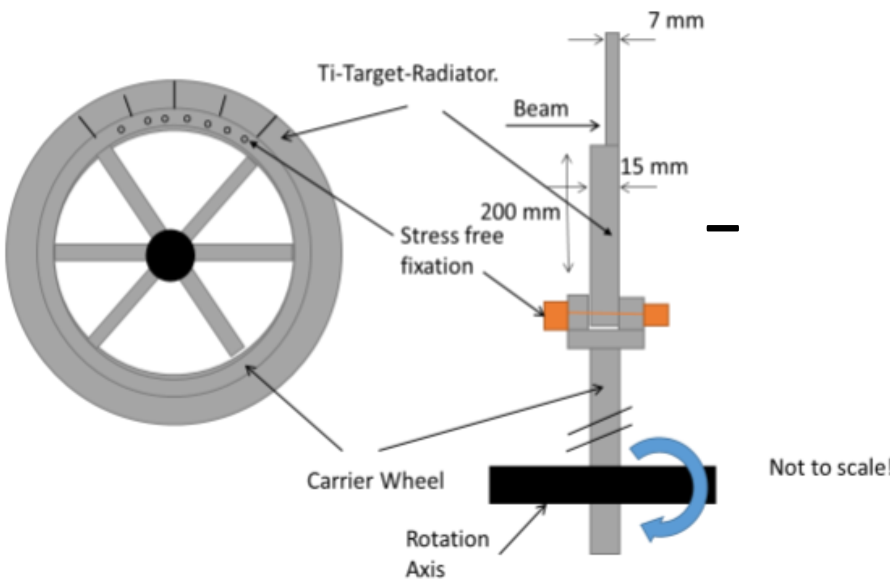


Fermi-Choppers für BRISP
Copyright: Prof. Dr. Pilgrim, Philipps-Universität Marburg

Principle layout: Ti wheel with diameter 1m, rotating at 100m/s, 2000rpm
Main components: cooling system, magnetic bearing , OMD



Target can be connected with carrier wheel of appropriate material to optimize cooling performance



Layout of wheel and details of target sectors detail mounted onto carrier wheel

- free thermal expansion
- Reduced eddy current
- synchronize rotation with beam pulses by fine tuning to avoid luminosity loss by expansion slots

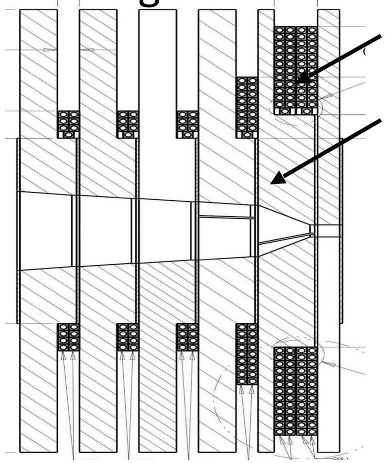
An OMD for the Collection of Positrons for the ILC-Undulator driven Source (WP 7).

A feasibility study and preliminary design and engineering parameters.

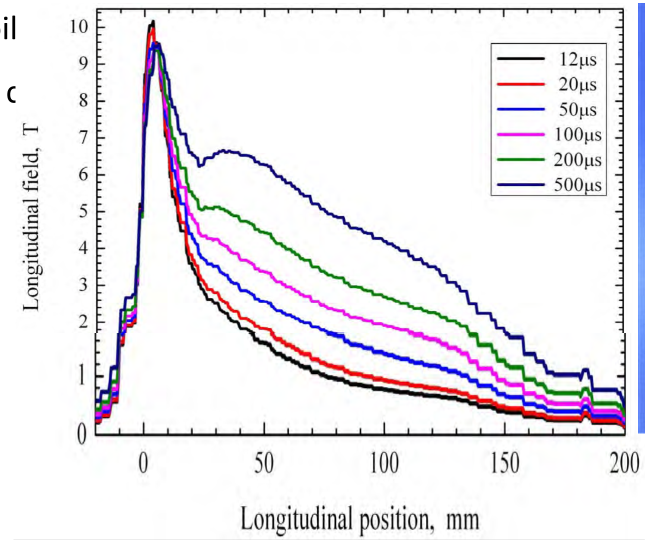
Previous Considerations and Design Studies

Ref.:
S. Antipov, PAC07 (Rot. Pos. Target in Pres. of OMD Field)
I. Bailey, EUROTeV-Report-2008-028,EPAC08 (Prototyp ILC Target Wheel)

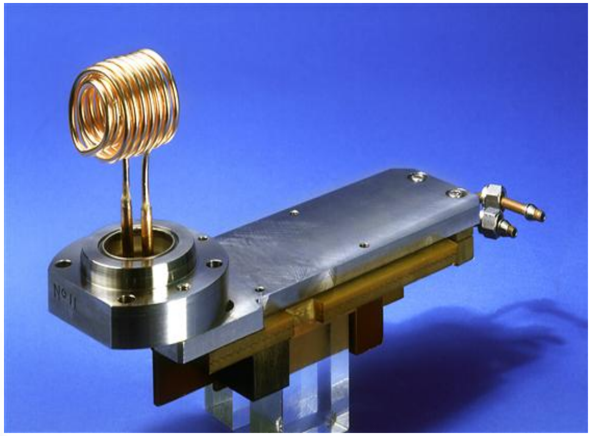
LLNL, Long Pulse Flux Concentrator.
J. Gronberg et.al. 2012



Spinning wheel, water cooled.
Ferro Fluid rotating vacuum seal.
Flux Concentrator for long pulses, coils cooled by liqu. Nitrogen or water.



