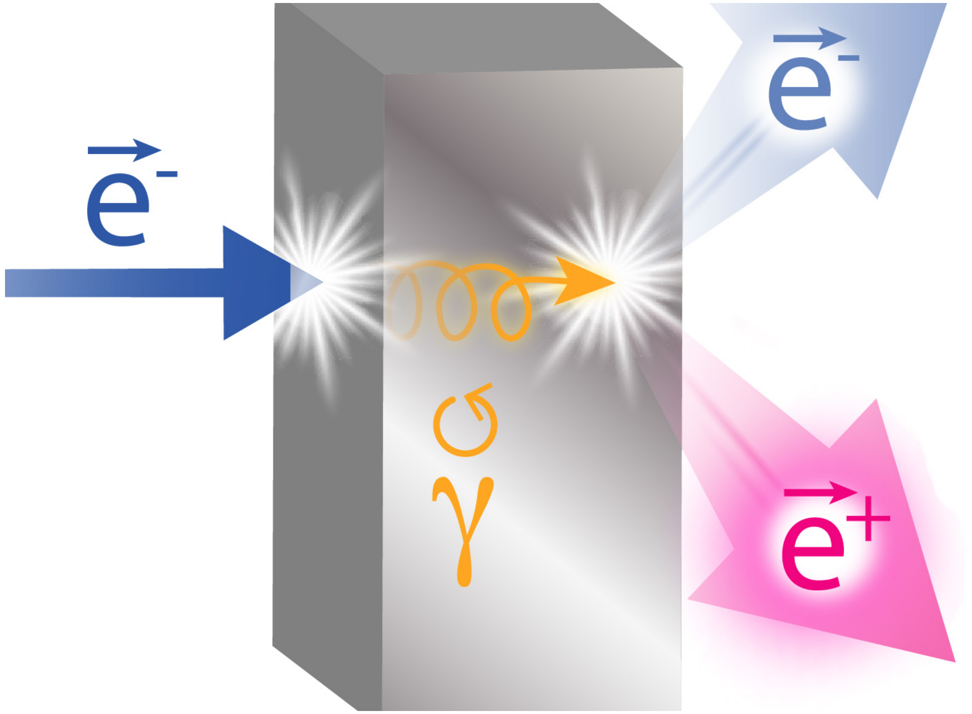
Ce+BAF : Positron Beams at Jefferson Lab

Joe Grames

J-FUTURE Workshop
Jefferson Lab / Messina University
March 28 – 30, 2022



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JSA

We’ve talked about this before, where do things stand today?

Physics side

- Positron physics workshops at JLab in 1999, 2009 and 2017
- Recent EPJA issue dedicated to e+ physics at Jefferson Lab
- Today, two conditionally approved PAC proposals exist

Accelerator side

- PEPPo experiment
- JLAAC recommendations
- Positron LDRD
- Expressed enthusiasm for e+ production using low, medium and high energy e- beams.

➢ Gun group has been busy : CEBAF injector upgrade for MOLLER and UITF for HDIce testing
➢ 2023 looks to be a great year to finally build a positron source, start with 8 MeV electron beam, learn from it
➢ In parallel, identify all positron users to help define our long term goals

Polarized Electrons for Polarized Positrons (PEPPo) @ CEBAF

PEPPo (**P**olarized **E**lectrons for **P**olarized **Po**sitrons) => ***demonstrate feasibility*** of using bremsstrahlung radiation of **MeV energy Polarized Electrons** for production of **Polarized Positrons**.

