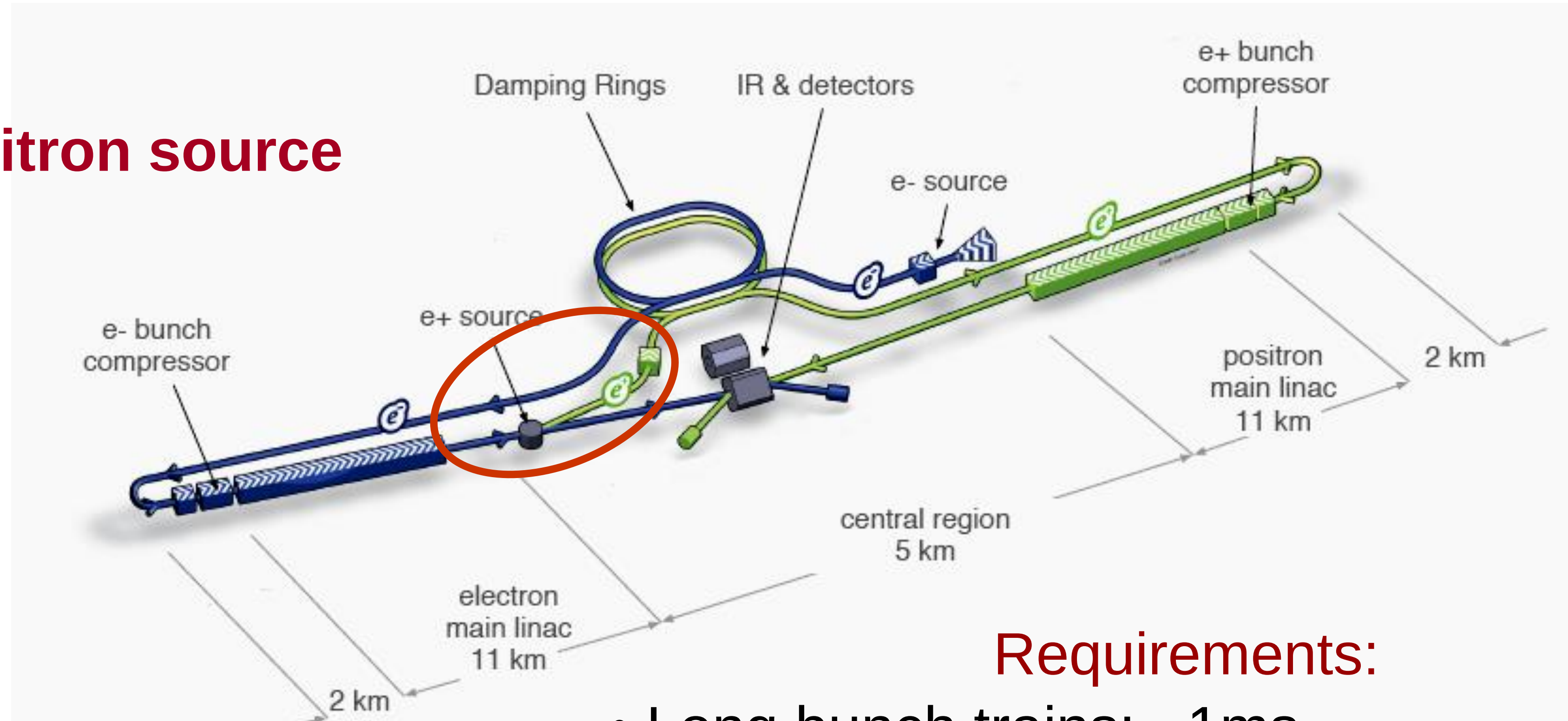
ILC Positron Source
Where are we, and what is still needed?

102nd ILC@DESY General Project Meeting
6 December 2013
Sabine Riemann, DESY Zeuthen

Outline

- Introduction
- ILC positron source
  - e+ production
  - Undulator based source
    - Undulator parameters
    - Target
    - Optical matching device (flux concentrator)
    - Source parameters
      - 240GeV…500GeV
      - Photon collimation & e+ polarization
    - Spin flipper
    - Upgrade to 1 TeV
- Alternative: conventional source
  - 300Hz scheme
- Summary

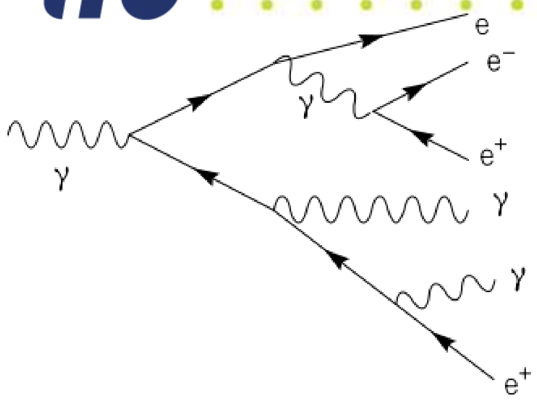
Positron source



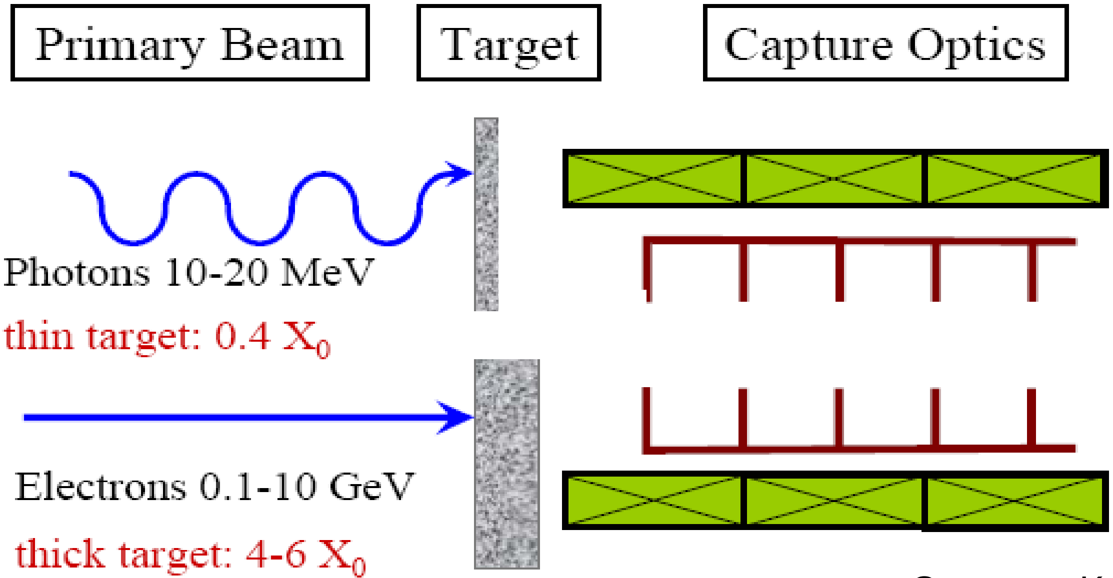
Requirements:

- Long bunch trains: ~1ms
  1312 (2625) bunches per train, rep rate 5Hz
  2×10^{10} particles/bunch
- Small emittance
- Beam polarization

Production of Positrons



Electromagnetic showers
to generate positrons



Courtesy: K. Floettmann

Problems

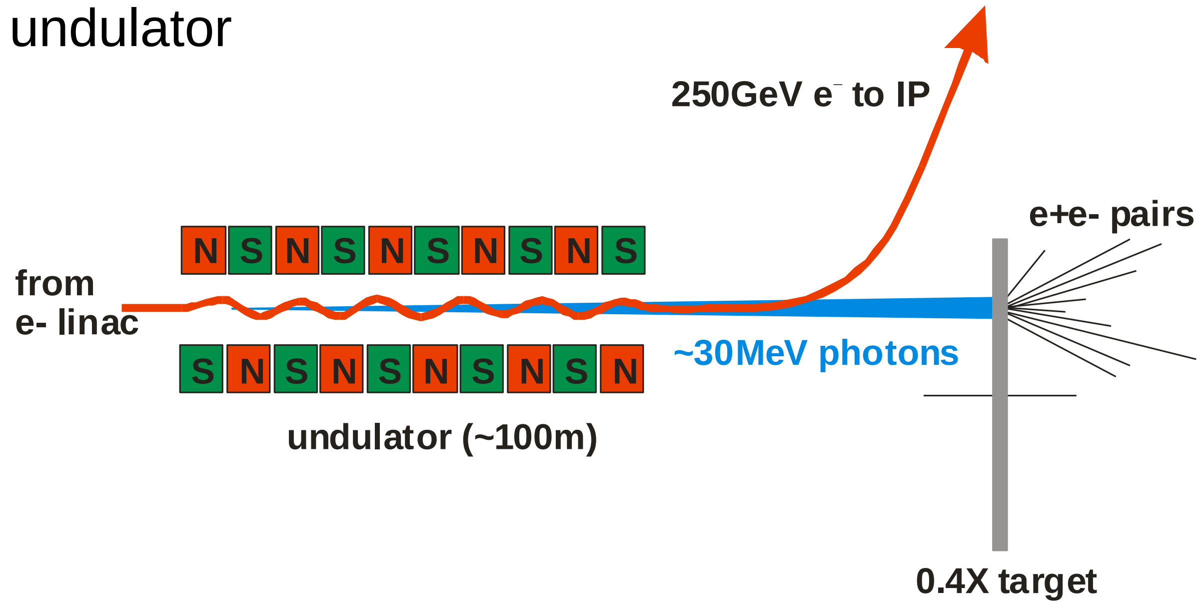
Large heat load

Huge heat load

Generation of Positrons using photons

How to create the intense photon beam?

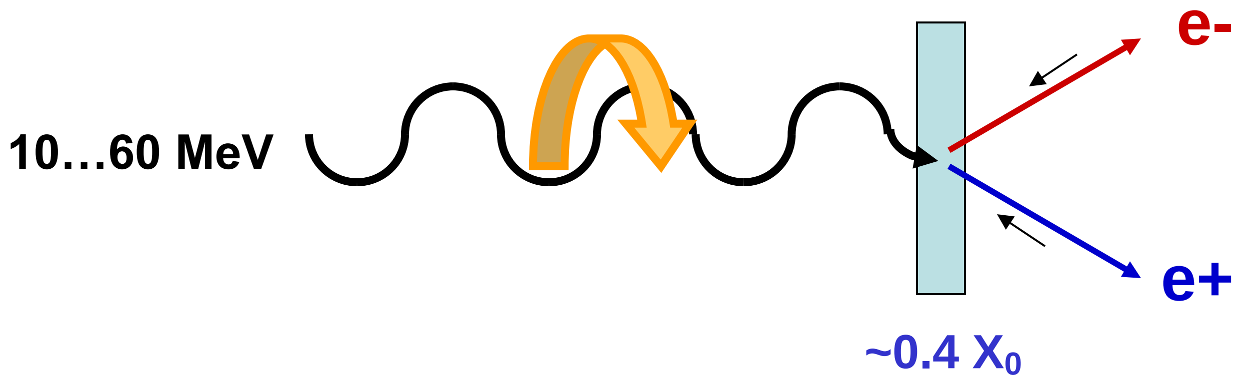
- Compton backscattering of laser light off an electron beam
- Undulator passed by e- beam
  - Planar undulator



→ photons are not circularly polarized

Generation of polarized positrons

- Circularly polarized photons produce longitudinally polarized positrons and electrons



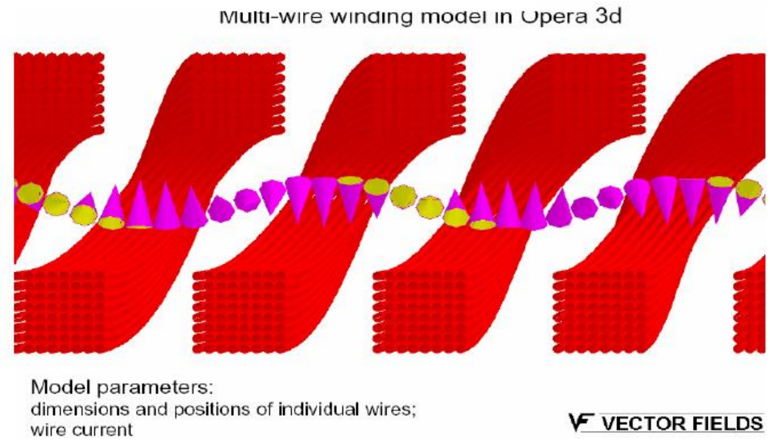
- Methods to produce polarized photons
  - Radiation from helical undulator (Balakhin, Mikhailichenko, BINP 79-85 (1979)),
    - Proof-of-principle exp. E-166 experiment @ SLAC (Alexander et al., NIMA610:451-487,2009
  - Compton backscattering of circularly polarized laser light off an electron beam
    - Test experiment at KEK: Omori et al., Phys.Rev.Lett. 96, 114801 (2006)

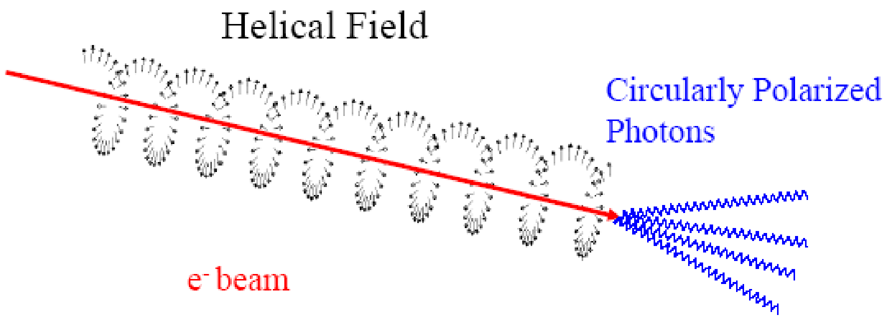
Generation of polarized Positrons

Helical undulator

→ Circularly polarized γ

→ generation of longitudinally polarized $e^{\pm}$





– Photon yield: helical undulator gives about 1.5…2 higher yield than planar undulator for the paameters of interest (See also Mikhailichenko, CLNS 04/1894)

– Polarization sign is determined by undulator (direction of the helical field)

ILC Undulator based e+ source

Undulator Parameters

- Photon energy (cut-off first harmonic) and undulator K value

$$E_1 \cong 23.7\,\mathrm{MeV}\frac{(E_e/50\mathrm{GeV})^2}{(\lambda_u/1\mathrm{mm})(1+K^2)}$$

$$K \cong 0.0934\frac{B_0}{1\mathrm{T}}\cdot\frac{\lambda_u}{1\mathrm{mm}}$$

λ_u = undulator period

- Number of photons
  - Increase intensity of γ beam by longer undulator

$$\frac{dN_{ph}}{dL} \cong \frac{30.6}{\lambda_u/1\mathrm{mm}}K^2 \; photons/m/e^-$$