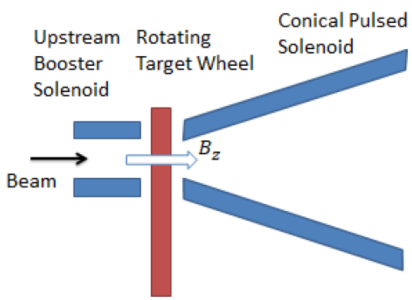
Long Pulse Flux Concentrator. P. Martyshkin-BINP-2014

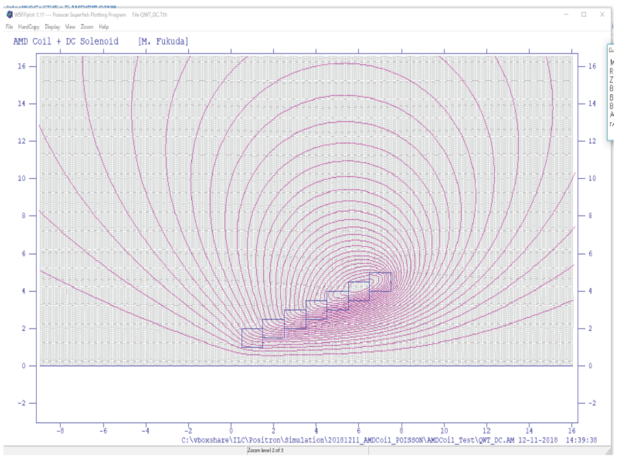


Short Pulsed LEP Solenoid.
0.83 T, 2.5 kA,100 Hz

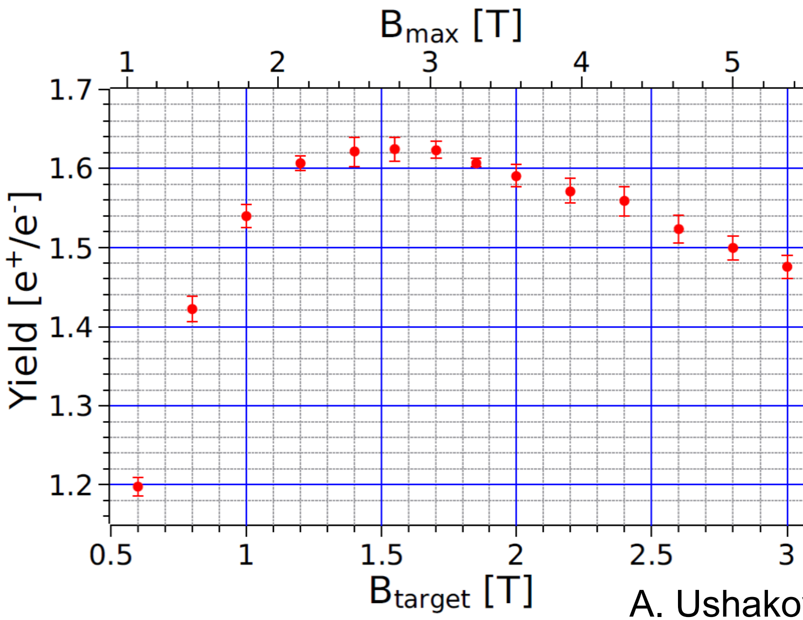
Pulsed solenoid

Idea presented by P. Sievers at POSIPOL18 and LCWS19, arXiv:2002.10919





- Currently, most favoured option
- Optimization to achieve 1.5e+/e-

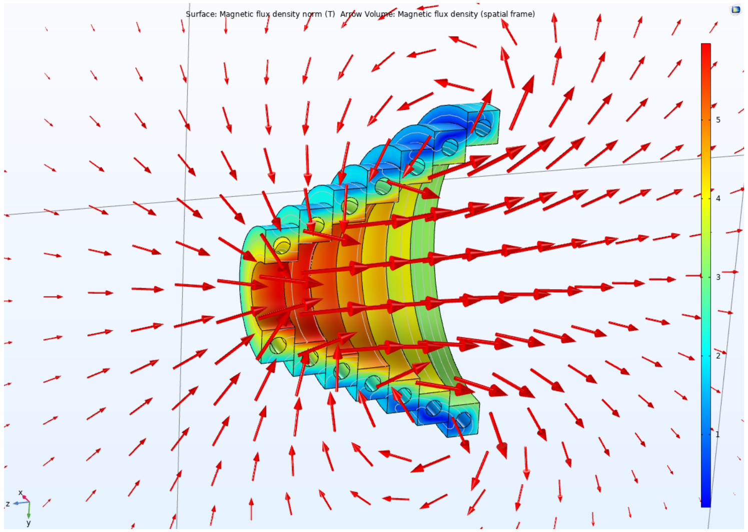


A. Ushakov

Peter started detailed simulations with Matthias Mentink, CERN

Ref.: M. Mentink-CERN (Priv. Comm. 21.1.2021). COMSOL-Multyphysics Code.

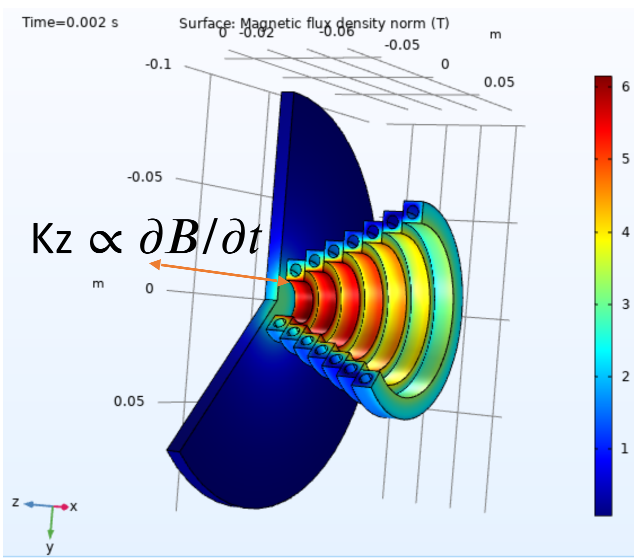
- Operating current: 50.5 kA
- Inductance: 1.4 µH
- Stored magnetic energy at full current: 1750 J
- Volume: 1.1e-4 m3
- Conductor cross-sectional area (not including hollow core) : 7.2e-5
- Conductor length: 1.3 m
- Assumed conductor resistivity: 1.7e-8 Ω×m
- Average dissipation, when considering skin effect: 9 kW