J. Grames, E. Voutier et al., JLab Experiment E12-11-105 (2011)

W (1mm)
<10 W beam

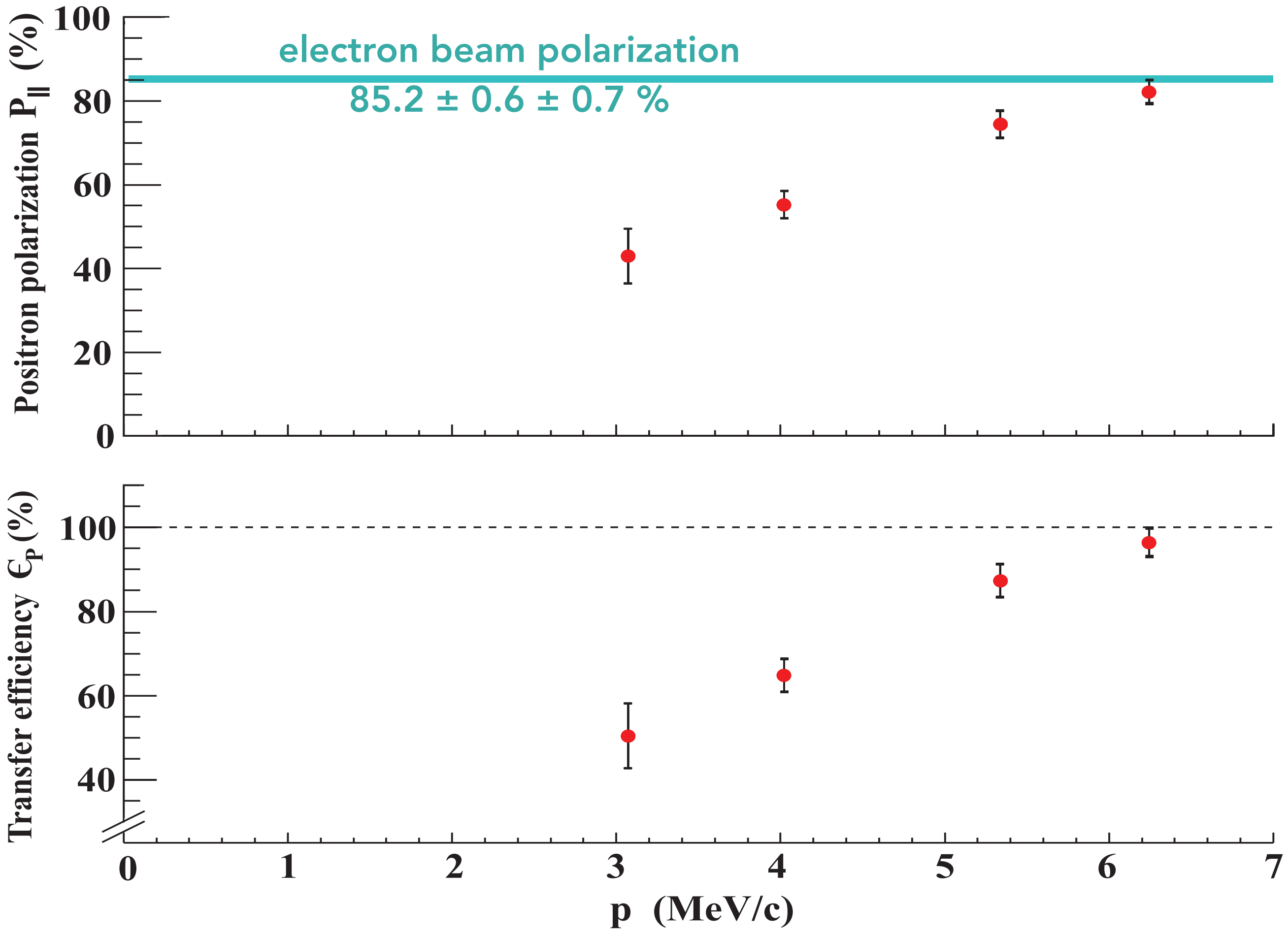
8 MeV, 1μA, 85% polarization

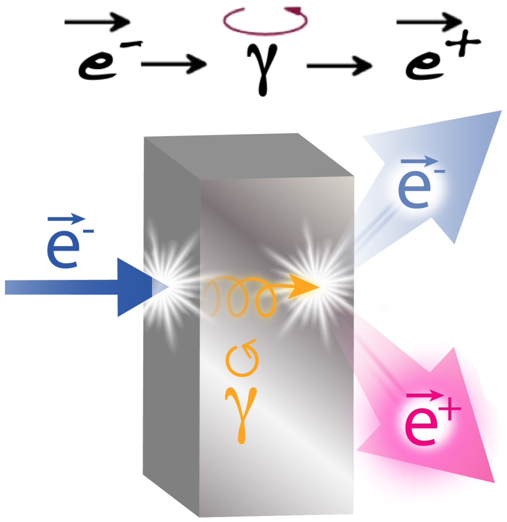
*PEPPo possible due to support from **SLAC** E166, **DESY**, **Princeton**, **Cornell**, **International Linear Collider Project** and the **Jefferson Science Associates***

Polarized Positron Production

(PEPPo Collaboration) D. Abbott et al. , Phys. Rev. Lett. 116 (2016) 214801

PEPPo demonstrated **efficient polarization transfer** of **8.2 MeV/c polarized electrons** to **positrons**, expanding polarized positron production using **MeV electron beam energies.**





Whenever producing e^+ from e^-, polarization is coming for free, if initial electrons are polarized.

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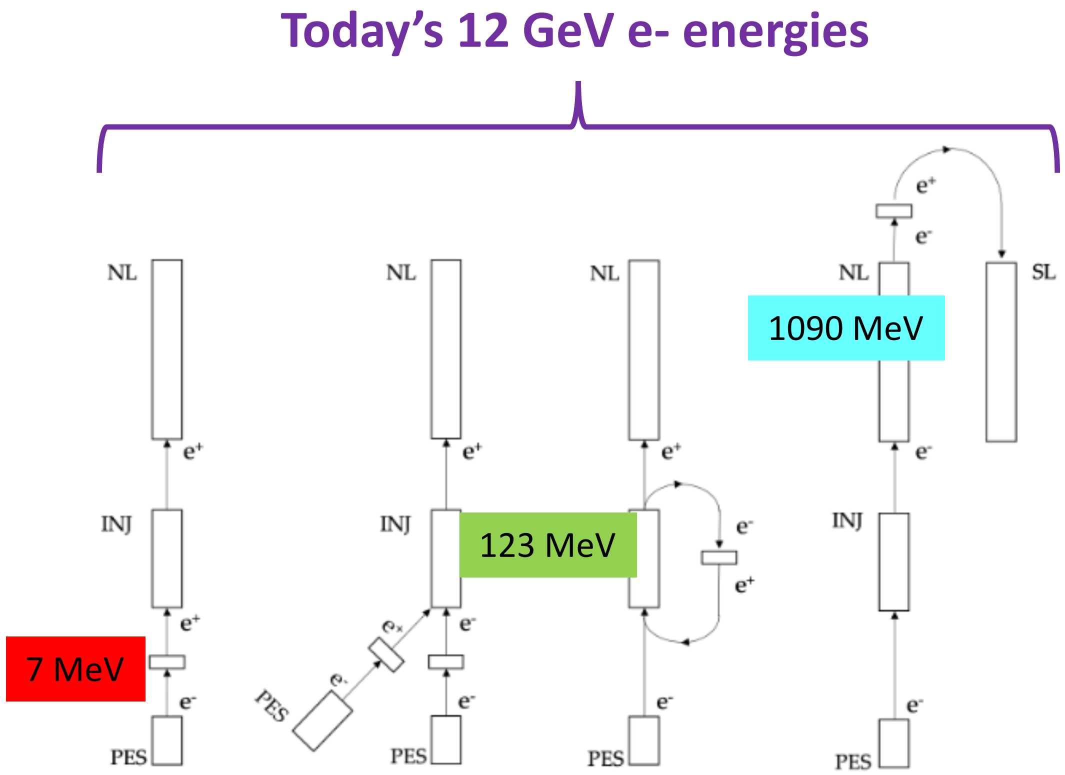
PEPPo approach is a new approach, it's time has come

"Conventional" unpolarized bremsstrahlung positron sources have been built and operated successfully