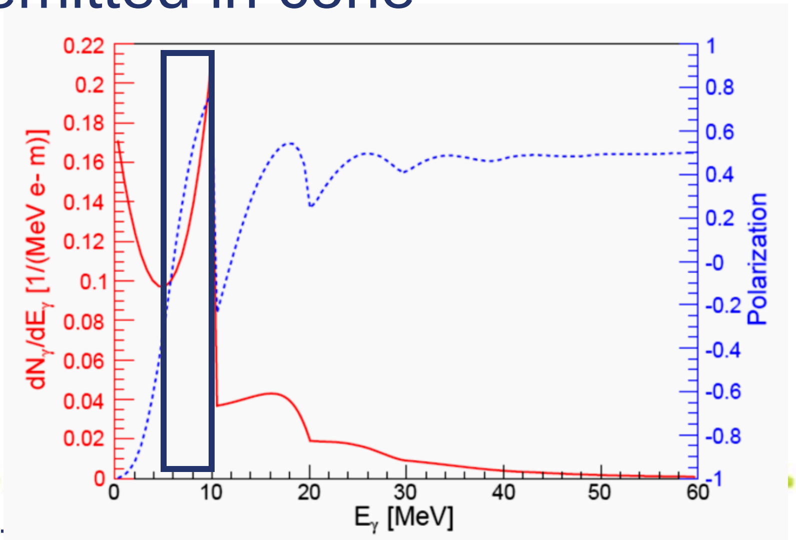
⇔ Y = 1.5 e+/e-

- Upper half of energy spectrum is emitted in cone

$$\theta = \frac{\sqrt{1+K^2}}{\gamma}$$

- Photon spectrum

  → Higher polarization with γ collimation



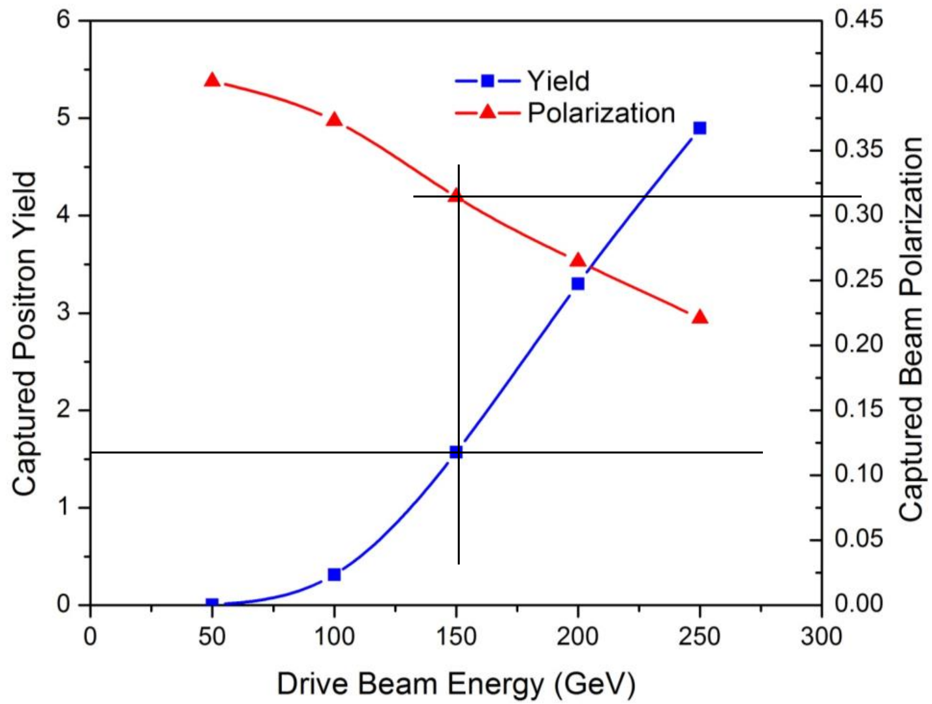
ILC Undulator

Parameters

Parameter	Value
Period (mm)	11.5
K	0.92
Field on Axis (T)	0.86
Beam aperture (mm)	5.85
First Harmonic Energy (MeV)	10.1
Nominal Drive Beam Energy(GeV)	150

Undulator windings:

NbTi

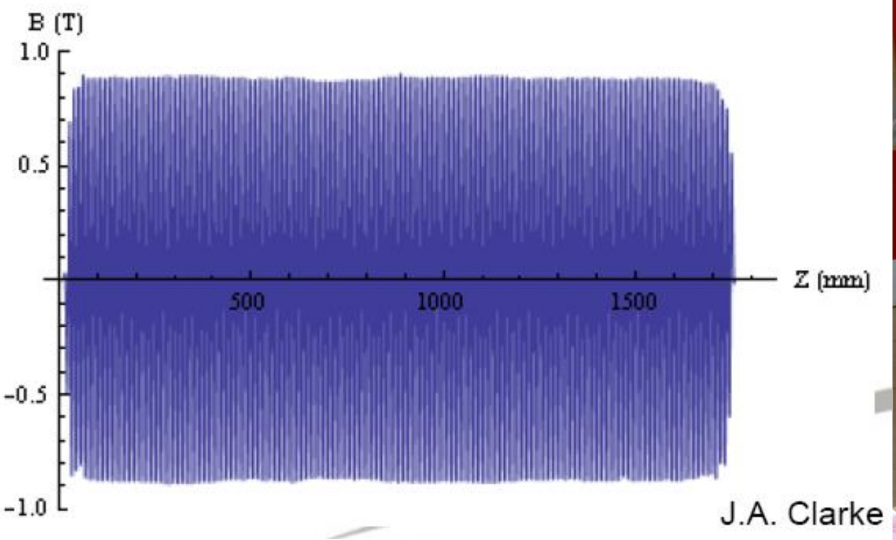


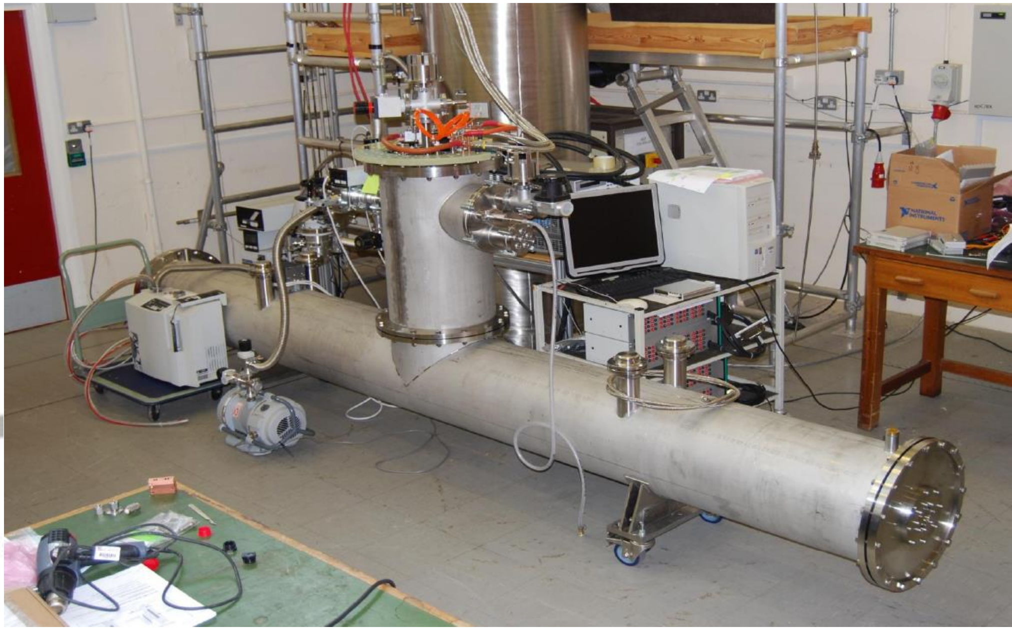
Positron yield and polarization vs drive e- beam energy (L_u=147m, no photon collimation)

➔ P ≈ 30%

ILC Undulator Prototype

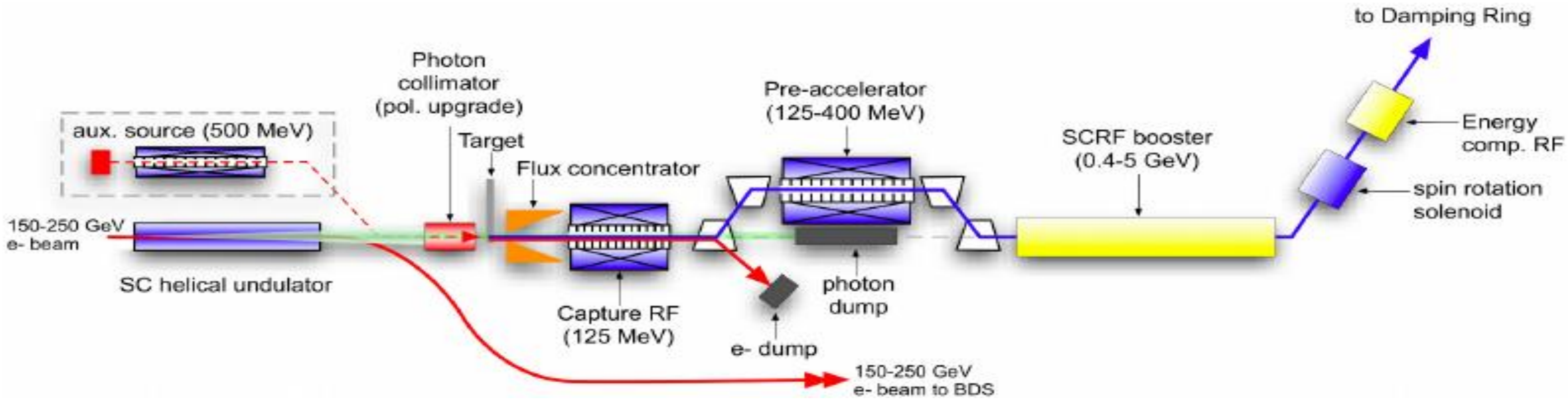
- sc undulator ⇔ high peak field
- 4m long prototype built at Daresbury Lab (UK):
  - Two 1.75m long undulators (11.5mm period)
  - RAL team has shown that both undulators have very high field quality
    - Field on axis 0.86 T (K=0.92) measured at 214 A
    - ILC specification ⇔ now show stopper identified





More details see J. Clarke, BAW-2 Meeting, SLAC Jan 2011

ILC Positron Source

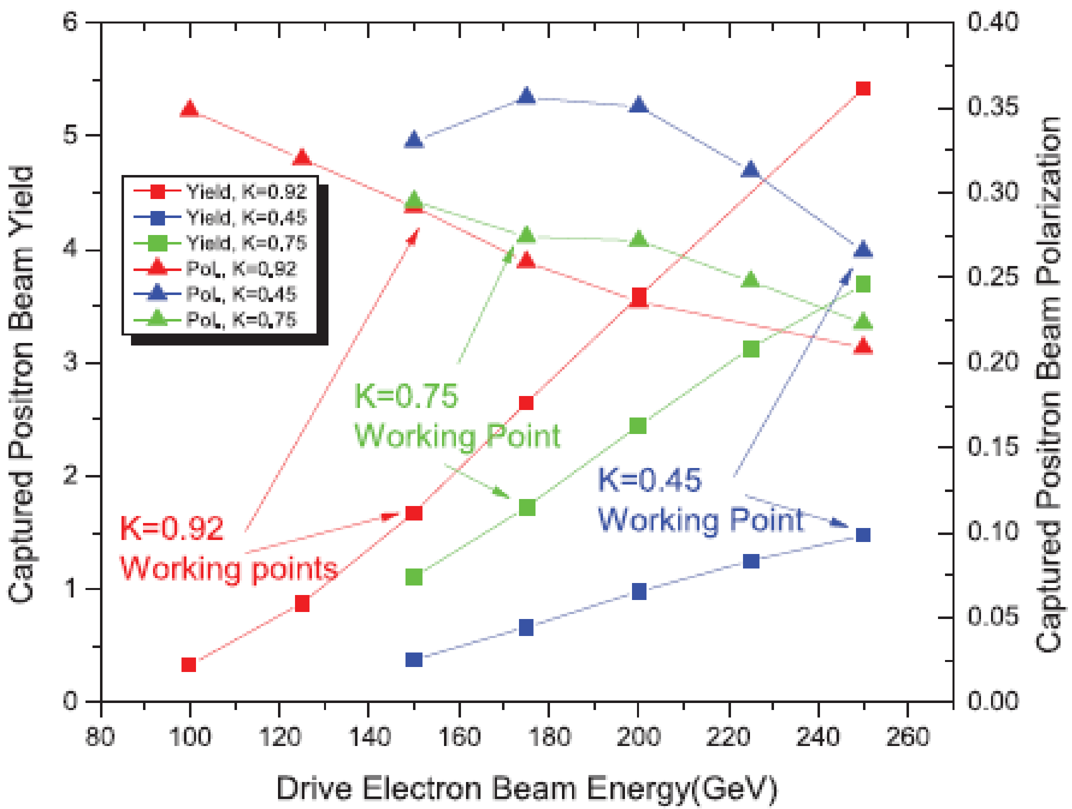


Positron source is located at the end of the electron linac

- **required positron yield Y=1.5 e+/e-**

- Superconducting <u>helical</u> undulator – 231m active length
  → positron beam is polarized
- Photon-Collimator to increase e+ pol
  - Removes part of photon beam with lower polarization
- e+ Production Target, 400m downstream the undulator
- Positron Capture: OMD (Optical Matching Device)
  - Pulsed flux concentrator

- e+ source is located at end of the linac ➔ polarization and yield are strongly coupled to the electron beam energy!
- Optimum undulator parameters (K, undulator length) depend on E_e
- With higher energies smaller beam photon beam spot size on target → high polarization is difficult to achieve for high energies (heat load on target and photon collimator)

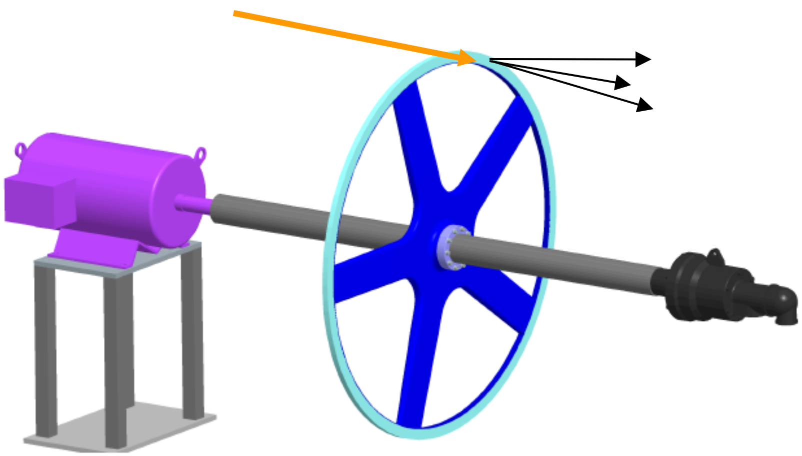


ILC TDR

Positron Target

- Material: Titanium alloy Ti-6%Al-4%V
  Thickness: 0.4 X_0 (1.4 cm)
- Incident photon spot size on target: σ ~ 1.7 mm (rms) (Ee- = 150GeV)
  ~ 1.2 mm (Ee- = 250GeV)
- Power deposition in target: RDR ~8% (10.4 kW)
  TDR 5-7% (< ~4kW)

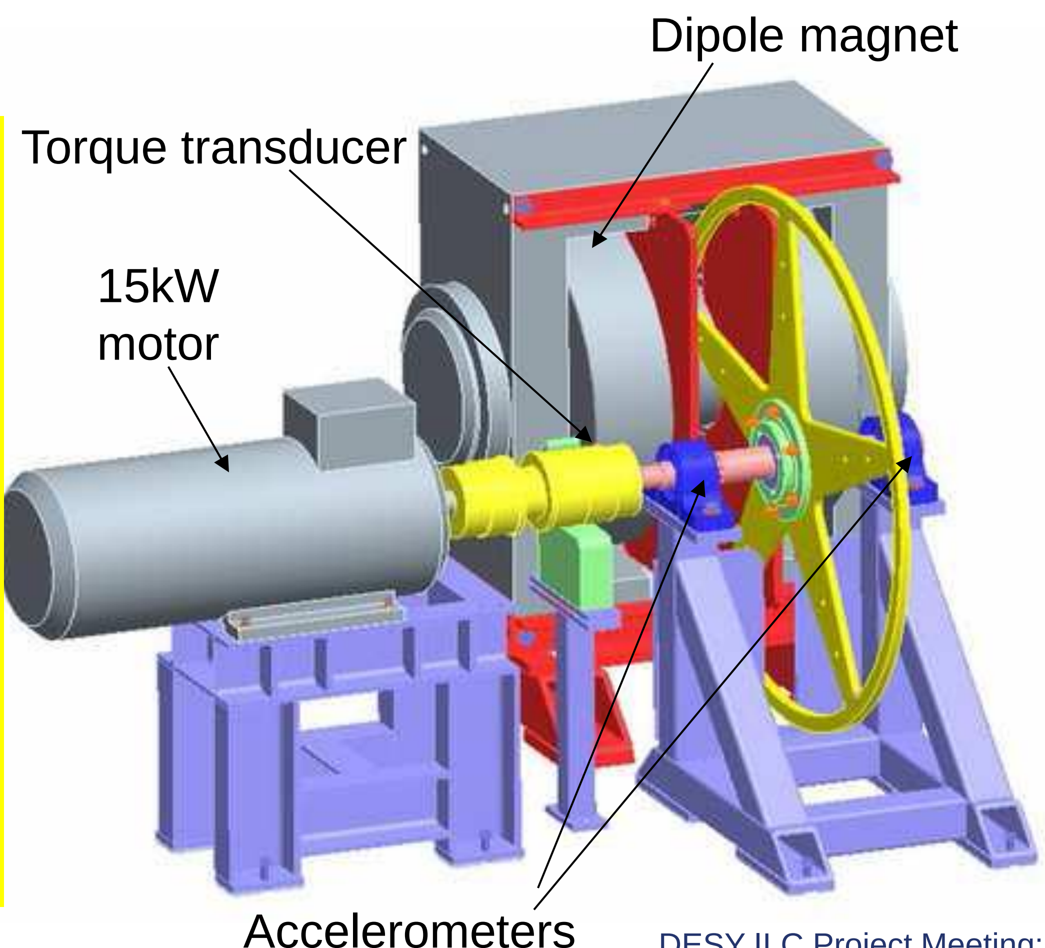
→ spinning wheel to avoid damage due to high energy deposition density
  - 2000 r.p.m. (100m/s)
  - Diameter: 1m
  - Wheel is in vacuum
  - water-cooled