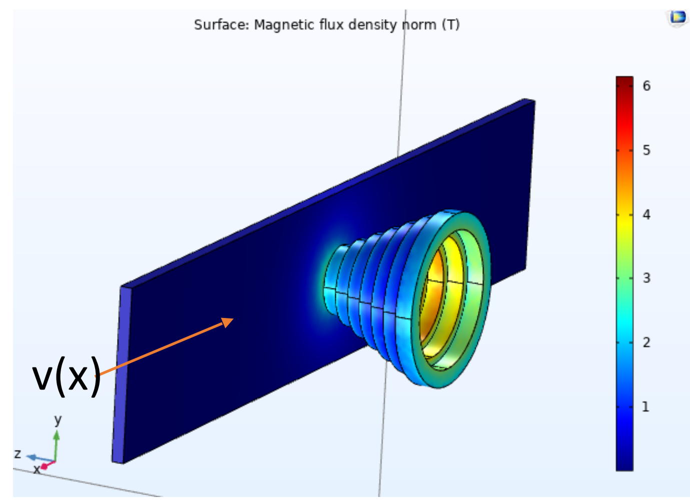


Preliminary values for the wheel with R=0.5 m, a peak field of 3.2 T and a pulse of 4 ms.

Due to the pulsed solenoid: Axial peak forces Kz and av. power Wz, deposited in the wheel:
$\ll$+/- 100 N/pulse and $\ll 100W$.

Due to the velocity of the wheel: Braking force Kx and power Wx, deposited in the wheel: < 200N/pulse and < 200W av.





To Do List for OMD and Conclusion.

- Yield to be optimized in the muliti-dimensional «Phase Space»:

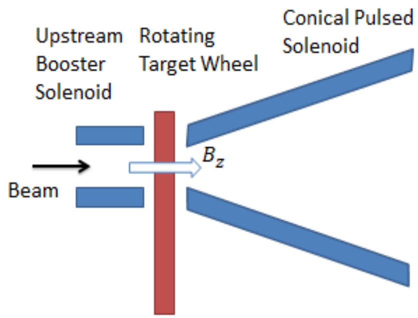
- Magnetic peak field and shapes.
- Time stability of the field over the 1 ms by pulse durations of $> 4ms$.
- Pulse duration and av. Joule heating and cooling of the coil.
- Magnetic forces and stresses in the coil.
- Life time of the solenoid under cyclic load and radiation damage.

- Volume and surface of the wheel for cooling by thermal radiation.
- Minimize temperatures and stresses in the spinning wheel due to the magnetic field of the solenoid (Laminate the target, iron flux trap).
- Cyclic mechanical loads transmitted to the magnetic bearings.
- Current leads and pulser.

- Maximum input parameters were chosen to exploit the limits of the system: Peak values 50 kA, 5.2 T.
- Realistic parameters: Peak field 3.2 T. Helps a lot in terms of forces and power: factor 2.5 down.
- Longer pulse duration for field stability causes a penalty for the deposited power.

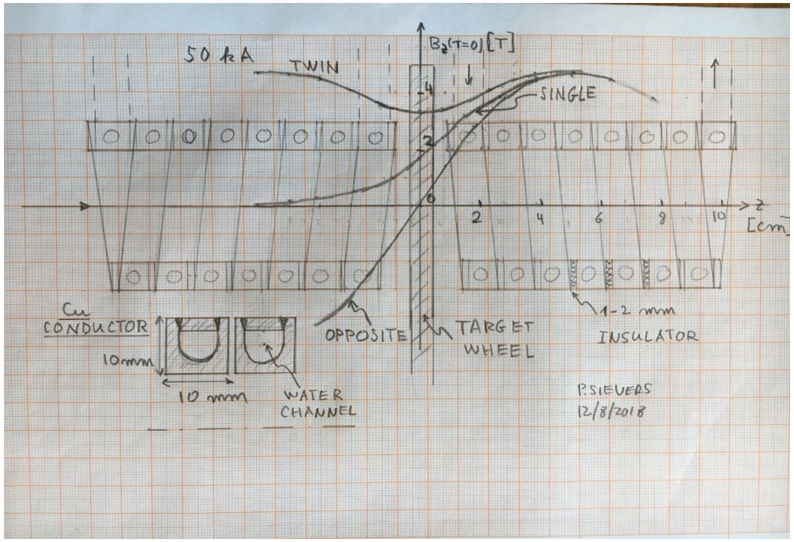
- Reliable predictions are possible by established FEM-codes.
- A prototype of the OMD can be built and tested within 2-3 years, provided a pulser is available.
- The mutual response between the spinning wheel and the solenoid can be benchmarked by using a stationary wheel in a solenoid with fast pulses of ~100 μs (Magnets used for induction heating?).

Possibilities to optimize the yield by adjusting the field in the target-solenoid gap.



Use the upstream coil as a Bucking Coil «opposite» or as a Booster Coil «twin».