- SLAC – Stanford Linear Accelerator Center (US)
- HERA – Hadron Electron Ring Accelerator (Germany)
- BELLE/KEK – National Laboratory for High Energy Physics (Japan)
- CESR – Cornell Electron Storage Ring (US)
- VEPP – Budker Institute of Nuclear Physics (Russia)
- BEPCII – Beijing Electron Positron Collider (China)

PEPPo builds upon this

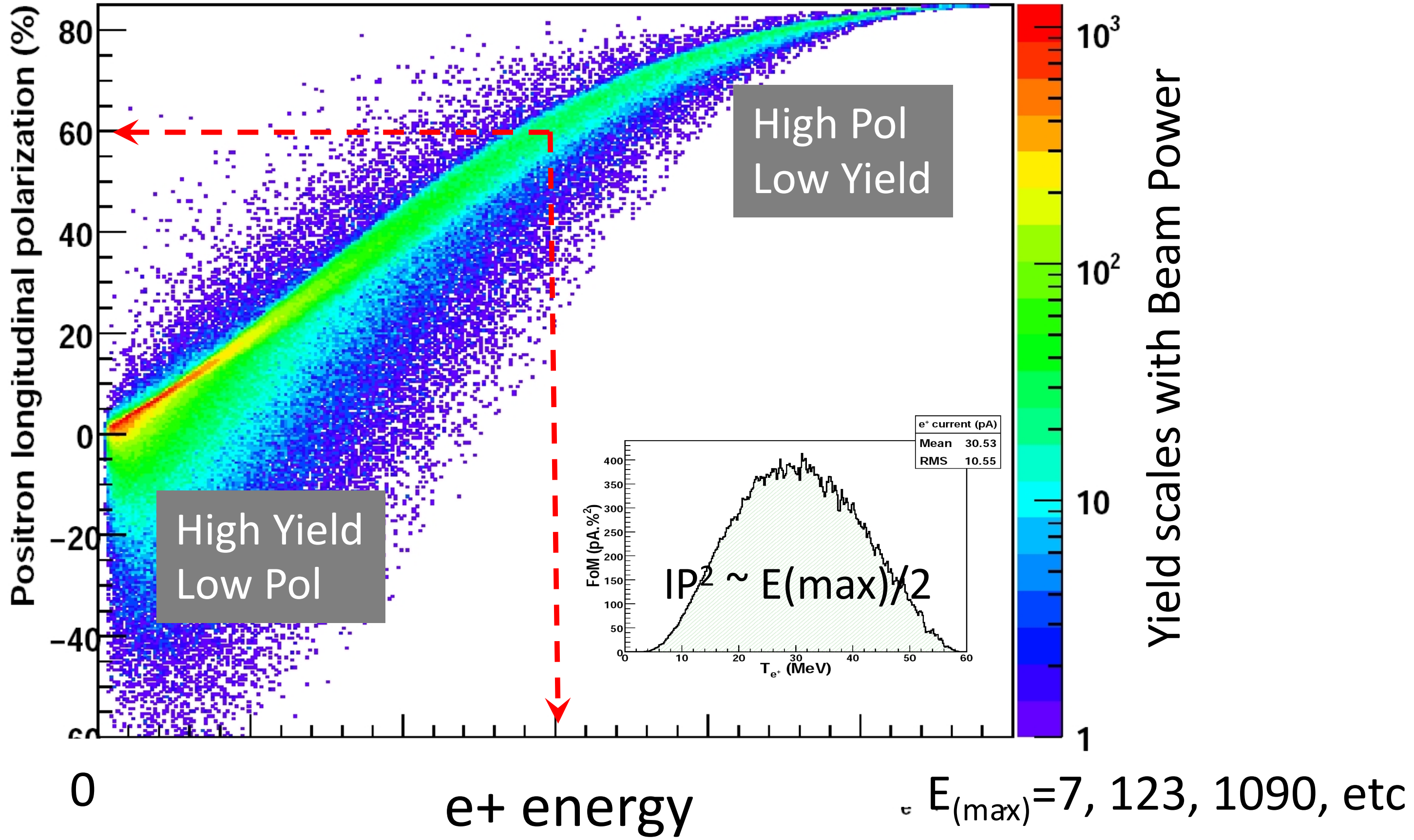
- e+ polarization / intensity configurable
- cw (all prior machines are pulsed)
- milliamp polarized e- source
- Integrates to 12 GeV CEBAF…
- …or higher energy CEBAF