- Potential problems
  - Stess waves due to cyclic heat load ⇔ target lifetime
  - High peak energy deposition
  - Eddy currents
  - rotating vacuum seals to be confirmed suitable

Immersed target: Eddy currents

- e+ target immersed in high magnetic field of capture section yields higher positron yield
- However: high speed rotation → eddy currents → target heating



Ken Davies - Daresbury Laboratory

Test eddy currents and mechanical stability

(Cockroft Institute)

Bailey et al., THPEC033, IPAC2010

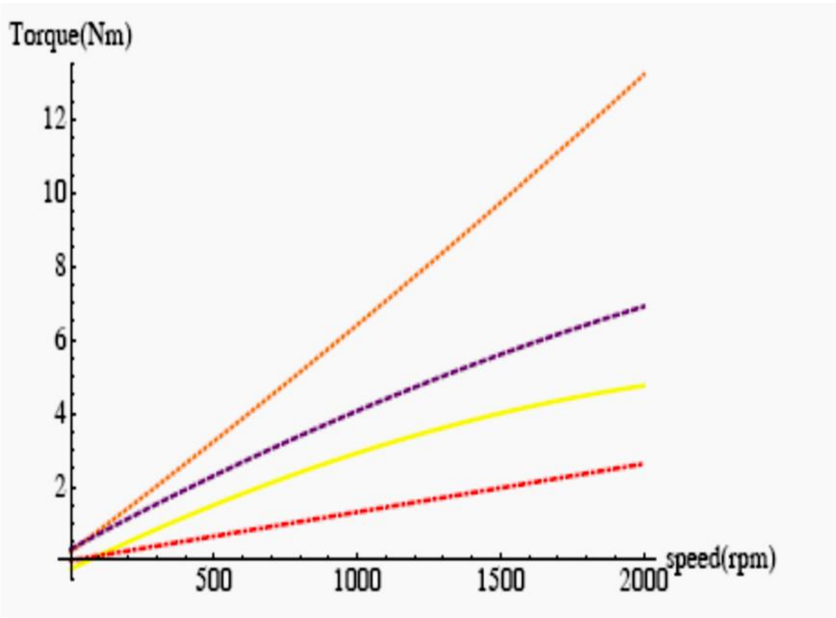
Measurements

- Torque associated with eddy current production in target wheel depending on
  - Immersion depth
  - Magnetic flux densities
- Rotor dynamics

Test eddy currents

Bailey et al., THPEC033, IPAC2010

Magn. Peak field = 0.5T



Immersion depth

50.25mm
30.25mm } fit
20.25mm
ELEKTRA simulation

Measurements

- All measurements taken for revolution rates <1800 rpm in fields up to 1.5 T

Results

- Measured torque values correspond to heat loads up to 4.7 kW for fields of 1T at 1500rpm
- Extrapolation to 8 kW at 2000 rpm
- benchmark (none of the simulation packages agreed with measurements)

➔ eddy current loads should be within the capabilities of water-cooled ILC target wheel

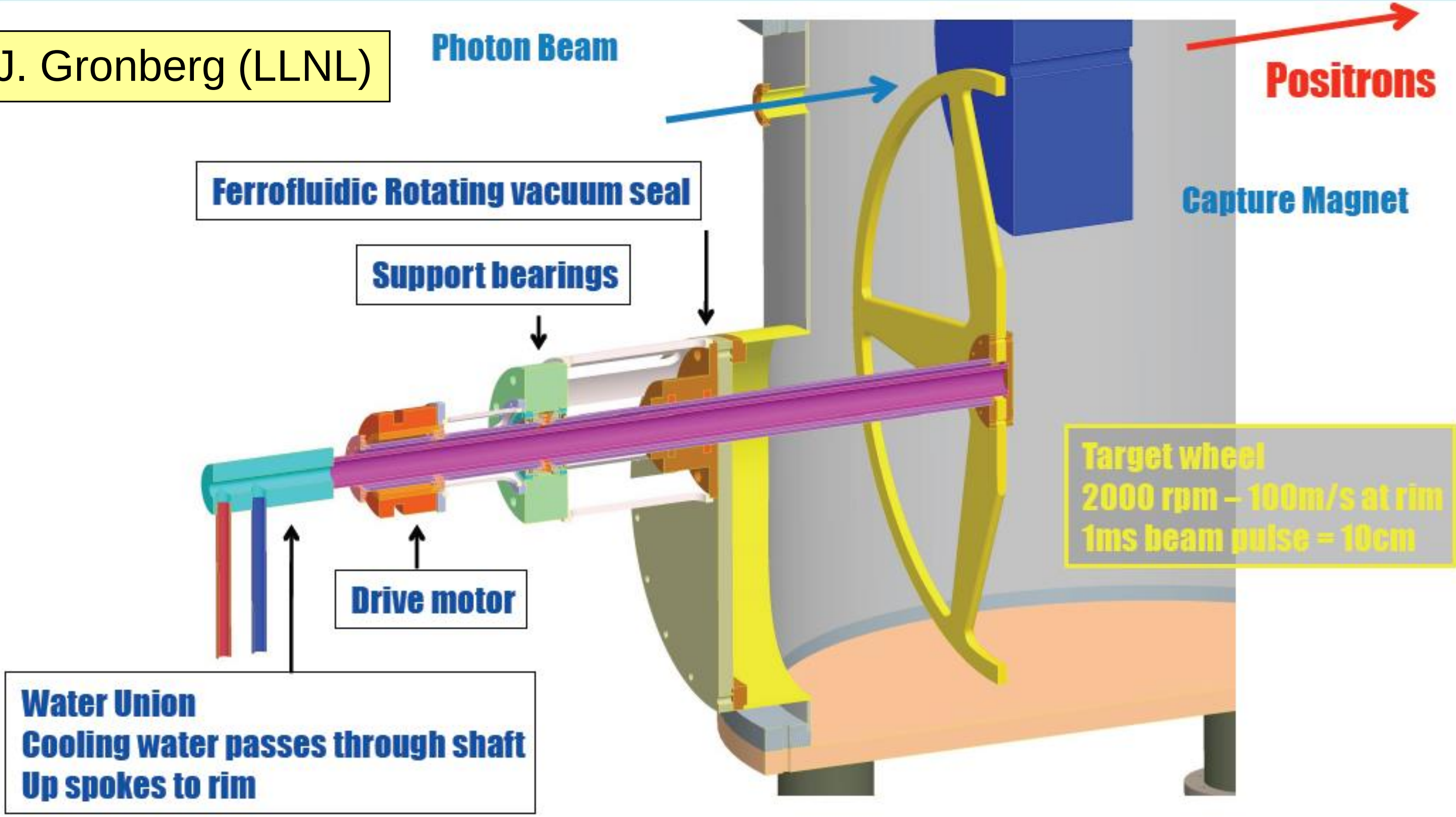
Target prototype with rotating seals

Spinning wheel (2000rpm), in vacuum

1m diameter

We are doing design and prototyping of the rotating shaft seal and the capture magnet

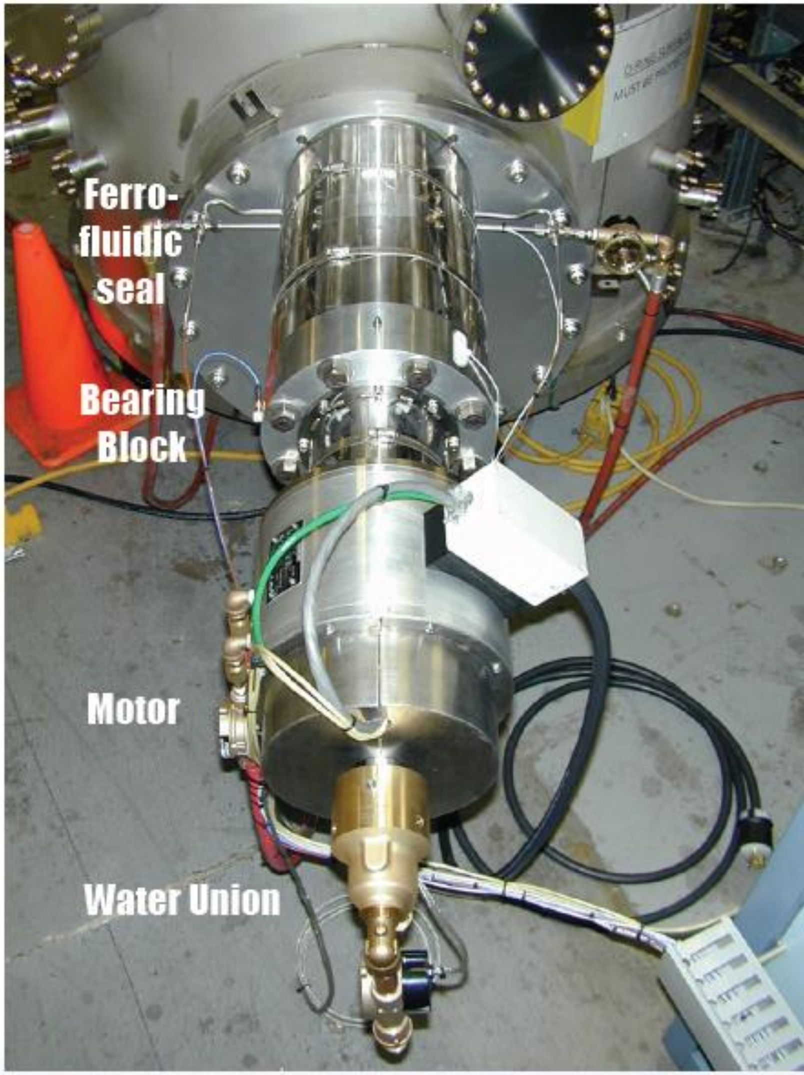
J. Gronberg (LLNL)



Target prototype

J. Gronberg et al.

- Prototype built by LLNL to test fast spinning up to 2000rpm
- Not yet demonstrated that it will work
- Ferrofluidic vacuum seals
  - ".. each has individual personality.."
  - Outgassing spikes
  - Significant heat dissipation at 2000rpm



Lawrence Livermore National Laboratory

Target 'risk' issues and improvements

'risk' issues

- Limited lifetime of vacuum seal (2000rpm)
  - LLNL prototype:
    - few weeks with vacuum spikes
    - No further experiments due to lack of funding
- No tests yet with water cooling
- No radiation damage tests

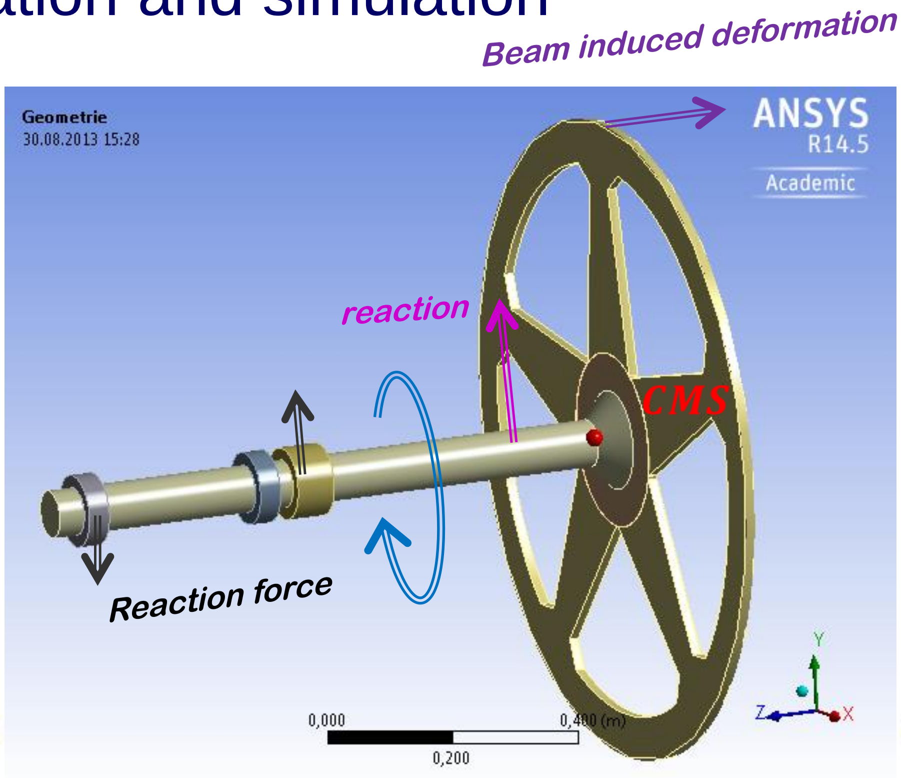
Potential improvements:

- Continue with spinning target (1000rpm instead 2000rpm)
- New type of sealing
- Differential pumping
- better cooling
- Alternative target design: 'bullet' target
  - First design proposal at ANL: bullet target system

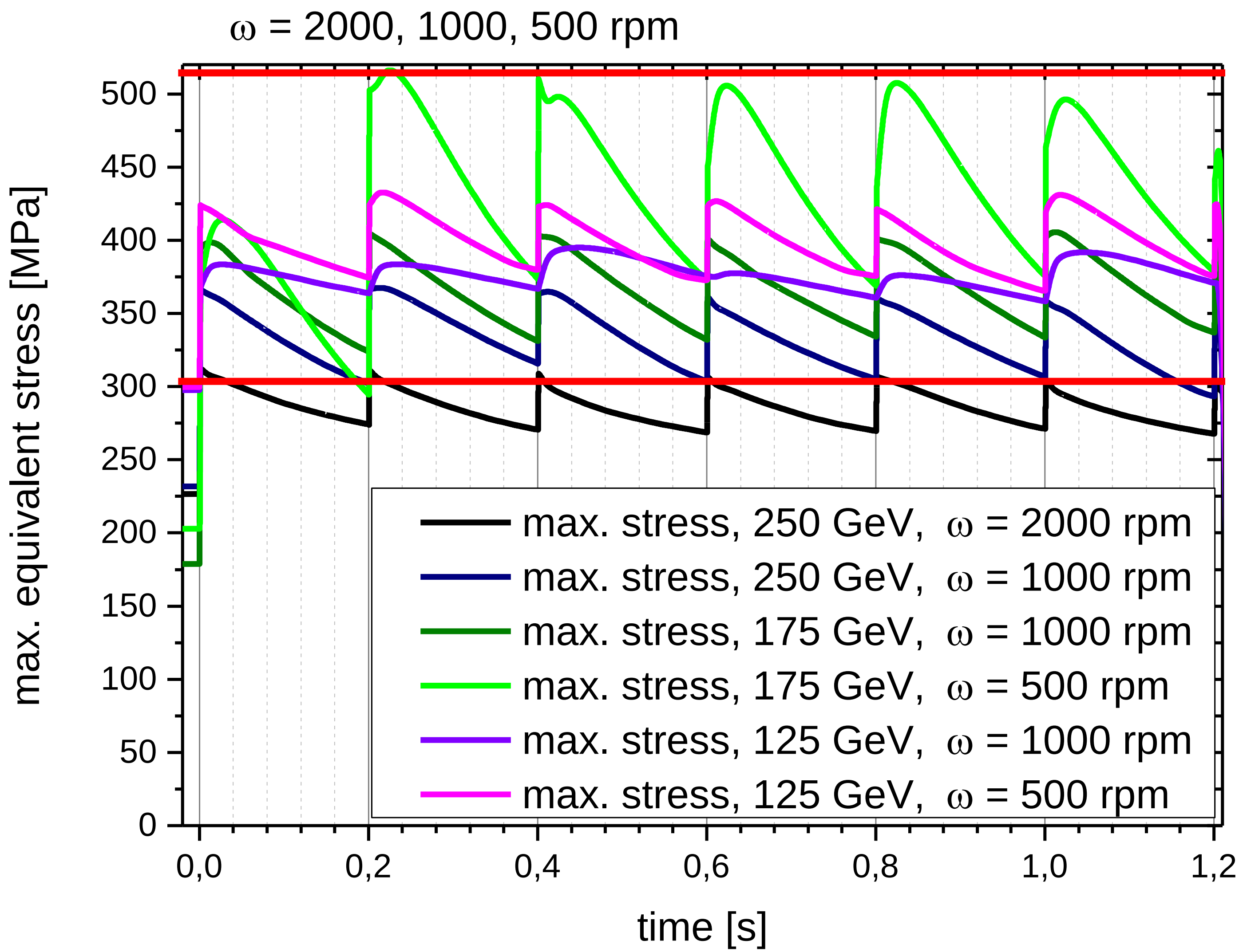
Target design improvements

- Lower rotation speed 2000rpm → 1000rpm?
- Friedrich Staufenbiel (POSIPOL13, LCWS13):
  - Simulation of dynamic response to cyclic heat load on target (ANSYS) → no shock waves
  - Inertia and torque calculation and simulation
  - Torque $|\tau| = m\, r^2\, \omega^2$
  - Lower ω increases energy deposition density in target

→ Heat load with lower ω?