Aperture 4 cm, 50 kA, 7 turns

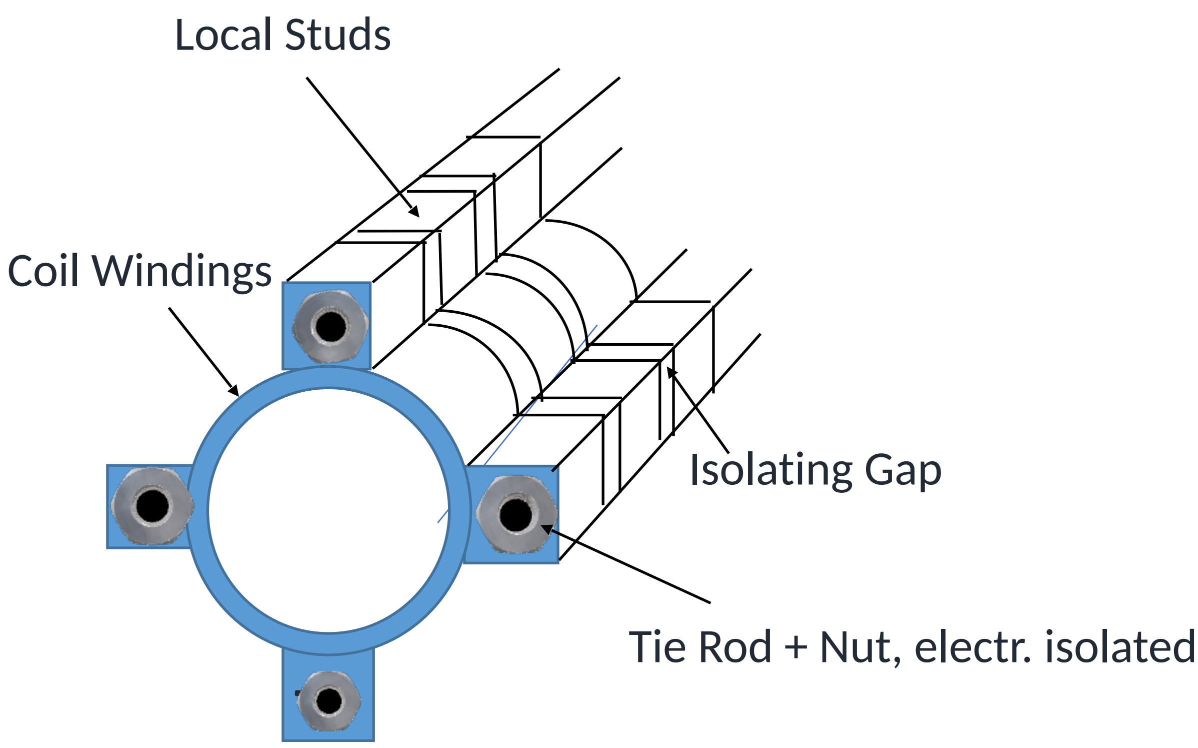


Design Parameters for the Conical Pulsed Solenoid.	
Half sine pulse duration	4 ms
Peak current	50 kA
Repetition rate	5 Hz
Average electrical power/m	6 kW
Water cooling flow	0.17 l/s
Temperature rise in cooling water	9 K
Peak magnetic field	5.2 T
Field at target	3. T
Field at target with upstream booster coil	4. T
Stress due to magnetic field	40 MPa
Beam effects at nose of the FC at r=1 cm	PEDD 13 J/g *
Average beam power density	600 W/ *
Thermal stress	100 MPa *
Displacement per atom (dpa)	0.15/ 5000 h *

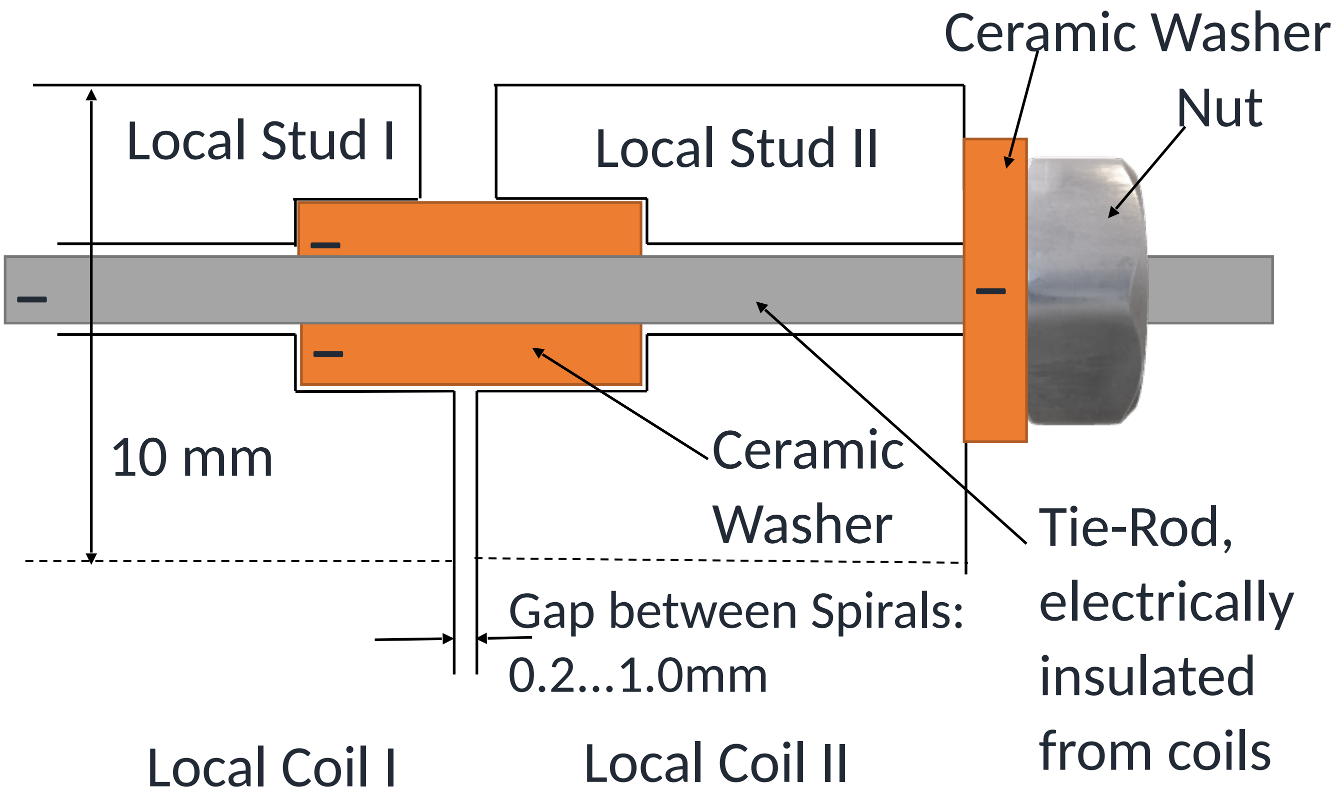
* Critical values!