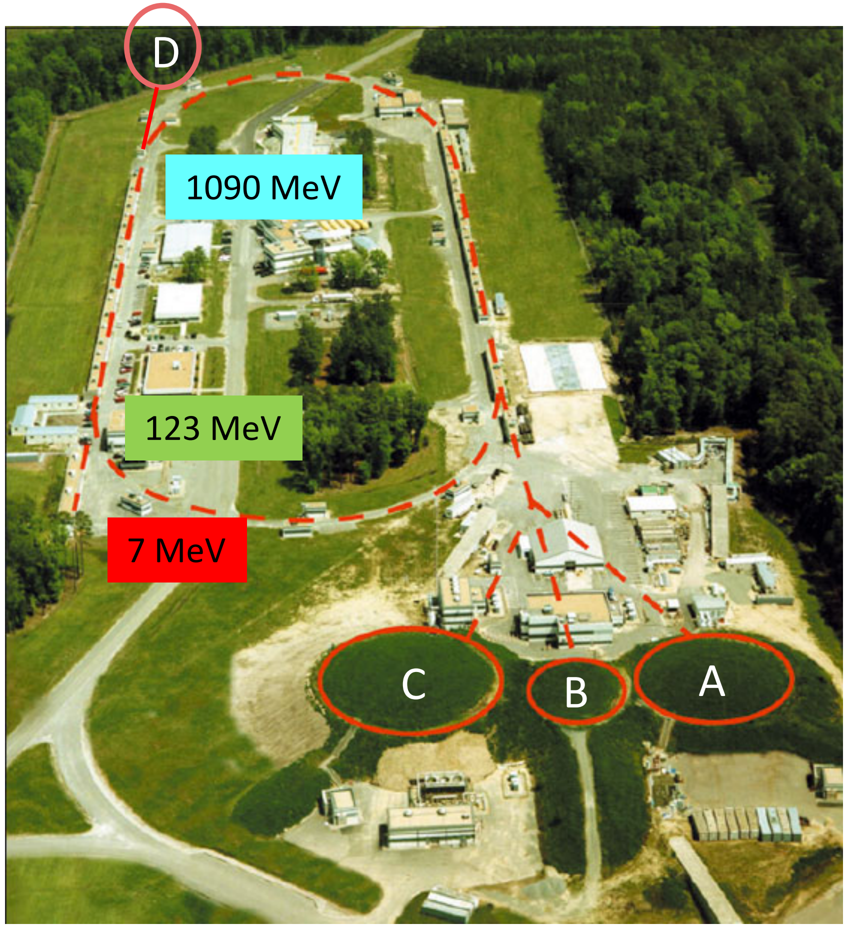


PEPPo – Polarization and Intensity Trade Off

The **Yield** (e+/e-) depends on the beam power ***Beam Energy x Beam Current***

Polarization transfer is universal whether the electron beam is 10 MeV, 100 MeV, 1 GeV, etc…





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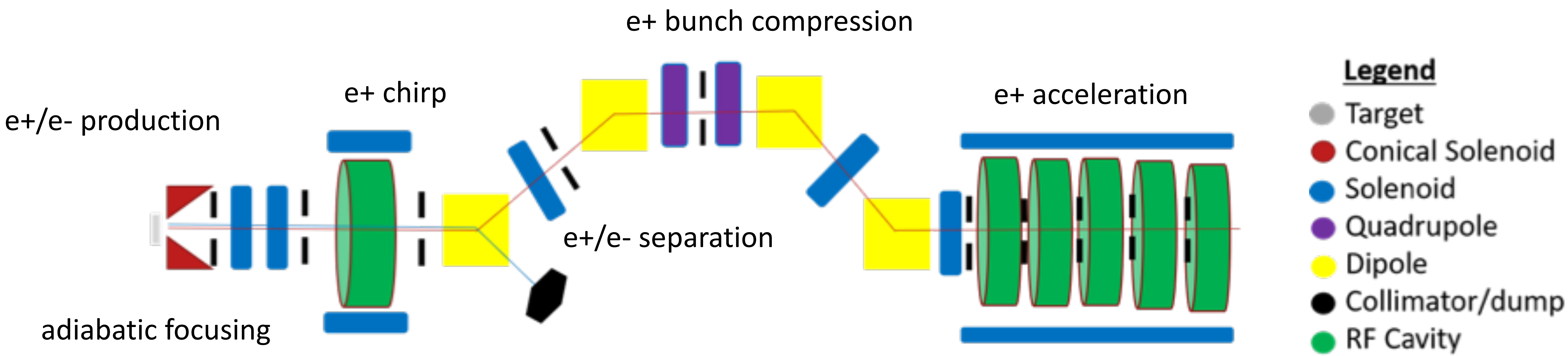
No matter the e-beam energy, the e+ source looks like….

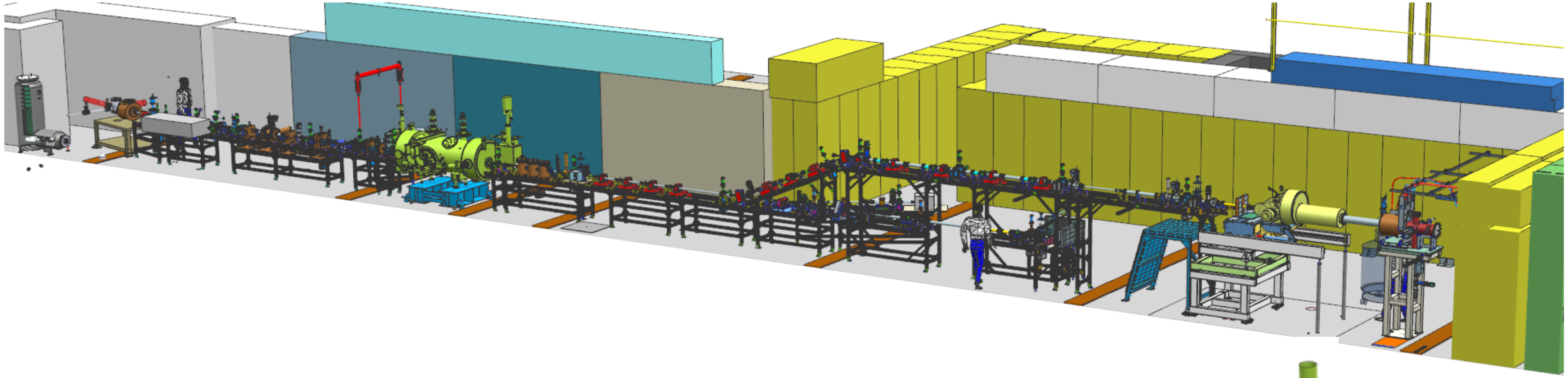
A positron injector model was designed to explore feasibility

- Target, magnet and collimation define transverse emittance
- Dipoles separate e-/e+ and define momentum spread
- Chicane compresses bunch length