Dynamical stress of the Ti-wheel



Ti-alloy fatigue stress limit

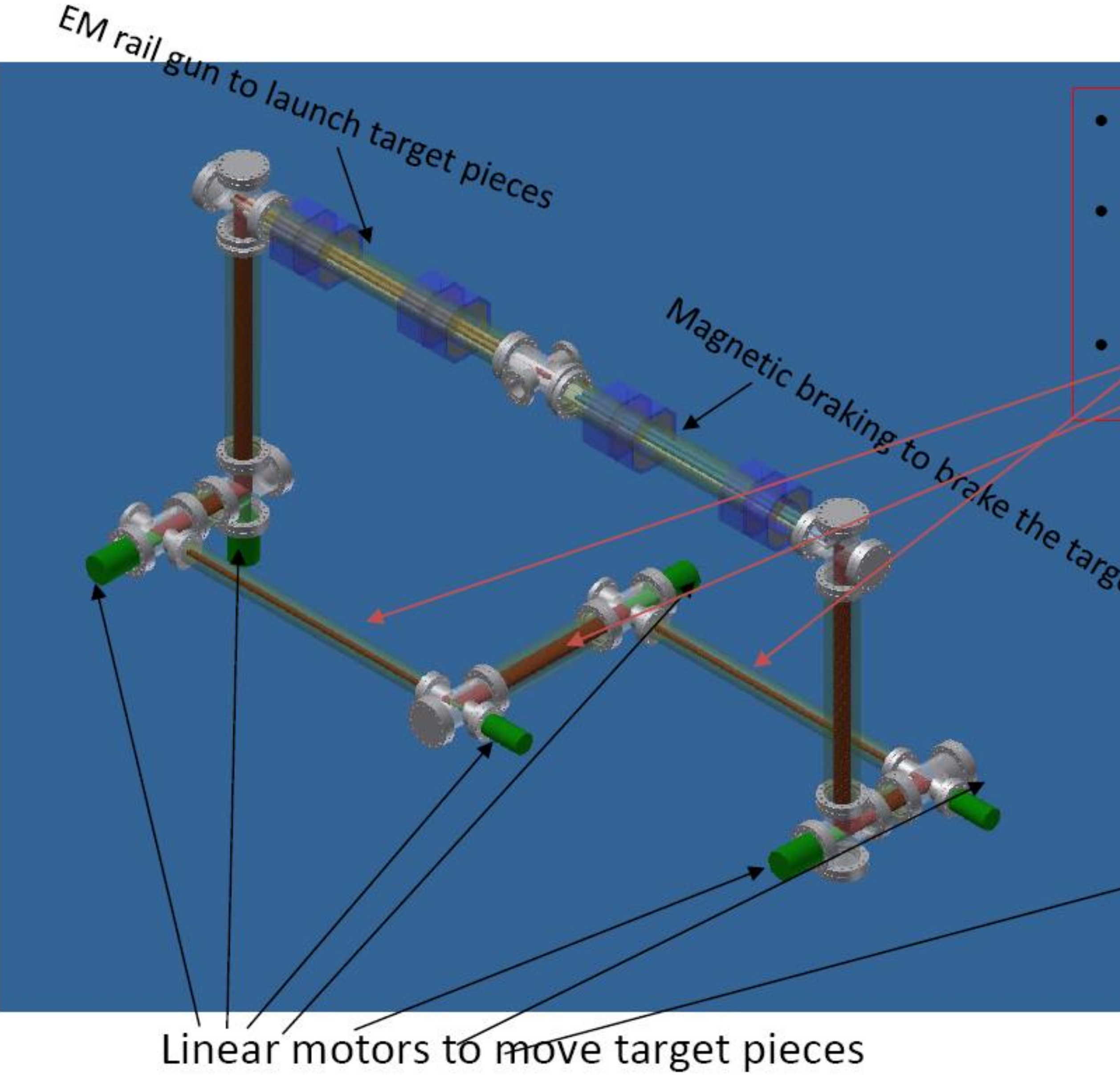
(to be checked and verified)

F. Staufenbiel, LCWS2013

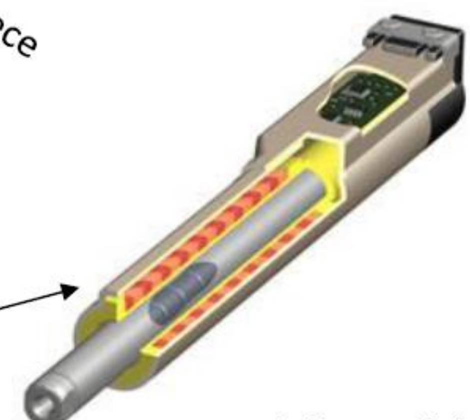
→ Reduction to ~1000rpm seems possible

Target system alternative

W. Gai (ANL

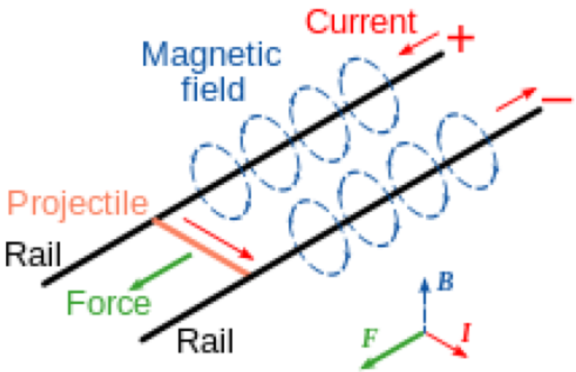


- Conduction cooling via the bottom of target.
- Inspection and replacing of damaged target can be easily done on along this path.
- Path can be easily adjusted to increase the cooling time.



Commercially available

Parameter estimation of the Rail gun for launching target



External permanent magnetic field will be applied to improve

- With the following assumptions:
  - length of rail 100cm, target bullet 1.4cmx1.4cmx6cm and rail has same cross section of target bullet
  - 1T external magnetic field and copper rail
- We estimated that:
  - The current required to accelerate the target from 0 to 50m/s is about 4.5kAmps
  - The average heating power of gun is about 700W

W. Gai

Rail gun target

- Braking
  - Eddy current braking
  - Magnetic braking with or without external power source
- Cooling
  - Conduction cooling in the recycling line
  - Turnarounds of bullets ⇔ ~60s cooling time
  - Details require simulation taking into account non-uniform energy deposition
  - Estimate: using a 10°C cooling agent outside on bottom of recycling line, 200°C can be cooled to 25°C within 46s

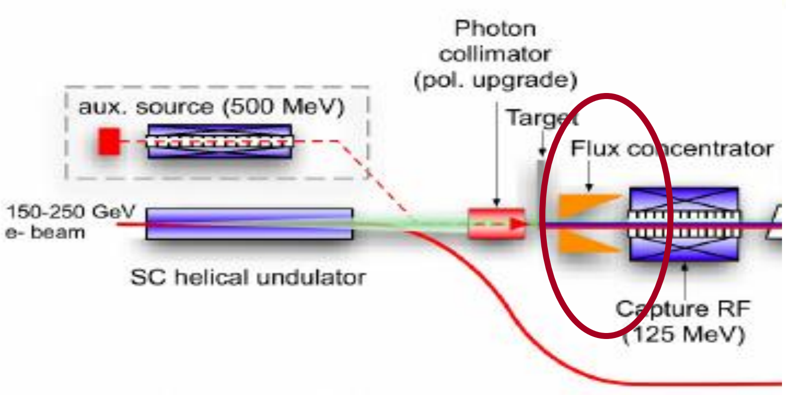
Further studies needed but it seems feasible

W. Gai

Optical matching device

– Pulsed flux concentrator

Pulsed Flux Concentrator

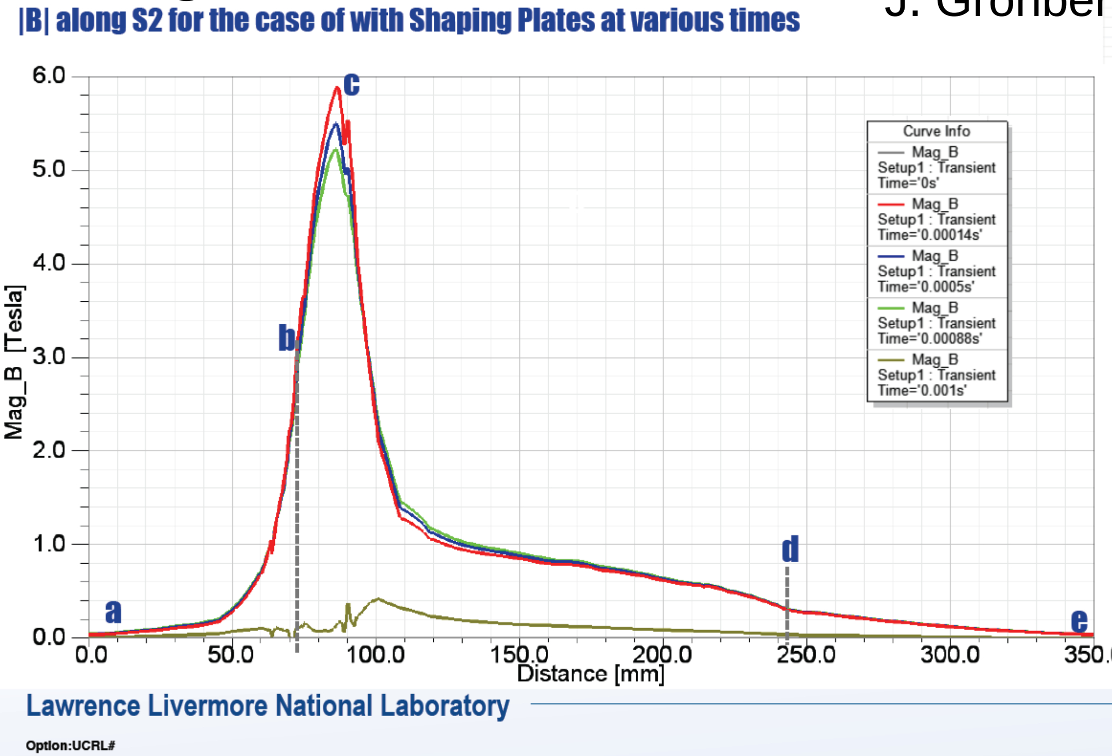


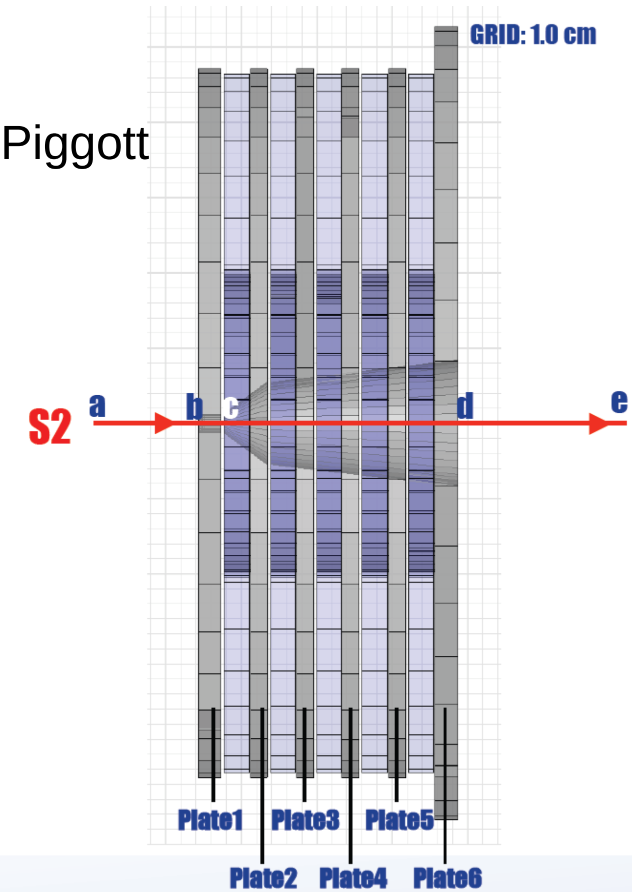
Pulsed flux concentrator:
capture efficiency to ~25%
(quarter wave transformer: $\varepsilon \sim 15\%$)

- low field on target (low eddy current)
- high peak field, 1ms flat top

Design: LLNL

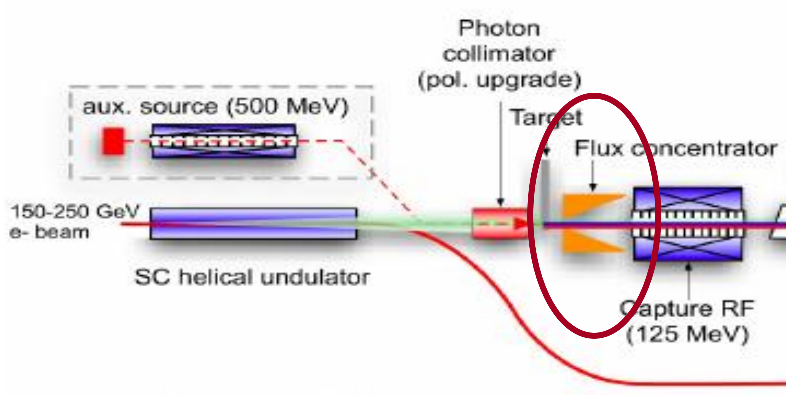
J. Gronberg, T. Piggott





at

Pulsed Flux Concentrator

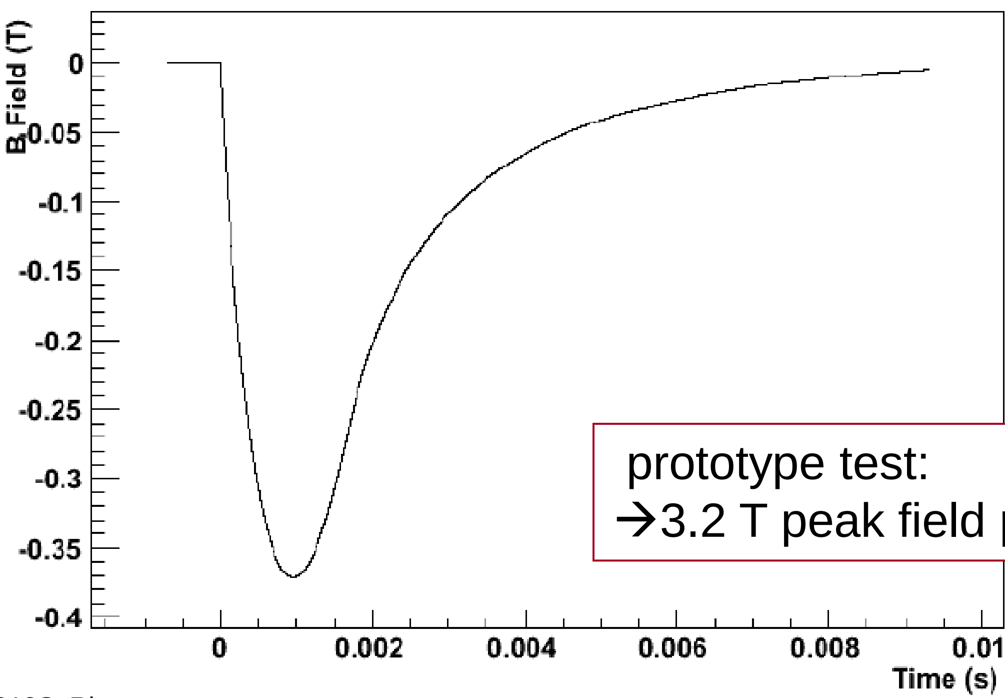


Pulsed flux concentrator to achieve capture efficiency of ~25%

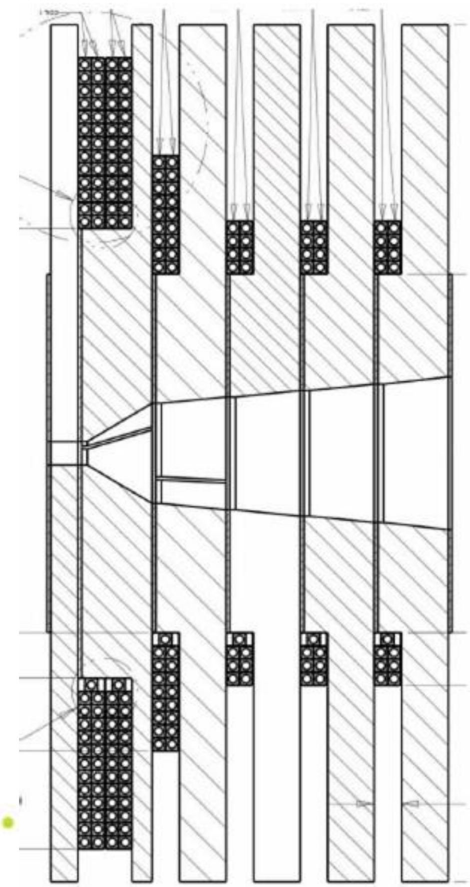
- low field on target (low eddy current)
- high peak field, 1ms flat top