Increase aperture to 3 cm. Compensate loss of field by upstream booster coil

Engineering Design of the pulsed Solenoid: a proposal.



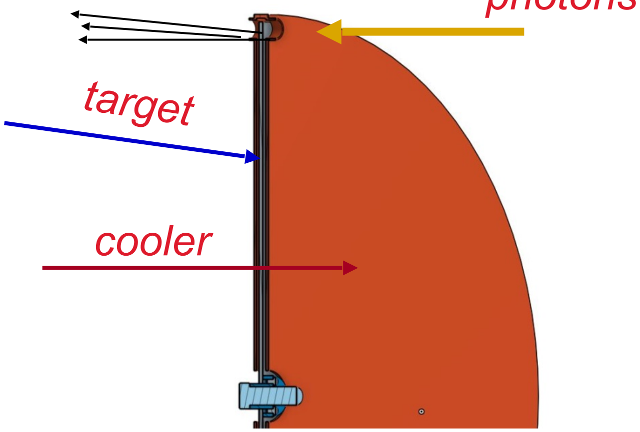
Layout for Clamping and Retaining the Coil Windings by tie rods



Cooling of the target wheel

- Few kW heat deposition can be removed with thermal radiation:
  - heat is radiated from spinning target to a stationary water-cooled cooler

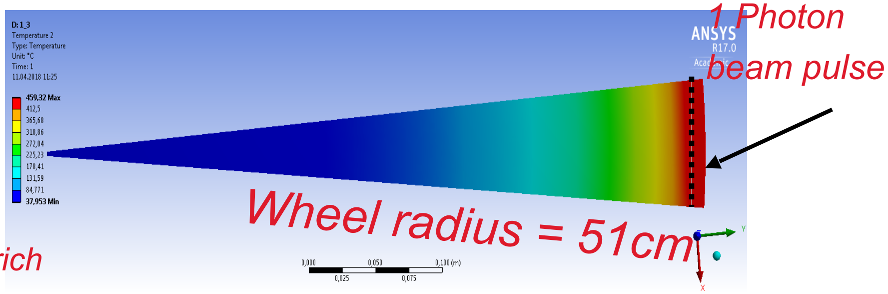
$$P \sim \sigma\varepsilon A\left(T_{radiator}^4 - T_{cool}^4\right)$$



  - ε = effective emissivity
  - Rough estimate: for 2kW power deposition about 0.6 m^2 are needed to keep material at 400^0 C average temperature (ε = 0.3)

- simulations for temperature distribution in the target wheel cooled by thermal radiation

Average temperature distribution in a target piece corresponding to 1 pulse length *(ε_{eff}= 0.33; ε_{Ti} = ε_{Cu}=0.5)*



F. Dietrich

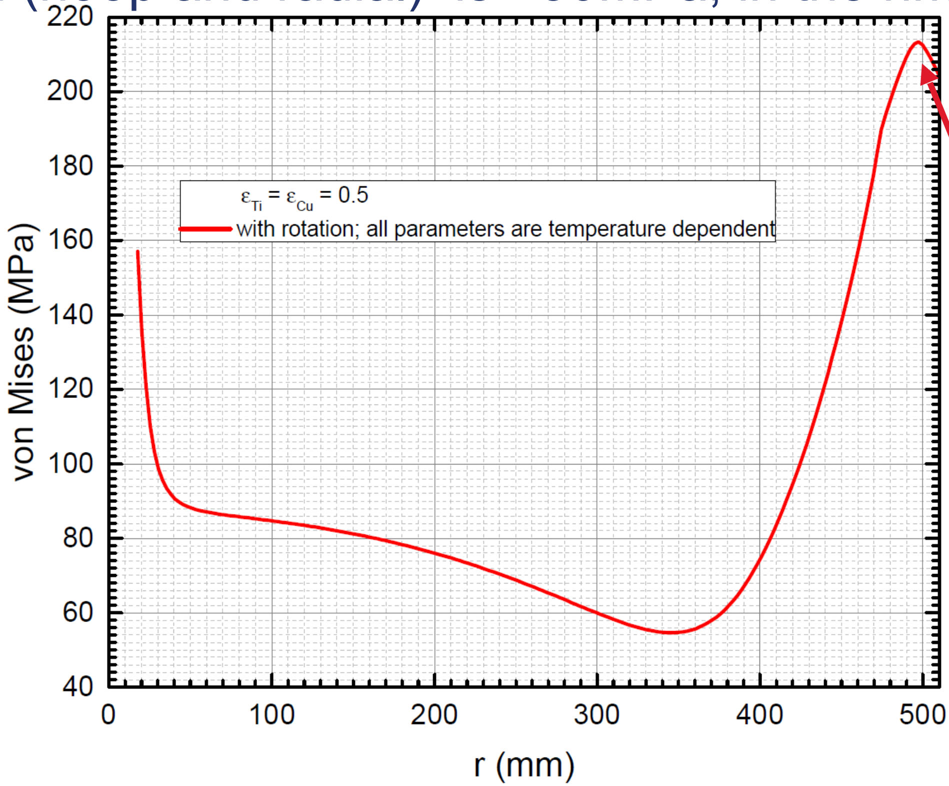
Average stress in target, ILC250, 1312b/pulse