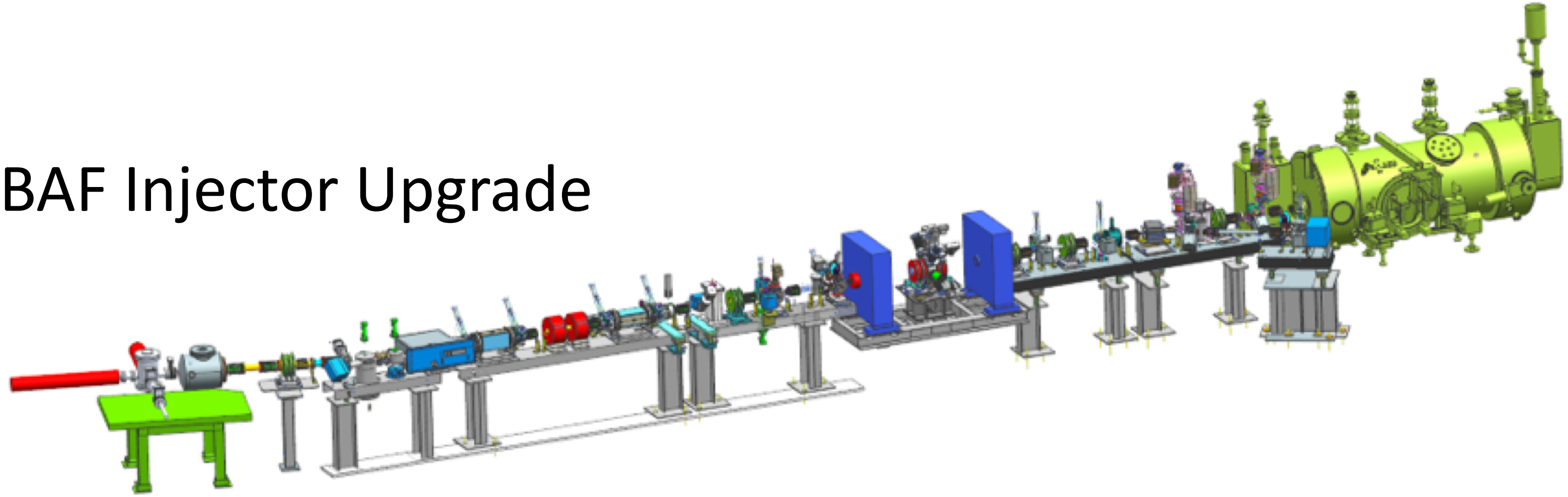


For past 5 years, we've been building injectors

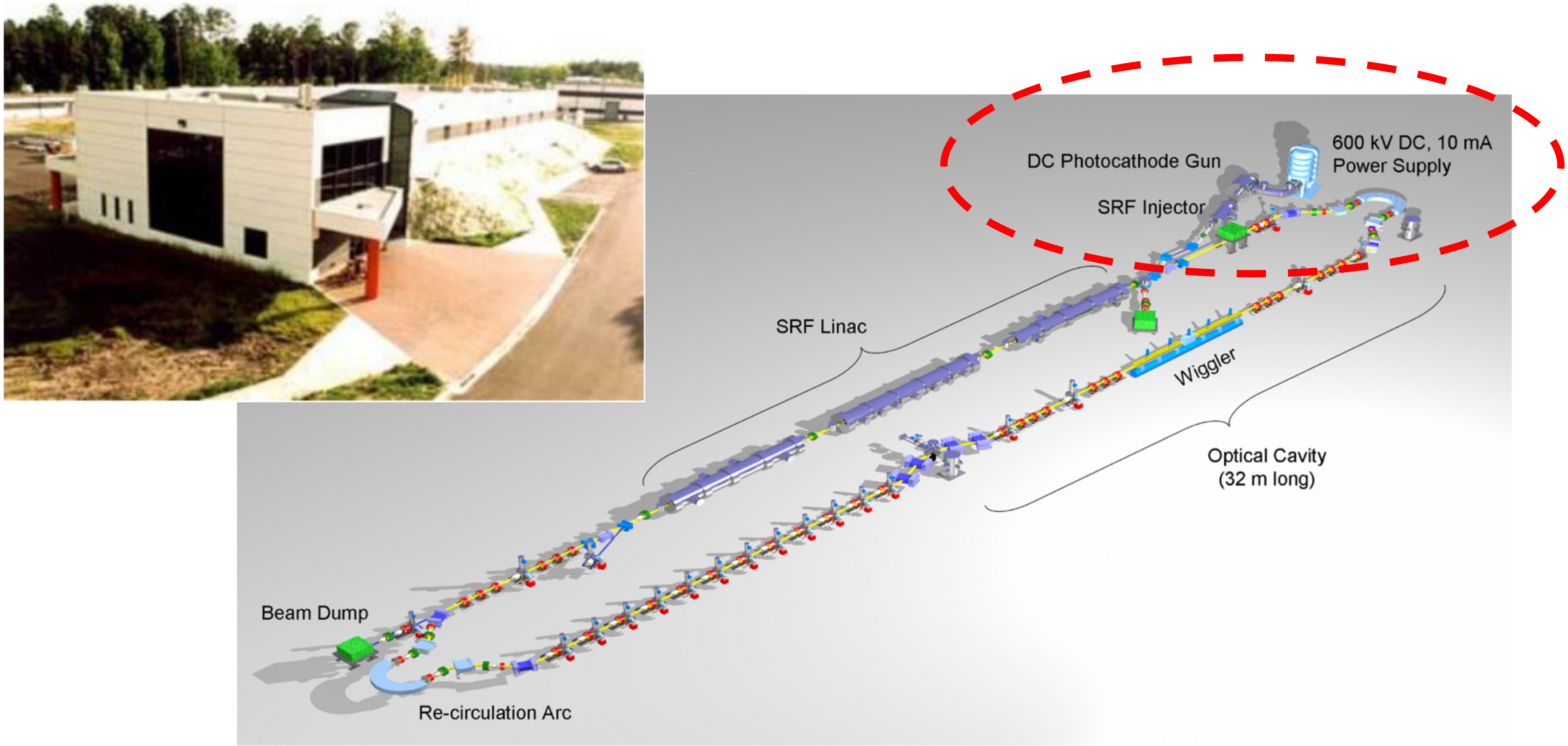
Upgraded Injector Test Facility