Prototype: LLNL

J. Gronberg

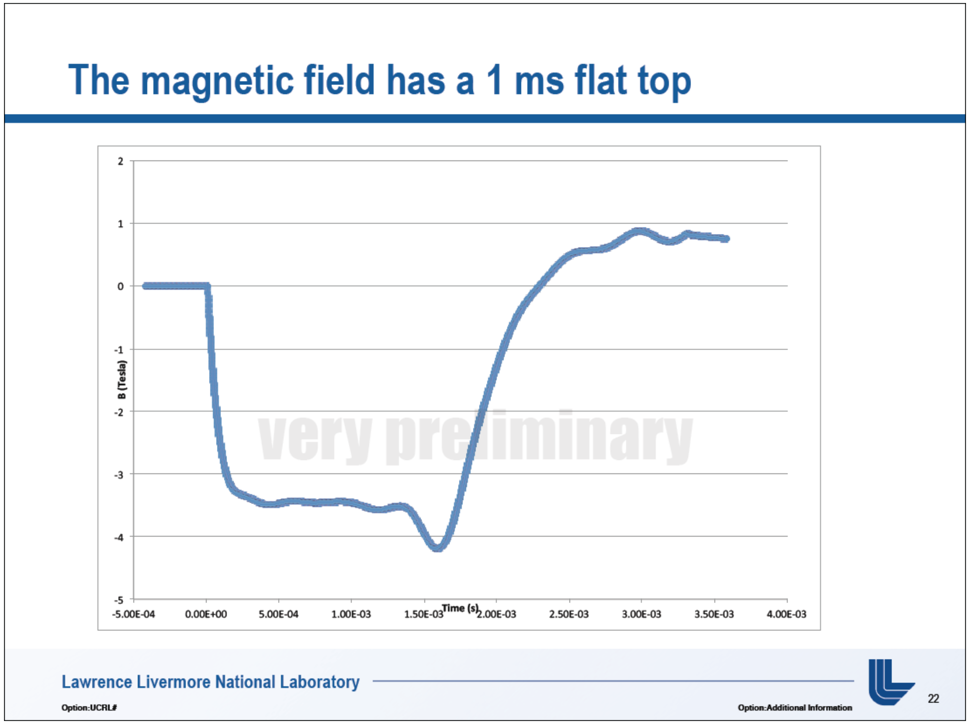


prototype test:
→3.2 T peak field possible



Flux concentrator

- Full field with 1ms flat top has been demonstrated



J. Gronberg, LLNL

- FC seems workable but still need to demonstrate full average power operation
  - Run with 5Hz over extended period and full average power with cooling

Source parameters

More details: see EDMS

e- Beam Parameters for e+ generation	Ecm (GeV)						
	200	230	250	350	500	500 L upgrade	1000
e+ per bunch at IP ($\times 10^{10}$)				2	2	2	1.74
Number of bunches per pulse	1312					2625	2450
Undulator period (cm)	1.15					1.15	4.3
Repetition rate (Hz)	5					5	4
Undulator strength (K value)				0.92	0.75	0.45	1
Beam energy (GeV)				178	253	253	503
Undulator length (m)				147		147	132
e- beam bunch separation (ns)	554					366	366
Power absorbed in e+ target (%)				7	5.2	5	4.4
Edep per bunch [J]				0.59	0.31	0.31	
Spot size on target (mm rms)				1.2	0.8	0.8	
Peak power density in target (J/g)				65.6	67.5	101.3	105.4
Polarization (no collimator) (%)				30	29	29	19

Nominal parameters

E_{cm} = 240 GeV

Higgs-Boson measurements

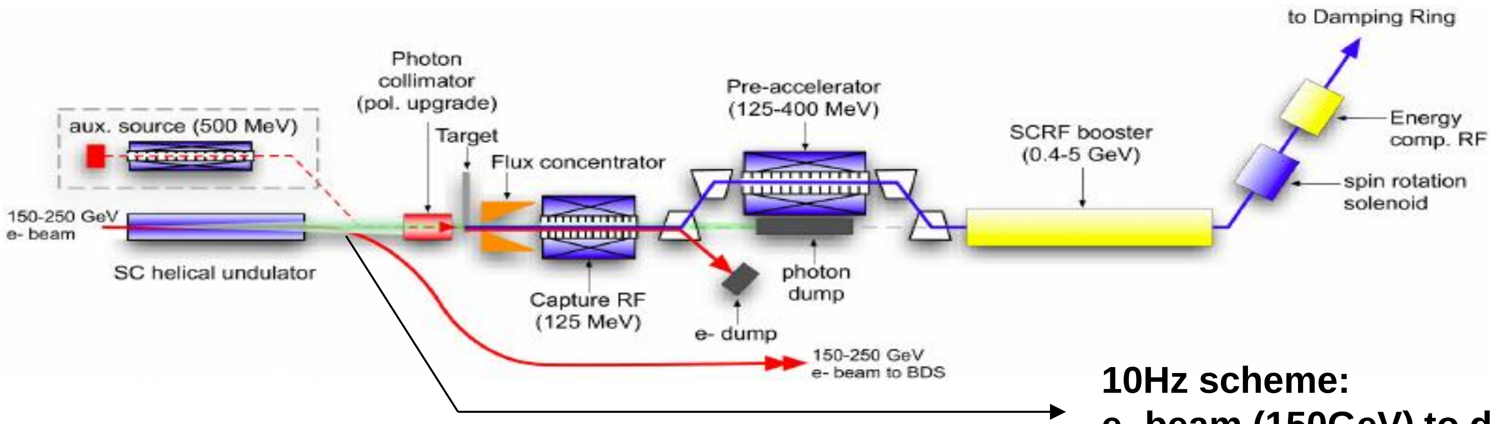
ILC as Higgs factory

E_{cm} = 240 GeV

– For E_e < 150 GeV yield is below 1.5

→ TDR: 10 Hz scheme

1. Alternating with e- beam for physics (Ee~120GeV) an e- beam with E_e=150GeV passes undulator generate γ for e+ production



10Hz scheme:
e- beam (150GeV) to dump

e- Beam Parameters for e+ generation	Ecm (GeV)						
	200	**230**	**250**	**350**	**500**	**500 L upgrade**	**1000**
e+ per bunch at IP ($\times 10^{10}$)	2			2	2	2	1.74
Number of bunches per pulse	1312					2625	2450
Undulator period (cm)	1.15					1.15	4.3
Nominal 5Hz mode							4Hz
Undulator strength (K value)				0.92	0.75	0.45	1
Beam energy (GeV)				178	253	253	503
Undulator length (m)				147		147	132
10Hz alternate pulse mode							
Undulator strength (K value)	0.92						
Beam energy for e+ prod.(GeV)	150						
Undulator length (m)	147						
Beam energy for lumi (GeV)	101	117	127				
e- beam bunch separation (ns)	554					366	366
Power absorbed in e+ target (%)	7			7	5.2	5	4.4
Spot size on target (mm rms)	1.4			1.2	0.8	0.8	
Peak power density in target (J/g)	51.7			65.6	67.5	101.3	105.4
Polarization (no collimator) (%)	31			30	29	29	19

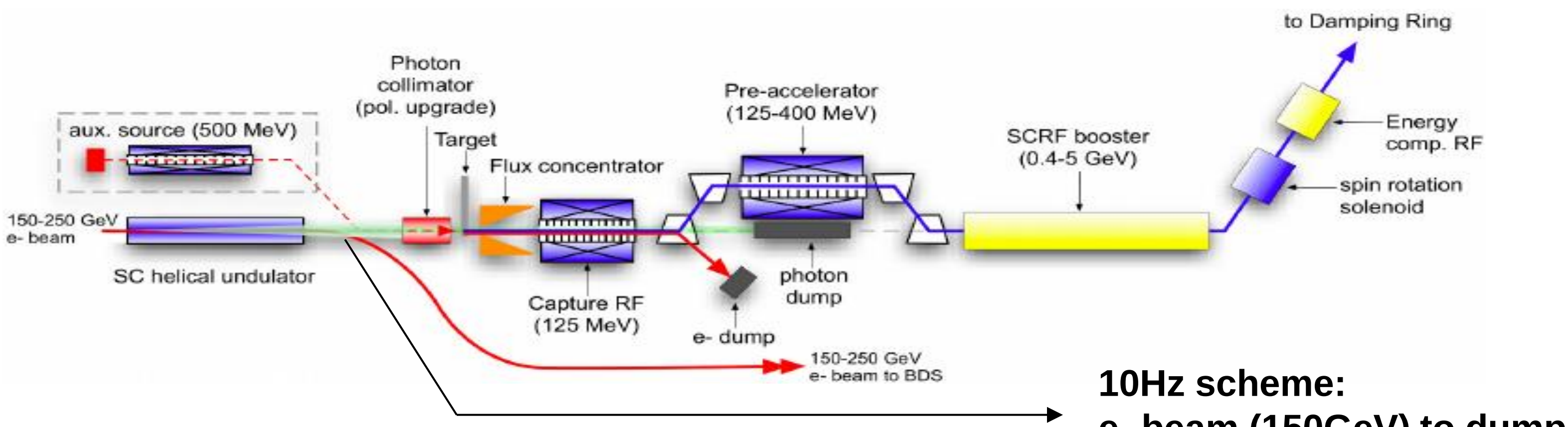
ILC as Higgs factory

E_{cm} = 240 GeV

– For E_e < 150 GeV yield is below 1.5

→ TDR: 10 Hz scheme

1. Alternating with e- beam for physics (Ee~120GeV) an e-beam with E_e=150GeV passes undulator generate γ for e+ production



2. Better: use almost full length of undulator and optimize system (A. Ushakov, LC-REP-2013-019)

$E_{cm} \approx 240$ GeV

Andriy Ushakov, LC-REP-2013-019:

Optimized positron capture section

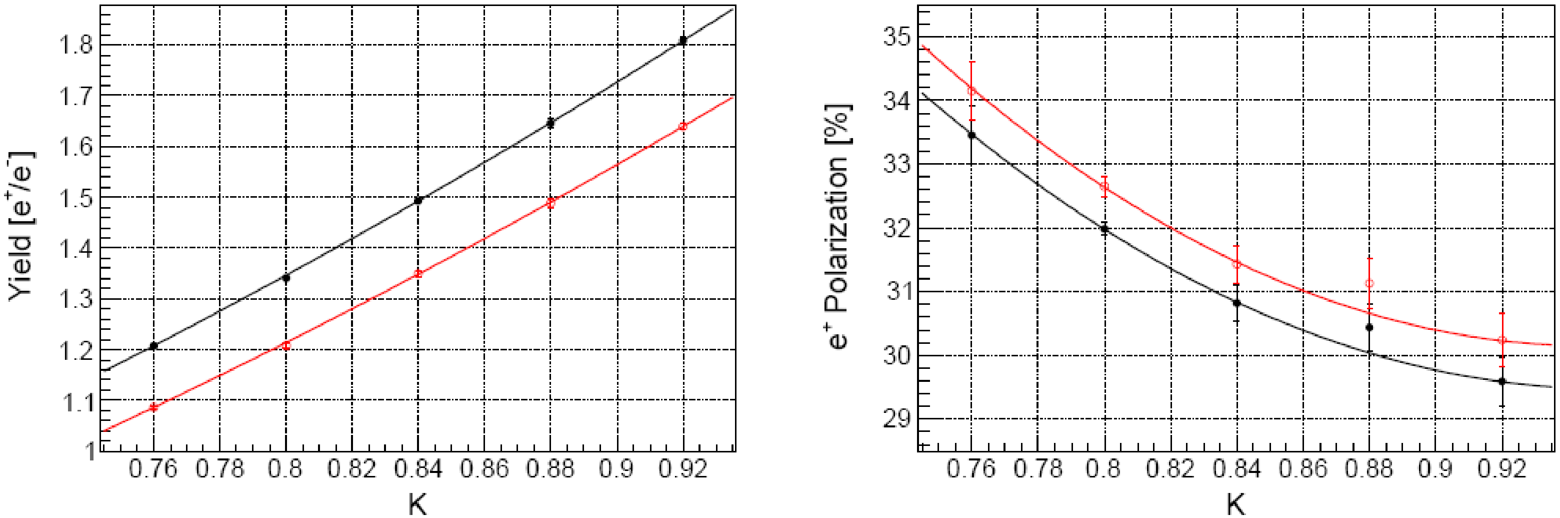


Figure 6: Positron yield (left) and polarization (right) vs undulator K value.