ANSYS simulations: Consider spinning target disc, thickness 7mm, r_{out}= 51cm ,beam hits target at r=50cm

- Material expansion ⇔ high thermal stress in beam impact region
- Stress due to rotation (hoop and radial) is <50MPa, in the rim region <10MPa

Average von Mises stress along wheel radius r

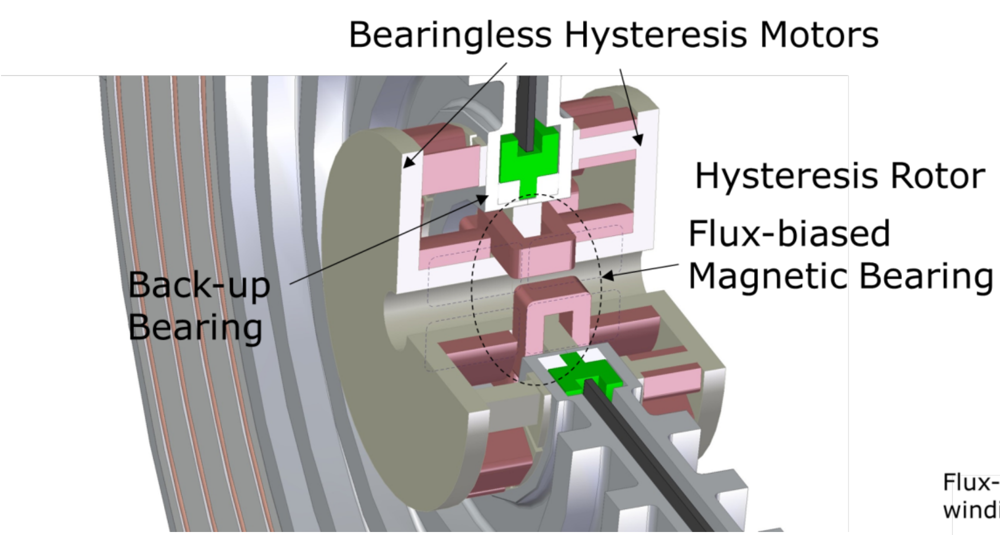
σ_{vM} < 220MPa

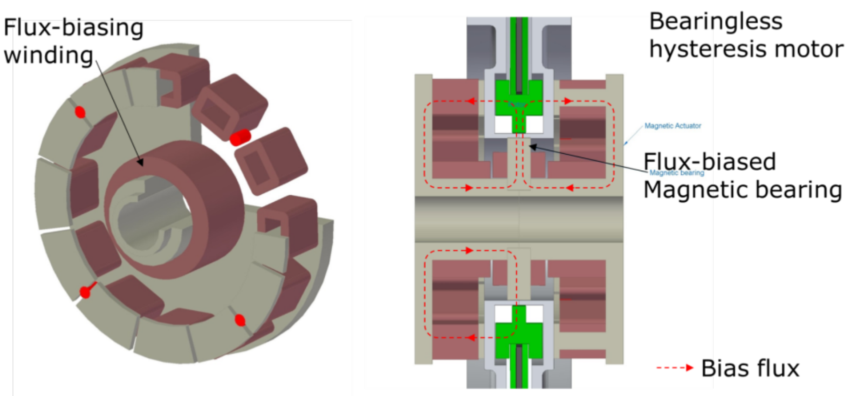


F. Dietrich

Drive and bearing

Design Proposal by M. Breidenbach et al, ICHEP 2016:





Capture optics

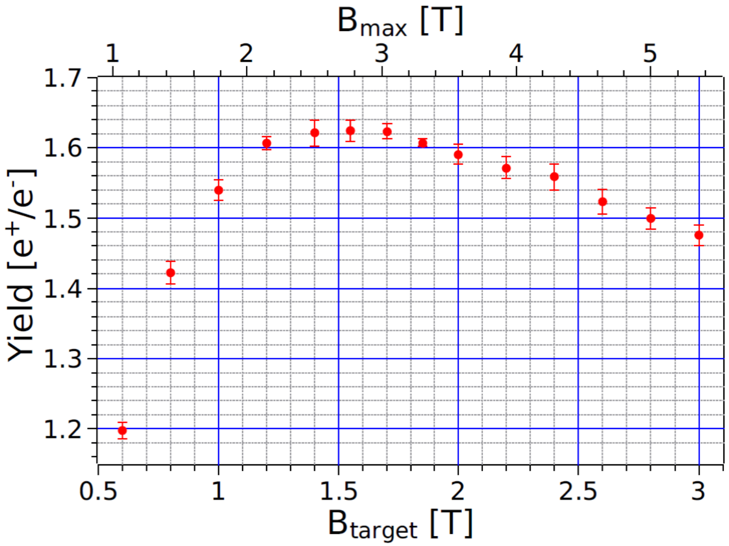
- High B field very close to target for high yield
- low (or zero) B field at target to avoid eddy currents
- TDR: Flux concentrator
- Prototyping at LLNL (J. Gronberg)
    - Bmax stable during 1ms pulse (1ms)
    - But B(z, t) , i.e. luminosity varies during pulse