CEBAF Injector Upgrade

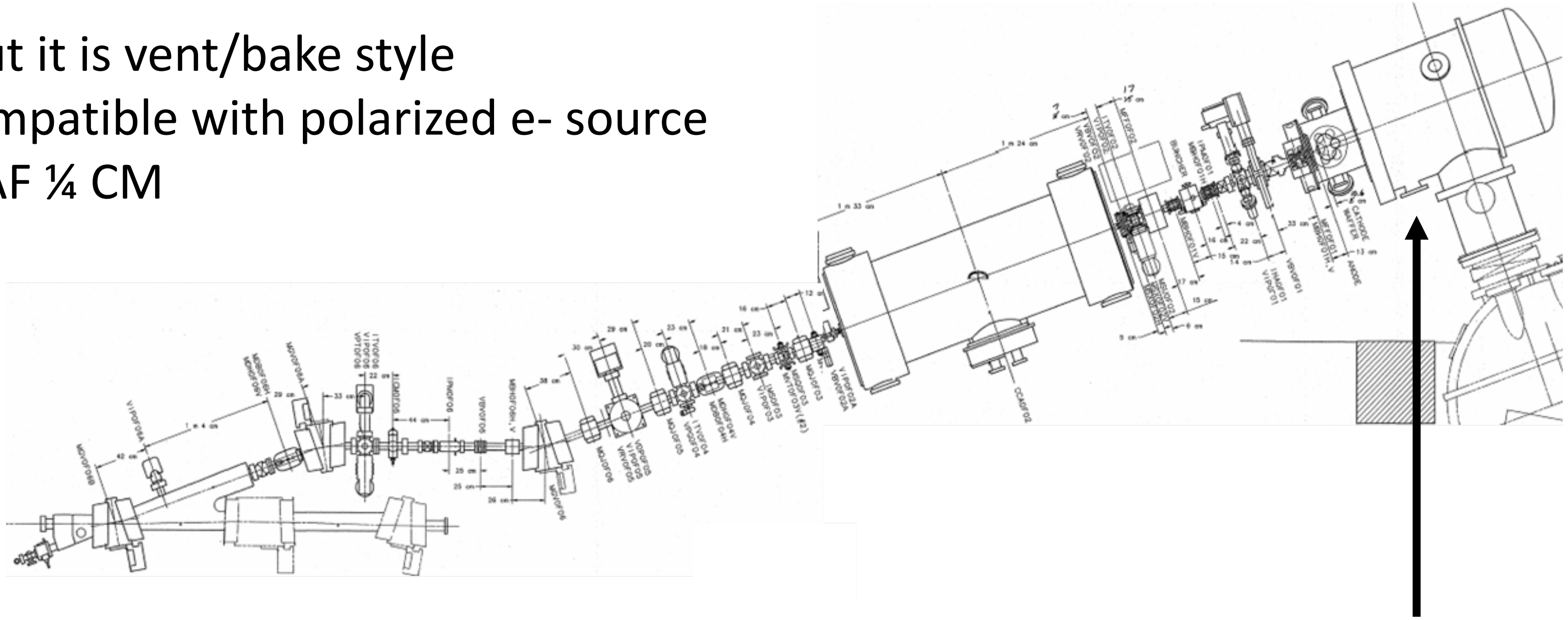


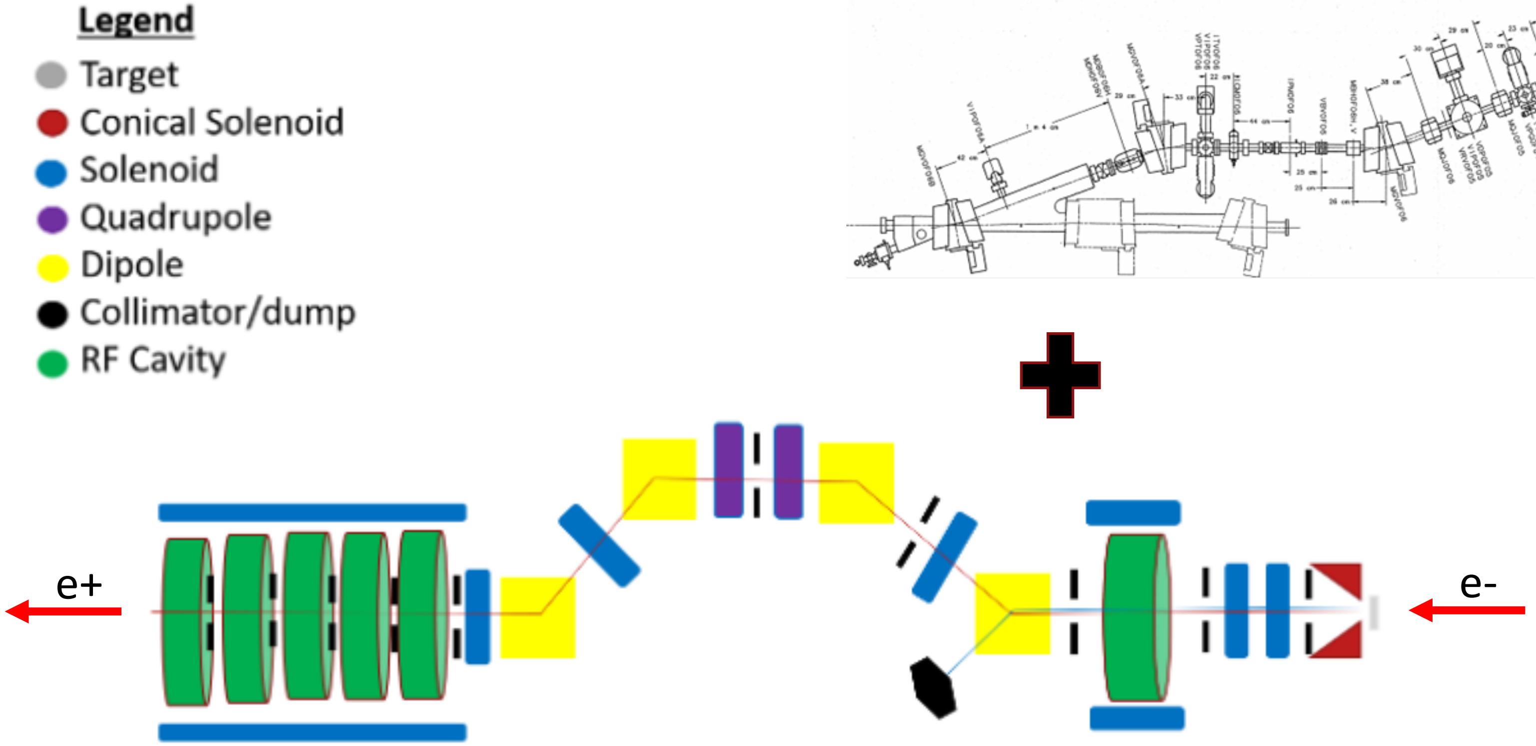
With CEBAF and HDIce obligations behind us, time to build e+ source