DR acceptance: Red = 9.6mm bunch length cut; black = 34mm bunch length cut

31% positron polarization for K = 0.84 and L_u = 192.5m

40% possible for K = 0.92 and photon collimator with iris radius of 3.5mm

e- Beam Parameters for e+ generation	Ecm (GeV)				
	240	**350**	**500**	**500 L upgrade**	**1000**
e+ per bunch at IP ($\times 10^{10}$)	2	2	2	2	1.74
Number of bunches per pulse	1312			2625	2450
Undulator period (cm)	1.15			1.15	4.3
Nominal 5Hz mode					4Hz
Undulator strength (K value)	**0.84**	0.92	0.75	0.45	1
Beam energy (GeV)	**120**	178	253	253	503
Undulator length (m)	**192**	147		147	132
10Hz alternate pulse mode					
e- beam bunch separation (ns)	554			366	366
Power absorbed in e+ target (%)	**9.2**	7	5.2	5	4.4
Spot size on target (mm rms)		1.2	0.8	0.8	
Peak power density in target (J/g)	**44**	65.6	67.5	101.3	105.4
Polarization (no collimator) (%)	**31**	30	29	29	19

E_{cm} = 350 GeV

Top-quark measurements
→ High positron pol desired

Photon collimator parameters for polarization upgrade

ILC TDR

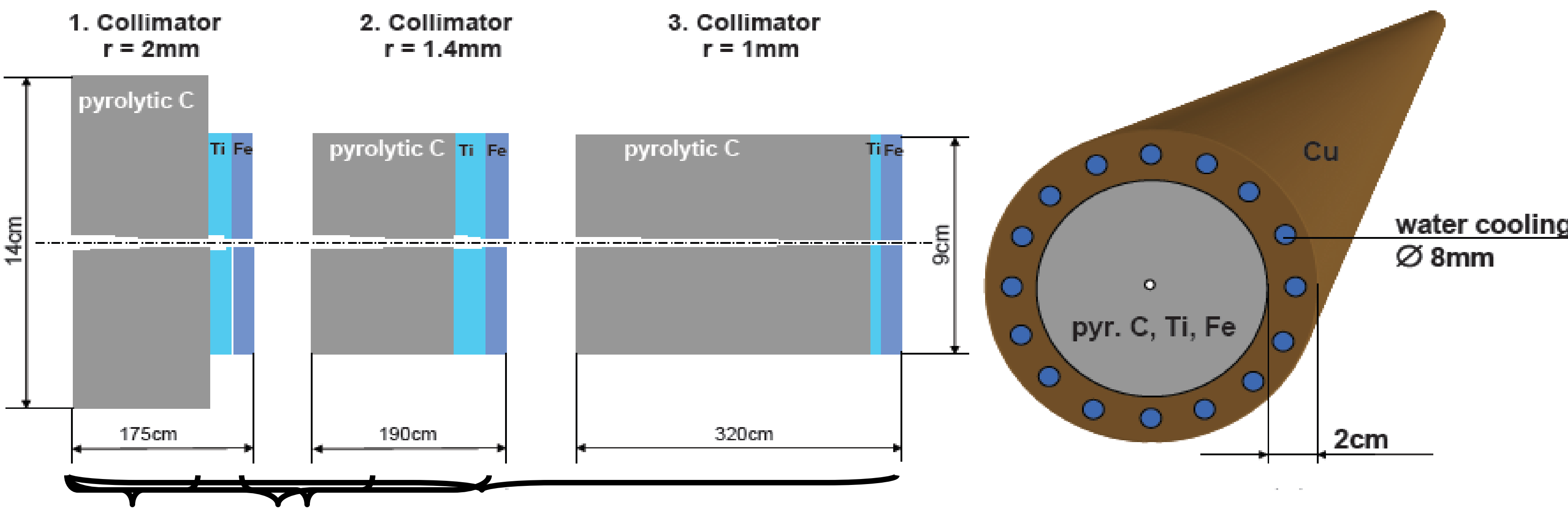
Parameter	Unit					L upgrade
Centre-of-mass energy	GeV	200-250	350	500	500	500
Drive-electron-beam energy	GeV	150	175	250	250	250
Undulator K value				0.92		
Undulator period	cm			1.15		
Positron polarisation	%	55	59	50	59	50
Collimator-iris radius	mm	2.0	1.4	1.0	0.7	1.0
Active undulator length	m	231	196	70	144	70
Photon beam power	kW	98.5	113.8	83	173	166
Power absorbed in collimator	kW	48.1	68.7	43.4	121	86.8
Power absorbed in collimator	%	48.8	60.4	52.3	70.1	52.3

60% e+ polarization at 350GeV ⬄ ~60% of photon beam power absorbed in collimator

→ high load on the collimator materials

Photon beam collimation

- Increase of e+ polarization using photon collimator
  - Details see talk of Friedrich Staufenbiel
  - Collimator parameters depend on energy
  - → Multistage collimator (3 stages with each pyr. C, Ti, Fe)



E_{e-} =150 GeV E_{e} = 175 GeV E_{e} =250 GeV

P_{e+} = 50% P_{e+} ≈ 60% P_{e+} ≈ 50%

E_{cm} = 500 GeV

Photon collimator parameters for polarization upgrade

ILC TDR

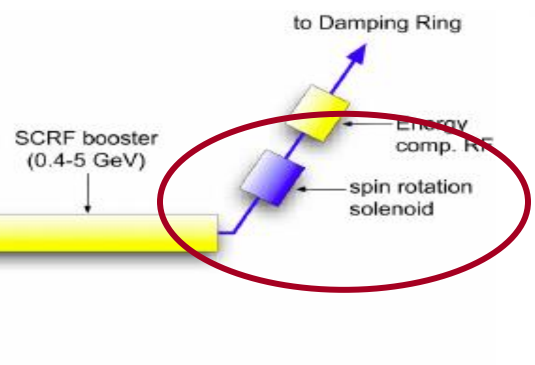
Parameter	Unit					L upgrade
Centre-of-mass energy	GeV	200-250	350	500	500	500
Drive-electron-beam energy	GeV	150	175	250	250	250
Undulator K value				0.92		
Undulator period	cm			1.15		
Positron polarisation	%	55	59	50	59	50
Collimator-iris radius	mm	2.0	1.4	1.0	0.7	1.0
Active undulator length	m	231	196	70	144	70
Photon beam power	kW	98.5	113.8	83	173	166
Power absorbed in collimator	kW	48.1	68.7	43.4	121	86.8
Power absorbed in collimator	%	48.8	60.4	52.3	70.1	52.3

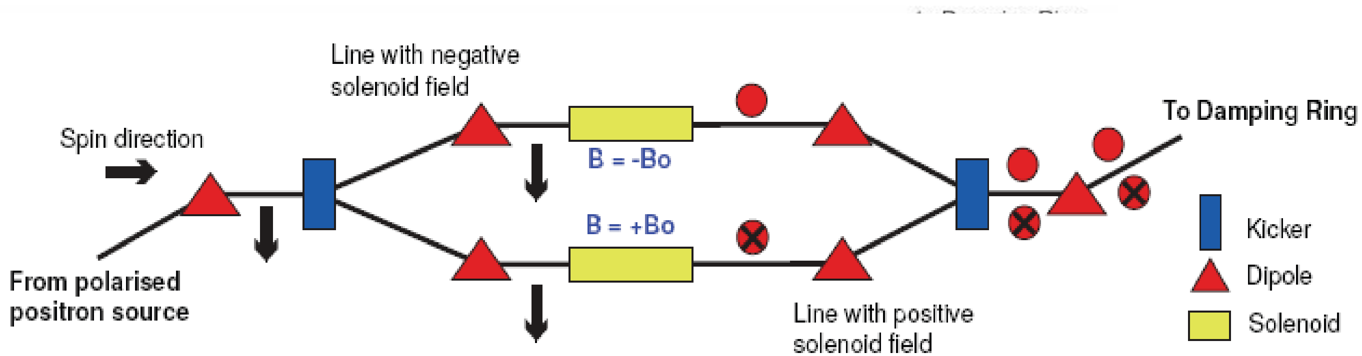
60% e+ polarization at 500GeV ⇔ collimator absorbs ~70% of photon beam power

→ 50% e+ polarization should be 'sufficient'

Spin flipper

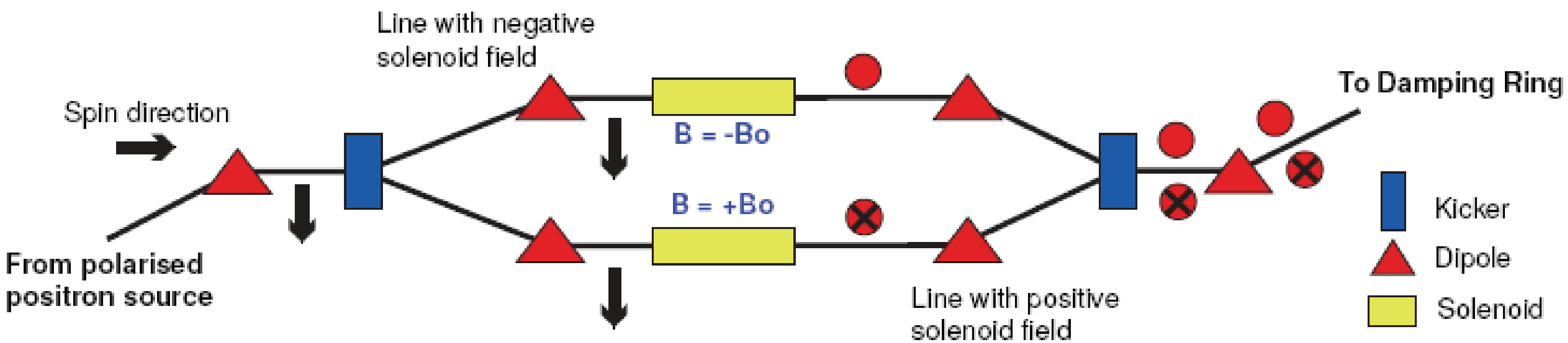
- Net polarization depends on direction of undulator windings
- Reversal of e+ helicity necessary
- It has to be synchronous with reversal of e- polarization to achieve
  - enhanced luminosity
  - Cancellation of time-dependent effects ⬄ small systematic errors
- Helicity reversal requires spin flipper
  - near the DR where the spins have to be rotated





Spin flipper

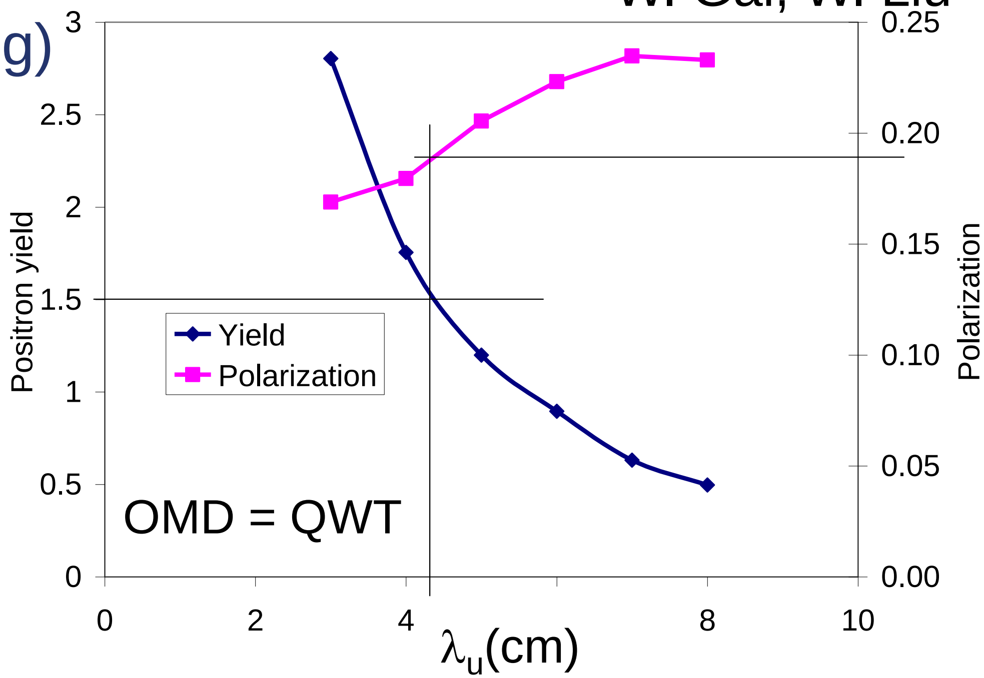
- beam is kicked into one of **two identical parallel transport lines** to rotate the spin
- Horizontal bends rotate the spin by 3 × 90° from the longitudinal to the transverse horizontal direction.
- In each of the two symmetric branches a 5m long solenoid with an integrated field of 26.2Tm aligns the spins parallel or anti-parallel to the B field in the damping ring.
- Both lines are merged using horizontal bends and matched to the PLTR lattice.
- The length of the splitter/flipper section section ~26m; horizontal offset of 0.54m for each branch



TeV upgrade scenarios

- Goal
  - A reasonable scheme for the 1 TeV option without major impact on the ILC configuration.
- Assumptions
  - Drive beam energy: 500 GeV
  - Target: 0.4 X0 Ti
  - Drift from end of undulator to target: 400m
  - OMD: FC
- Approach (Wei and Wanming)
  - Longer undulator period, λ_u = 4.3cm
  - K = 1 (B = 0.25T)
  - P = 20% ☹
  - Polarization upgrade requires small collimator iris (0.85mm)

W. Gai, W. Liu

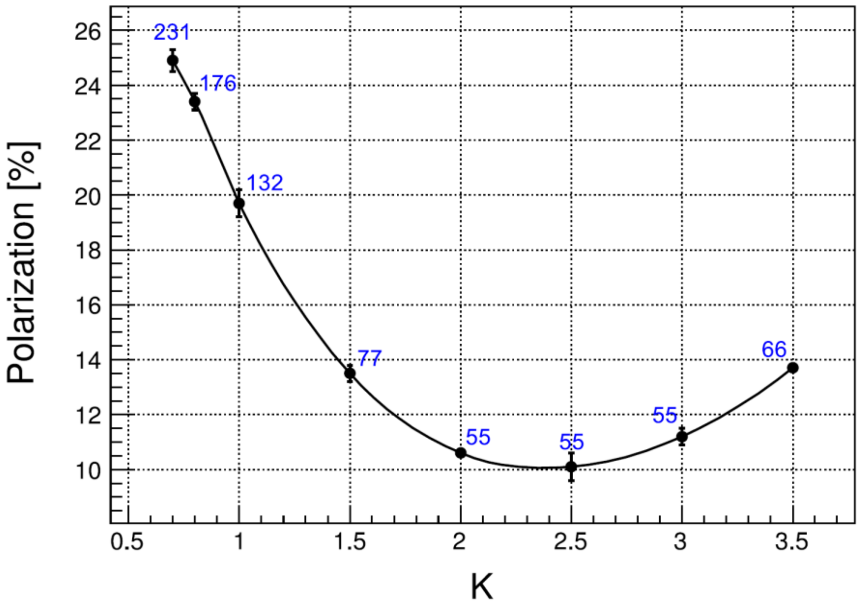


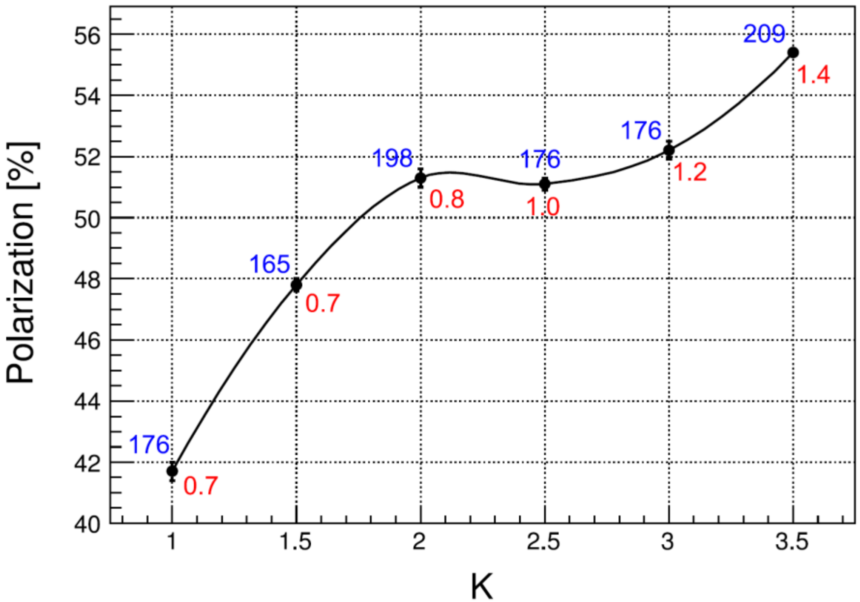
Polarization vs K

VERY PRELIMINARY !!!!

A. Ushakov

Yield $\gtrsim 1.5$





blue numbers – required active undulator length [m]
red numbers – collimator radius [mm]

- Highest polarization of source without collimator is 25%
- What is highest *K* or *B*-field of undulator with 4.3 cm period?