QWT

- current design: e+ yield to low for ILC250

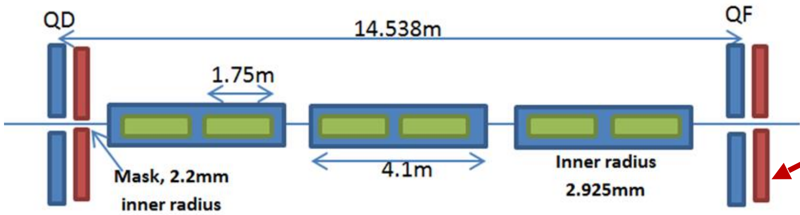
Pulsed solenoid

– Pulsed B field at target
– increases e+ yield but
– increases load at target
– only slightly



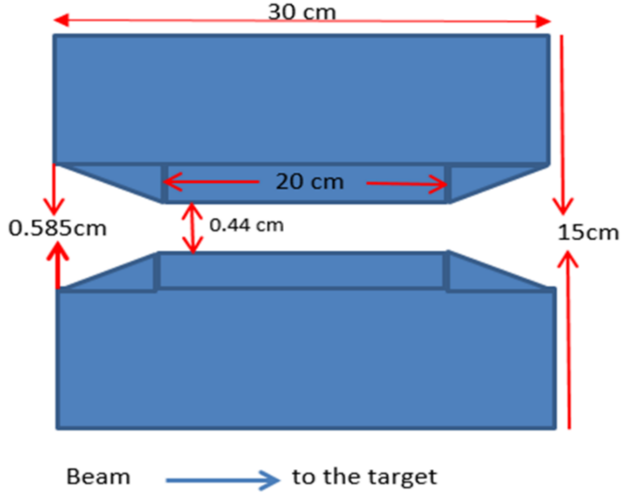
Power Deposition on Undulator wall must be < 1W/m

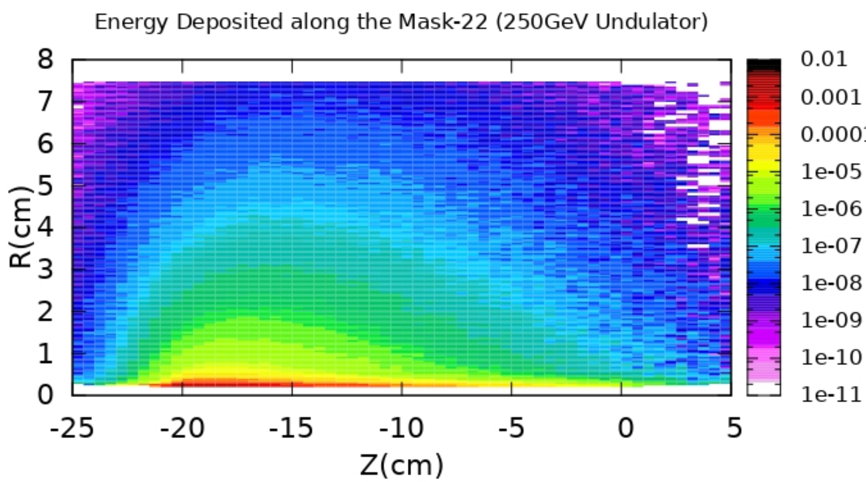
K. Alharbi



22 masks to protect undulator wall

Mask design (Cu)



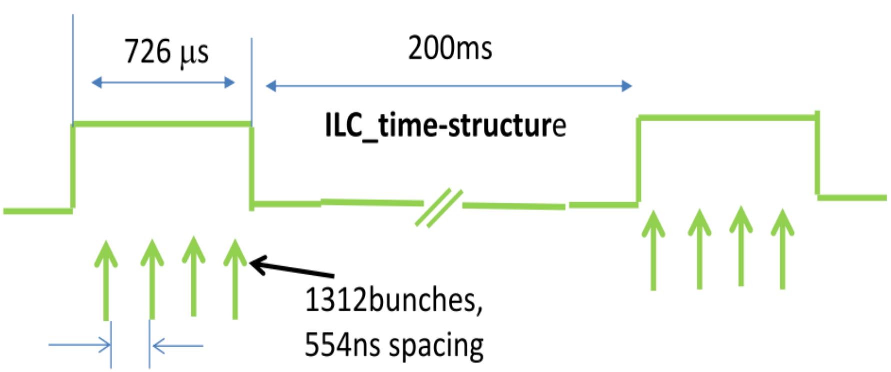


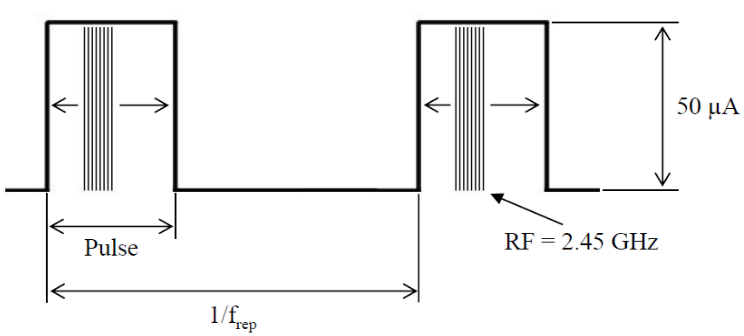
	Deposited power [W]	PEDD [J/g/Pulse]	ΔT_{max} [K/Pulse]
ILC250 (mask 22)	335	8.07	20.97

Target Tests:

	ILC e+ target	MAMI	
Beam particles	photons	electrons	
Average energy	7.5…40MeV	14MeV, 3.5MeV, 180MeV(plan)	
ΔT_{max} /pulse	60-120K	50-350K	
Max energy deposition density	~60J/g	~50-200J/g	
Eff. pulse length on material	25-55μs	1-5ms	O(50μs)
Eff. pulse rep rate on material	0.17 Hz	1Hz …120Hz	
Displacement per atom (dpa)	~0.3-0.5 per year	~0.33/24h (14MeV) ~0.22/24h (4MeV)	

IPAC2017, IPAC2014, IPAC2012



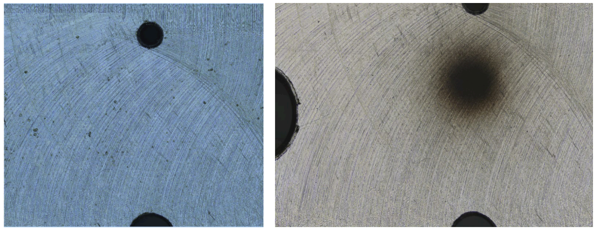


Target analyses via synchrotron diffraction

T. Lengler, BThesis2020

- analyze target materials via scanning as well as synchrotron diffraction methods
- advantage of synchrotron diffraction: both surface as well as structure of targets with several mm thickness can be precisely studied
- Analysis via Synchrotron diffraction: x-rays of 87.1 keV with different beams size

Target before and after radiation:

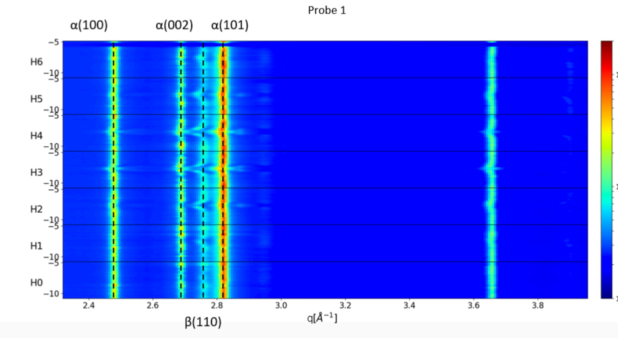


Before After

Results of diffraction method:

- Phase transitions between α- and β-phase in Ti-alloy observed in case of heavy overloading
- Thin foils of Ti and Ti alloys stand high PEDD

α/β phase transitions in Ti-6Al-4V:



Further plans: Target tests with e- of 180 MeV with different materials (W, Al,.)

- synchrotron diffraction at PETRAIII: detailed surface analyses and different angle resolution incl. det. of phase parameters

ILC250 and GigaZ options

ILC250:

- 125GeV e- beam requires high K and maximum active undulator length of 231m
  - Upper half of energy spectrum is emitted in cone ~1/γ masks are necessary to limit the energy deposition in the undulator walls to 1W/m

GigaZ: see arXiv:1908.08212

- 3.7+3.7 Hz scheme: use 125GeV e- beam for positron production, alternating with 45.6GeV beam for physics
- A 45.6GeV e- beam has low power, photon energy is low → no problem for target.

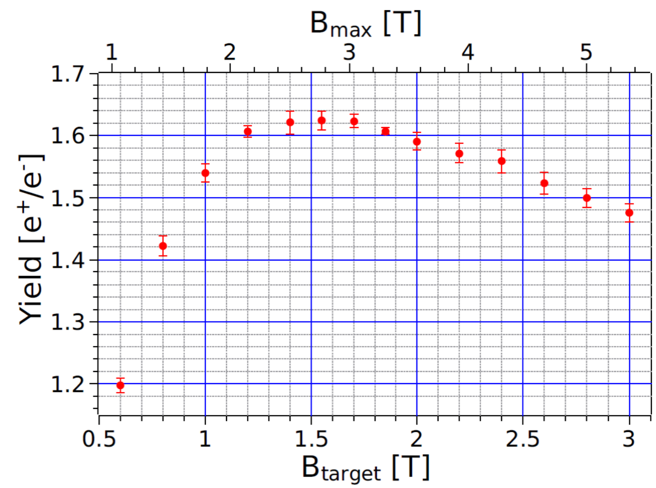
OMD: Pulsed solenoid

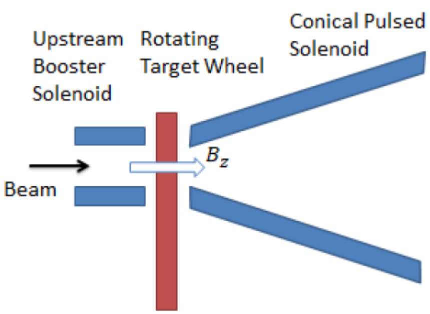
arXiv: 2002.10919

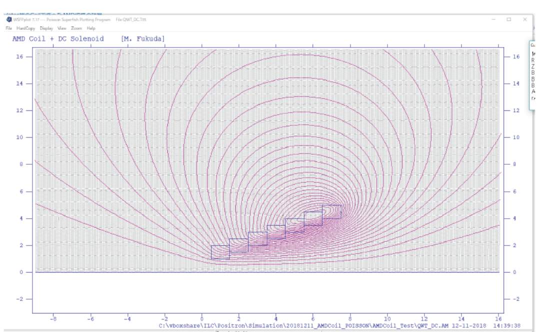
Idea presented by P. Sievers at POSIPOL18 and LCWS19, see also proceedings

Pulsed B field at target

- increases e+ yield
- Increases load at target only slightly







Peak magnetic field	5.2 T
Field at target	3 T
Field at target with upstream booster coil	4 T
Stress due to magnetic field	$\leq$ 40 MPa
Beam induced effects at entrance of the solenoid, r=1 cm	PEDD 13 J/g
Average beam power deposition	600 W/cm^3
Thermal stress	$\approx$ 100 MPa
displacement per atom (dpa)	0.15/5000 h