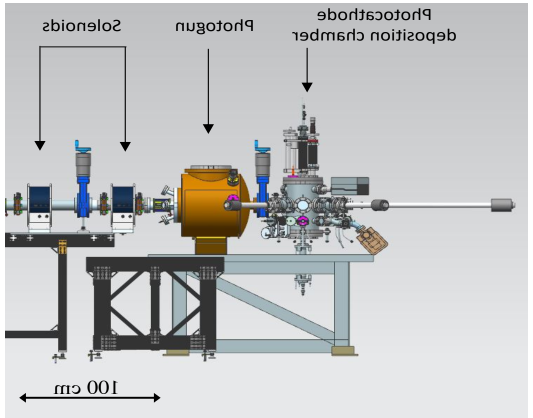
Producing polarized e+ at LERF

- LERF gun still holds world records, but it is vent/bake style
- LERF ¼ CM has a helium leak, not compatible with polarized e- source
- Install new load locked gun and CEBAF ¼ CM





Polarized positron source conceptual layout



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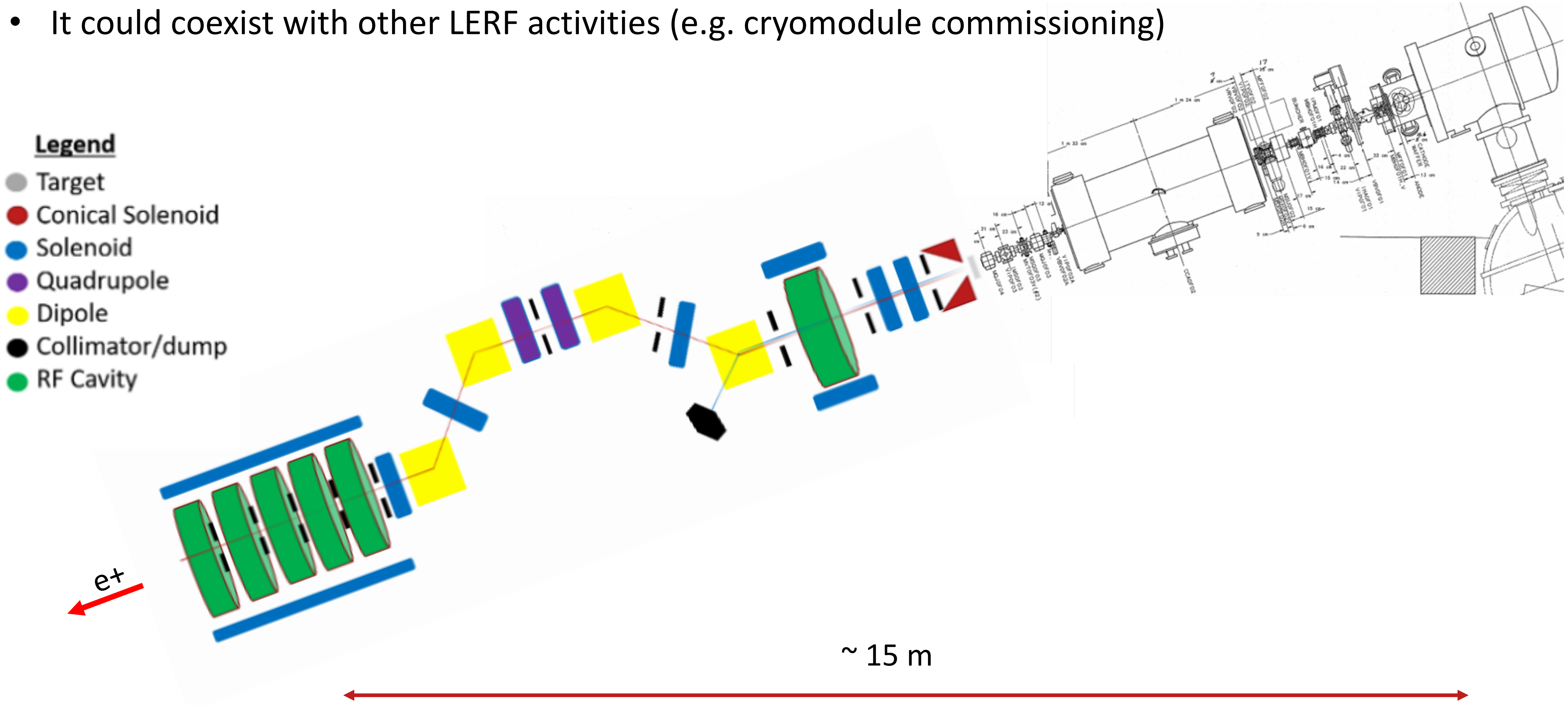
Polarized Electron – Positron Injector

- Injector we proposed to build and learn from is compact
- It could coexist with other LERF activities (e.g. cryomodule commissioning)