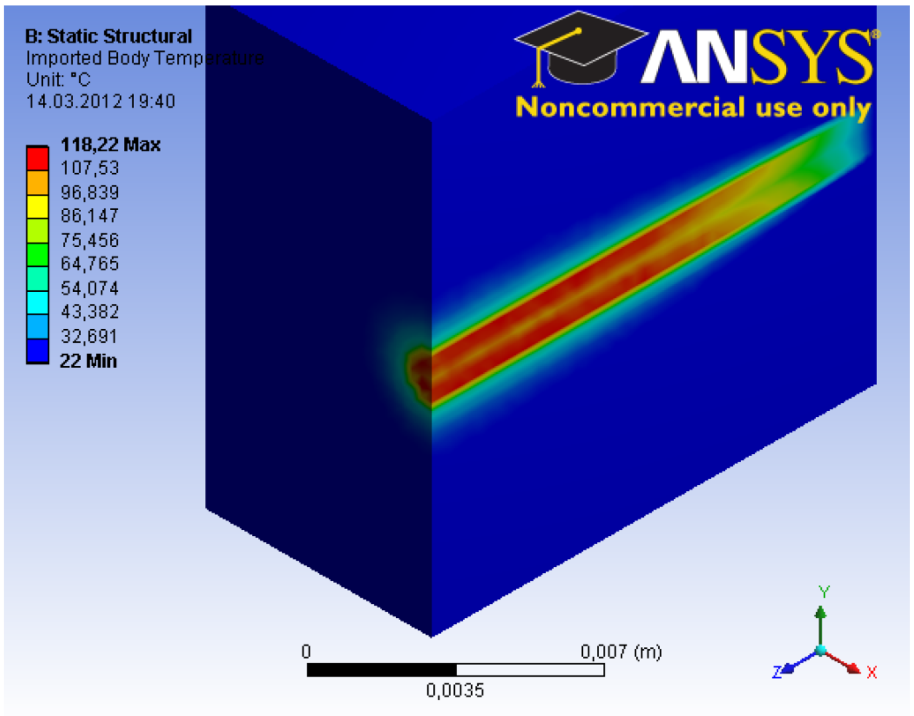
Temperature Map

Static Stress

A. Ushakov

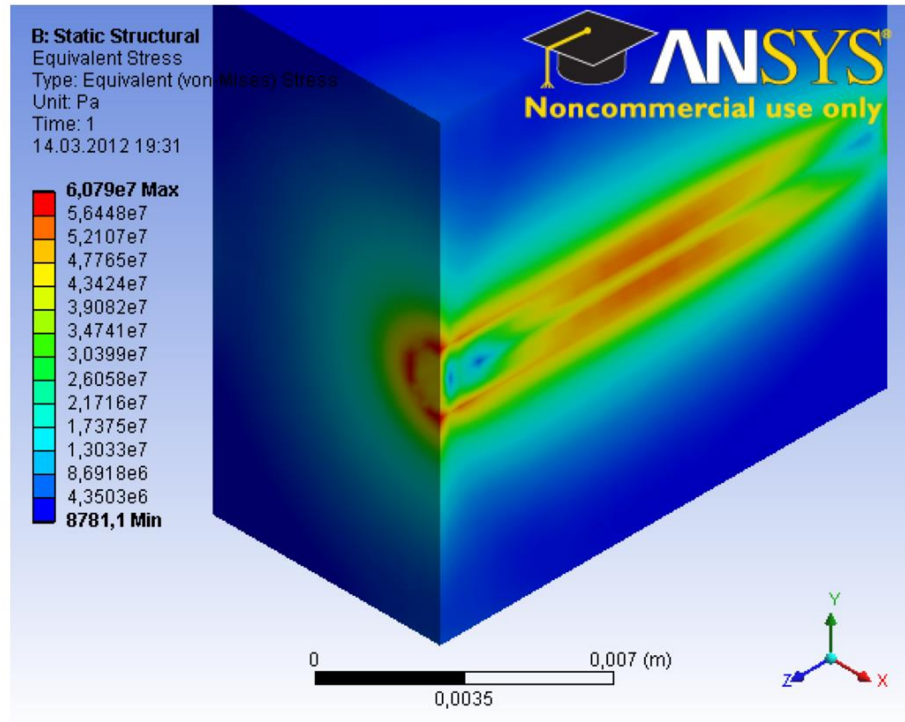
at the end of pulse (t = 0)

500 GeV e^-, $K = 2.0$, $\lambda = 4.3$ cm,
$L_u = 198$ m, $R_{col} = 0.8$ mm,
39.4 bunches



$\delta T_{max} = 96\,^{\circ}$C/pulse

500 GeV e^-



$\sigma_{max} = 61$ MPa

E_{cms}=1TeV, K=2, λ_u=4.3cm

Concerns:

1. higher K implies higher E loss in of drive beam
2. Higher energy deposition in undulator ?

→ Should be checked

- Jim Clarke:
  - No problem to built undulator with 4.3cm and K=2
  - Energy deposition in undulator shouldn't be serious problem if corresponding collimators are implemented in undulator

To have reasonable polarization for physics, the 1TeV parameters should be reconsidered

Alternative: Conventional source

“300 Hz Scheme” (proposed by KEK colleagues)

300 Hz scheme

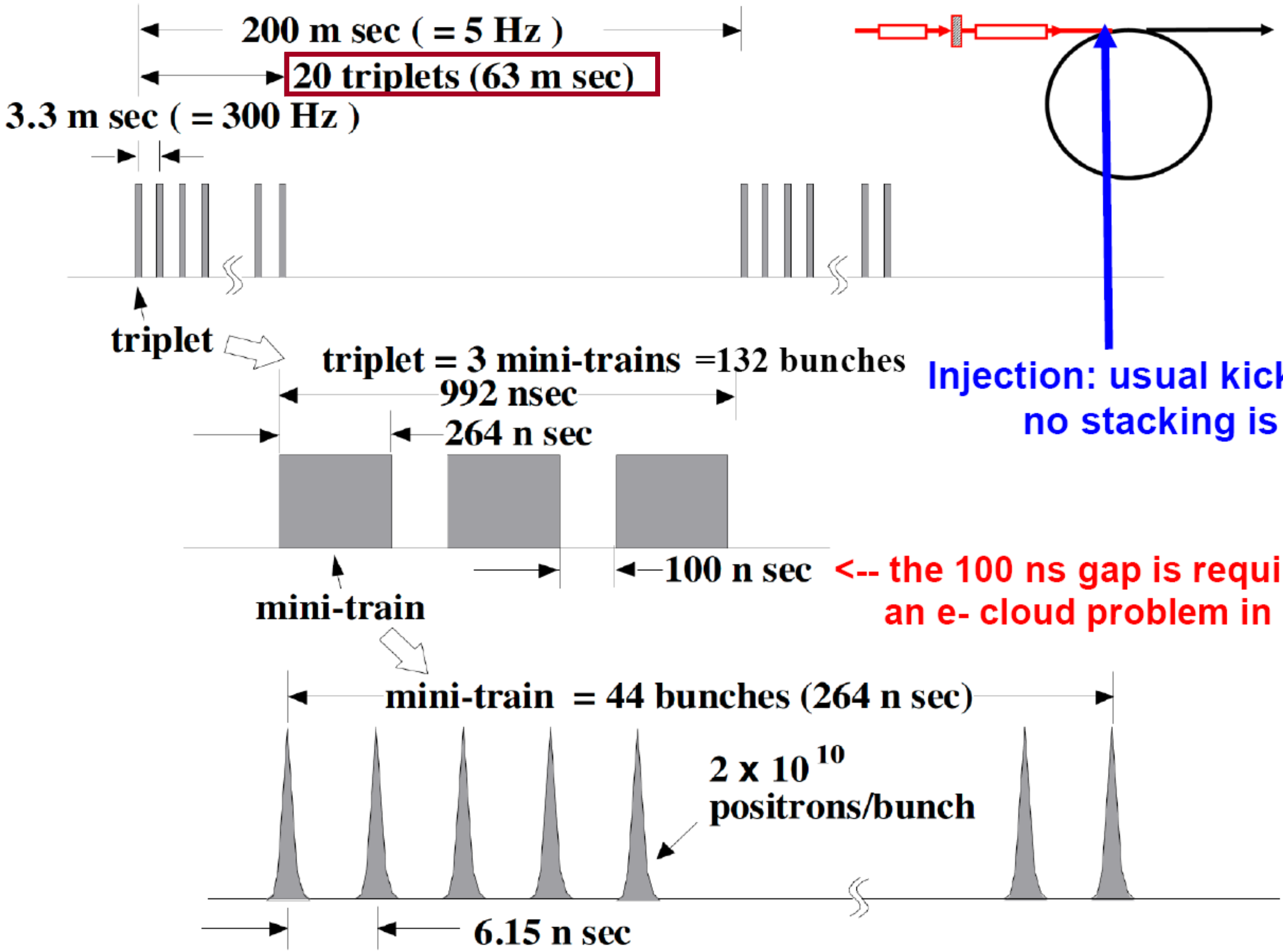
T. Omori

Idea:

- Conventional source (4 X0 tungsten target)
- Time stretched e+ generation (63ms instead of 1ms) → peak energy deposition can be better distributed:
  - **2640 bunches** per train; 2640 = 20 × 132
  - Train divided into **20 triplets** = 20 × 3 Mini-Trains
    (3 Mini-Trains = triplet)
  - Triplets are generated with 300Hz ⇔ triplet-to-triplet space is 3.3ms
  - **20 triplets** are created in 63ms
- With 6GeV e- and beam size σ = 4mm the peak energy ddeposition density is below 35J/g (limit from SLC target)

Beam before DR

T. Omori



Injection: usual kicker (~ 1 us)
no stacking is necessary

<-- the 100 ns gap is required to cure an e- cloud problem in e+ DR.

T. Omori

Conventional e+ Source for ILC

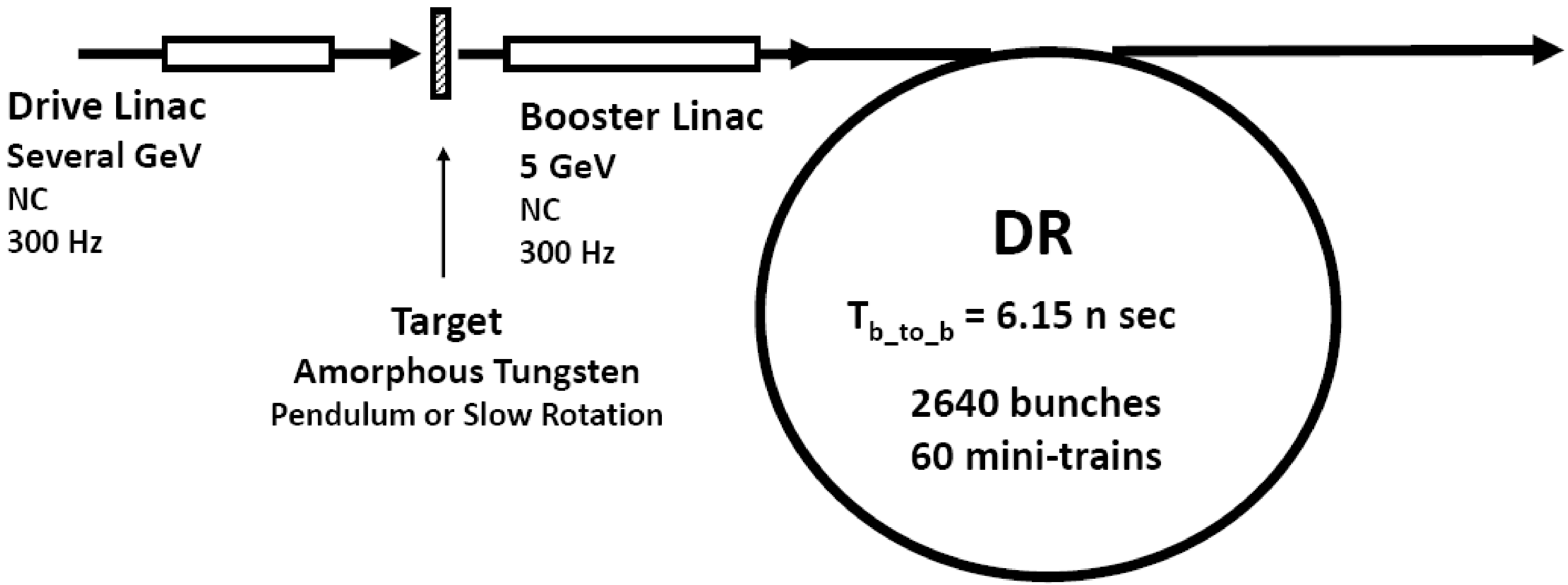
Normal Conducting Drive and Booster Linacs in 300 Hz operation

e+ creation

20 triplets, rep. = 300 Hz
- triplet = 3 mini-trains with gaps
- 44 bunches/mini-train, $T_{b\_to\_b}$ = 6.15 n sec

go to main linac

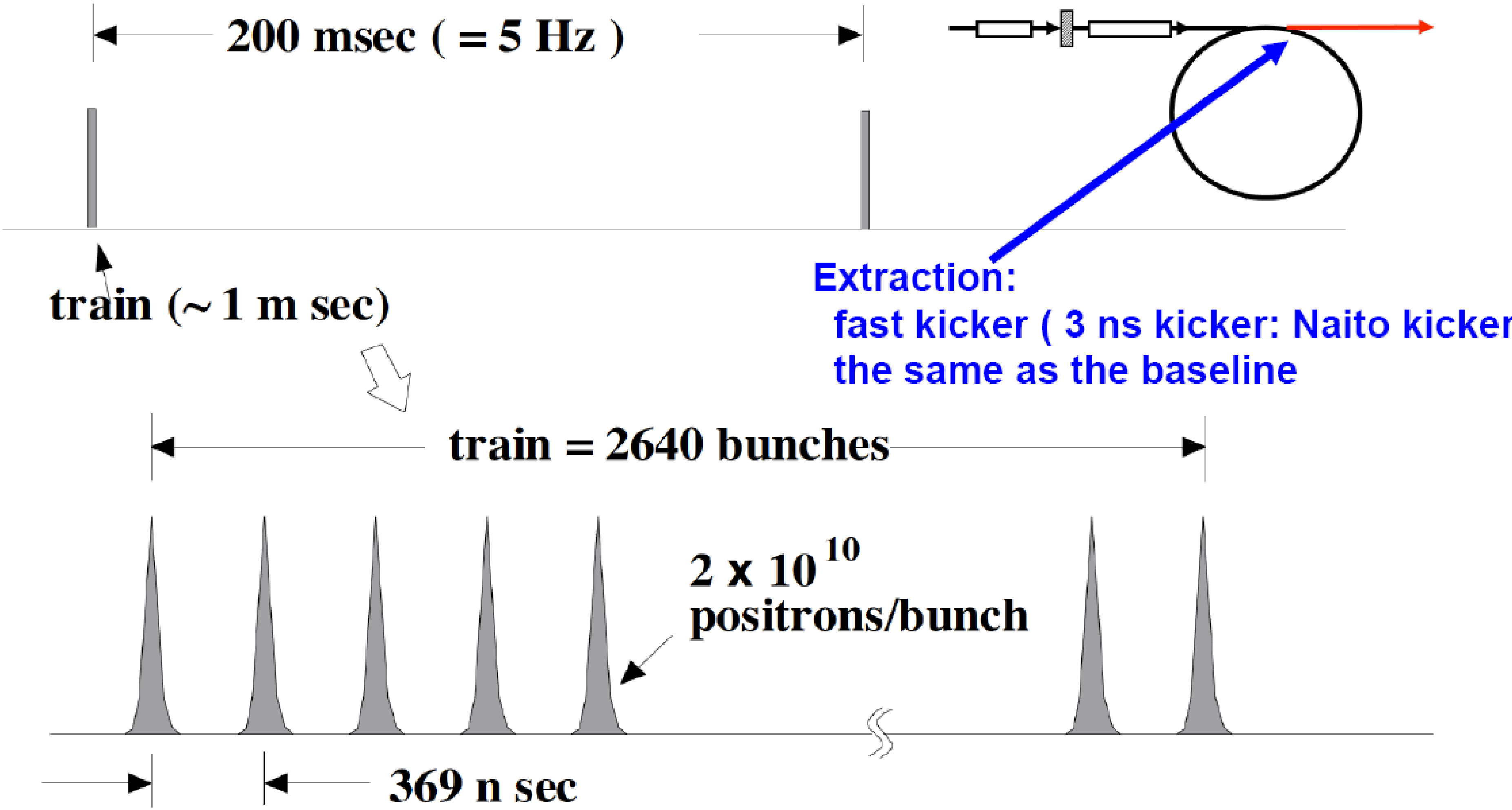
2640 bunches/train, rep. = 5 Hz
- $T_{b\_to\_b}$ = 369 n sec



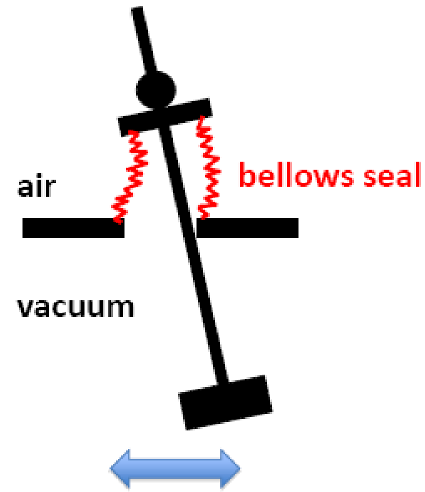
Time remaining for damping = 137 m sec

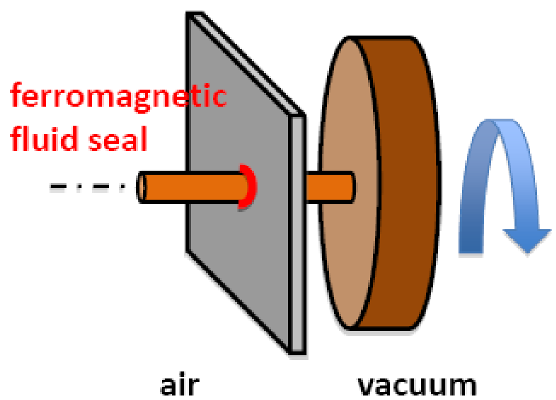
We create 2640 bunches in 63 m sec

Beam after DR



- Target (~35kW power deposition)
  - Speed 5m/s required
- options:
  - 5Hz Pendulum target
    - First protypes showed cracks
  - Rotating wheel
  - Work/protoyping is ongoing





More details see talks at LCWS13, POSIPOL13

Summary

- beam dynamic simulations, including spin tracking by several institutes have been performed (not discussed in the talk)
- Sc undulator constructed and tested
  - 4m long prototype fulfills ILC spec (K=0.92, λ=1.15 cm)
- A fast spinning target wheel constructed and tested at UK (2000rpm)
- Target load and thermo-mechanical stress calculations performed
- Remote handling target design exists
- Collimator design exists
- Major components such as OMD, normal conducting pre-accelerator are tested (ok)
- few risk issues:
  - experimental study on rotating target vacuum Ferro fluidic seal at LLNL showed:
    - Limited life time of a vacuum seal
    - no further experiments (e.g. other type of seal) due to lack of funding
    - Not yet tested: radiation damage, impact of cooling water on wheel dynamics
  - There is plan for a rotating seal leak test at KEK planned, but at much lower rotation speed.

Summary

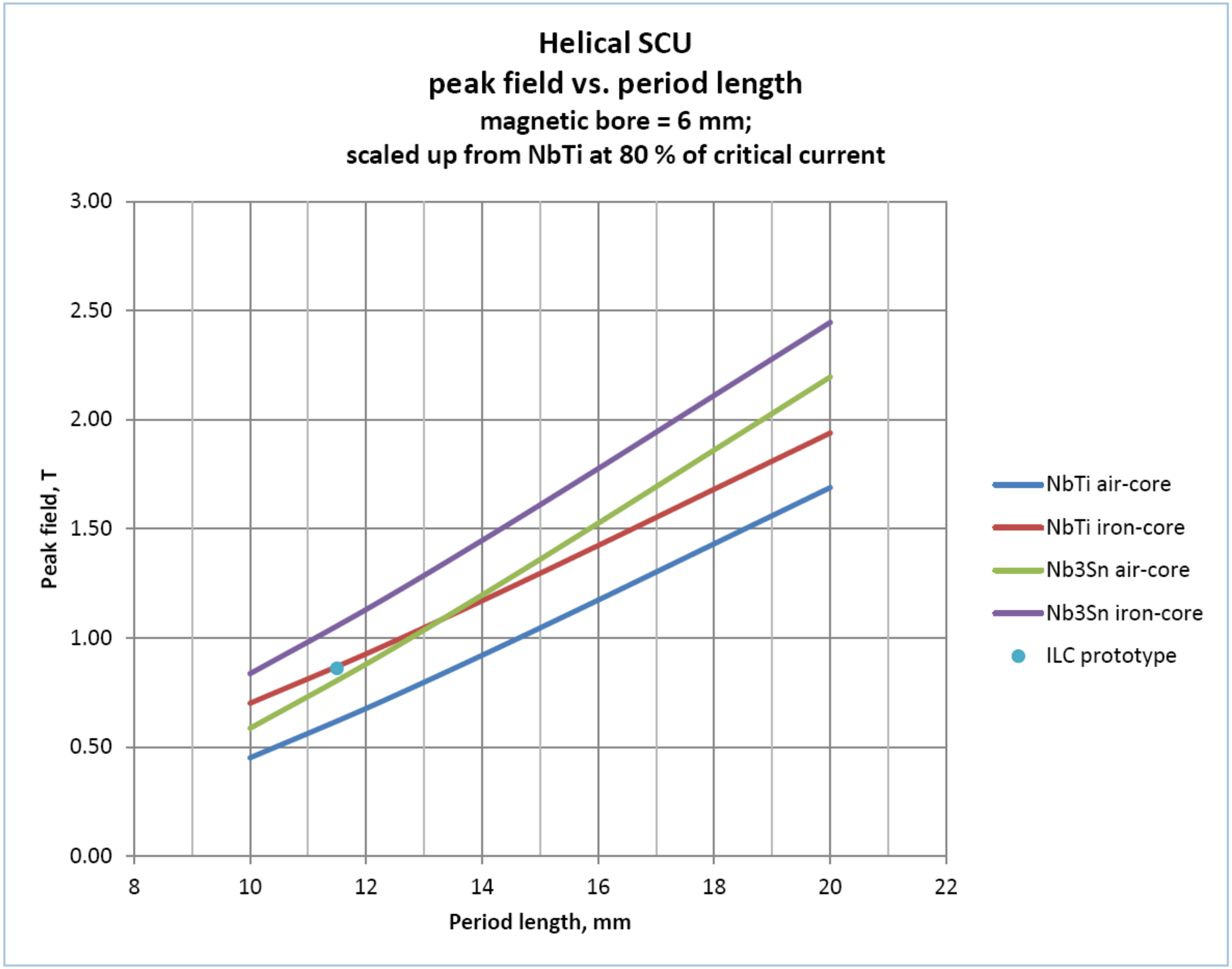
- Working plan
  - Further study on spinning target,
  - Including: a new type of sealing material, better cooling, and incorporate differential pumping
  - pursue alternative: self-contained bullet type target system (W. Gai, ANL)
  - Examine a conv. source as back up solution (300 Hz option)

- 300Hz scheme: to be studied
  - Target: Shocks, stresses, and cooling
  - beam timing issues
    - Start to end beam dynamics simulation is required.
    - Interface with damping ring simulation.
  - Develop a floor plan so that the whole system can be fit into the baseline configuration (undulator scheme)
  - Costing according to ILC methodology.

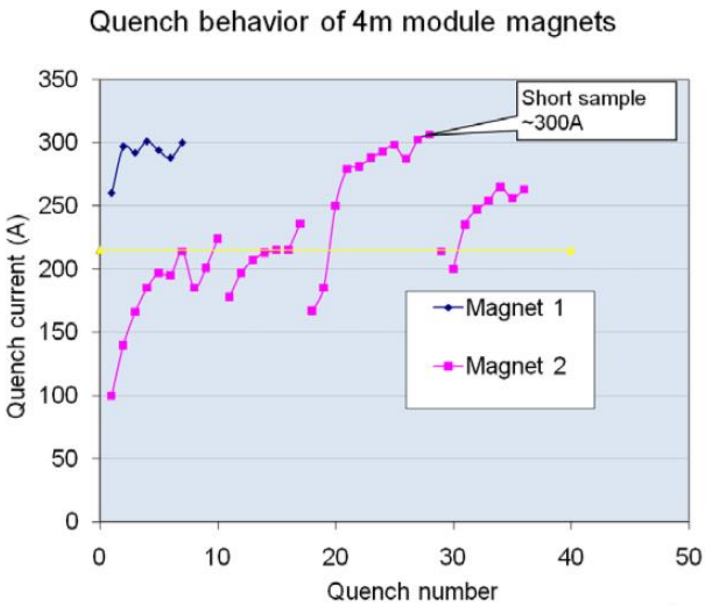
- During the discussions at ACFA, POSIPOL, LCWS, the e+ group member agreed that all tasks can be solved if   enough R&D resources are available.

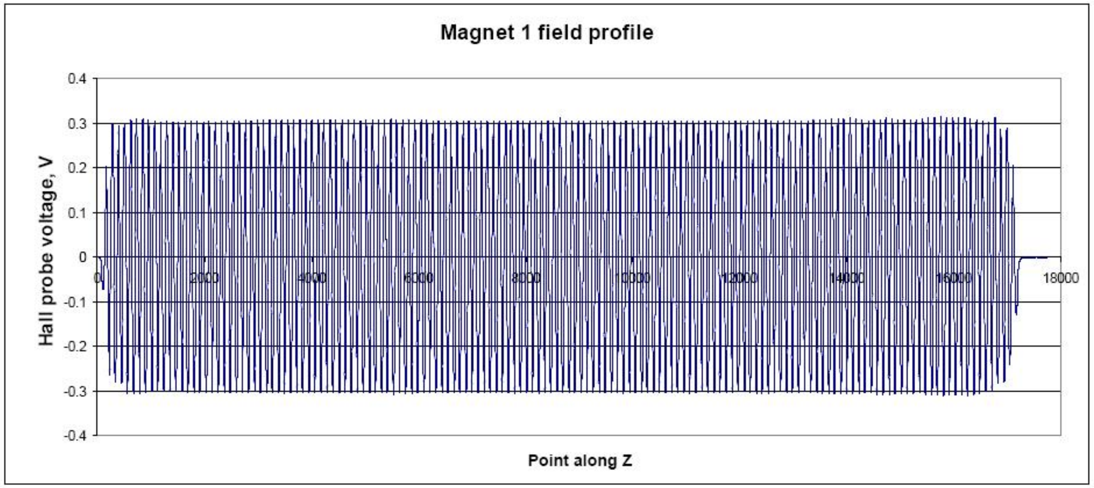
- Backup

Expected field from a helical SCU



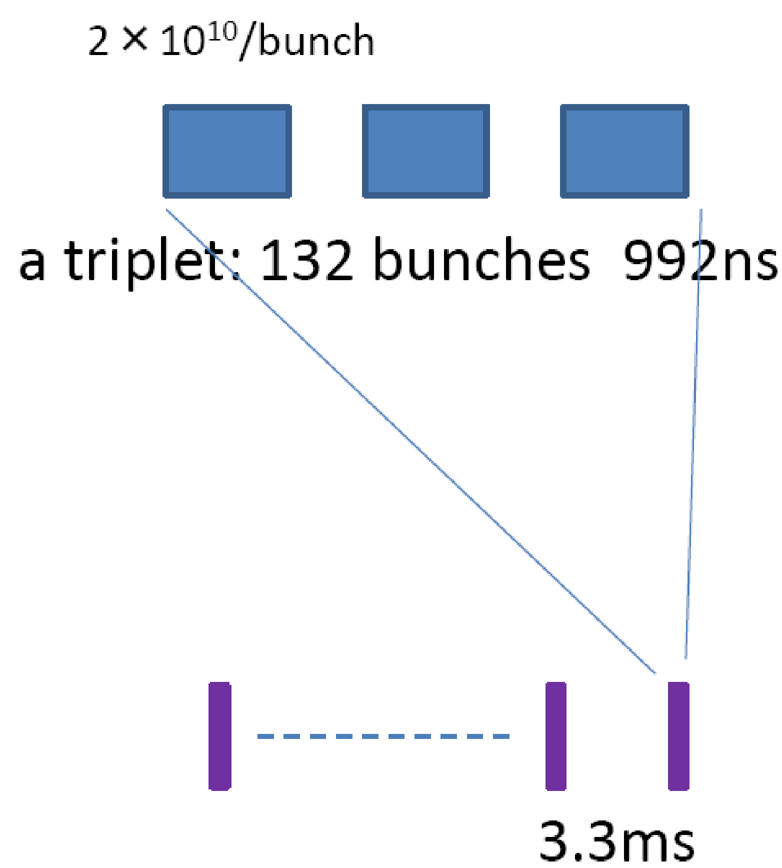
4-m module magnets test





Linacs

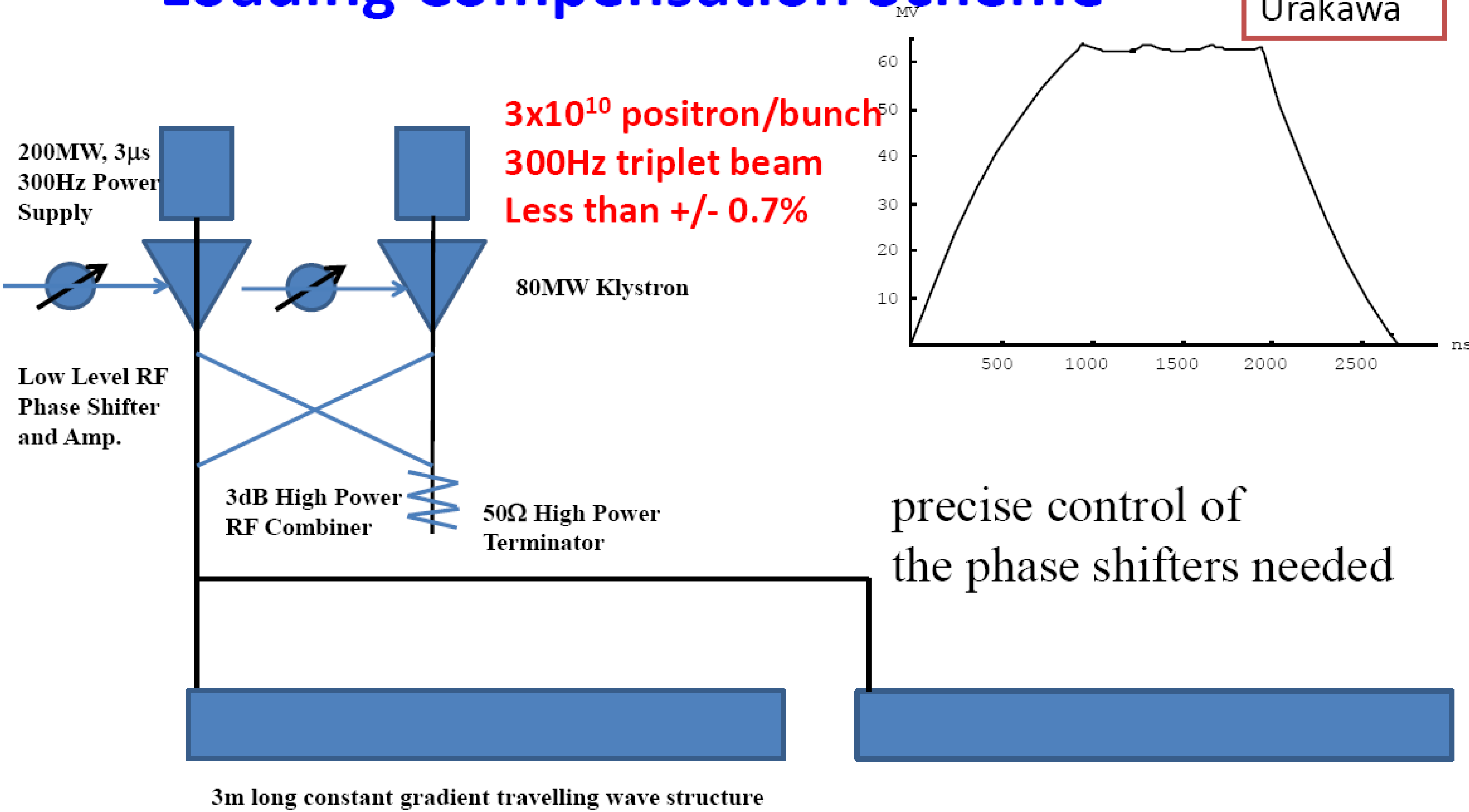
- Driver linac (~6GeV)
  - high current
  - high rep rate (300Hz)
- Booster linac (~5GeV)
  - high rep rate
  - accurate loading compensation (due to uneven bunch structure)



a train: 20 triplet
= 2640 bunches 63ms

Loading Compensation Scheme

Urakawa



3x10^10 positron/bunch
300Hz triplet beam
Less than +/- 0.7%

precise control of
the phase shifters needed

Test at ATF linac being planned