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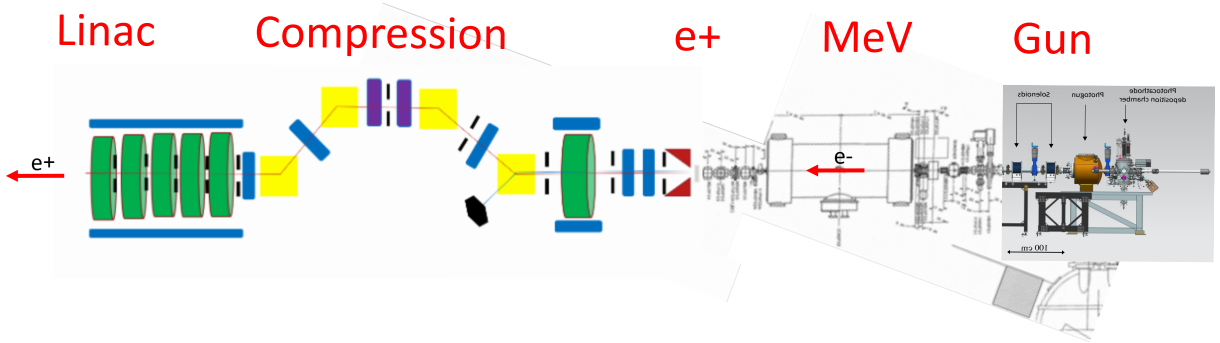
Goal – over the next 5 years, at the LERF

Build a positron injector

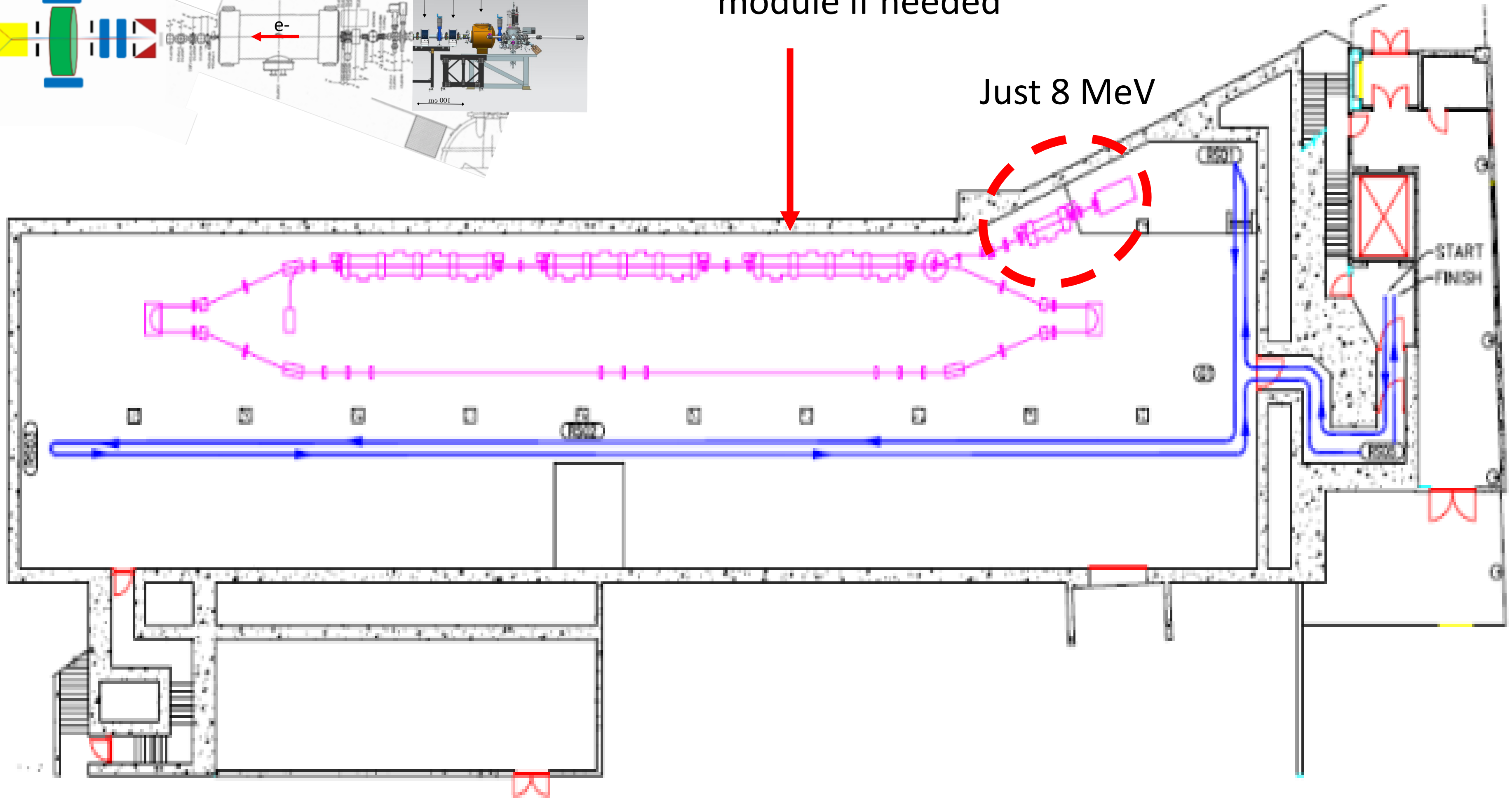
- 350 kV gun polarized electron beam with 1000 C lifetime at 1mA
- e- beam through ¼ CM, 8 MeV electron beam
- Optics model of the positron source including especially the positron distribution downstream of target and capture/bunching sections
- e- and e+ beamline layout
- Positron target that can take >10 kW
- Solenoid magnet, >0.5 T, positron spatial capture
- RF cavity, positron temporal capture
- e+ diagnostic beamline

>100 nA unpolarized or >10 nA polarized positron beams

LERF is well suited – 8 MeV to cut our teeth, higher energy when needed



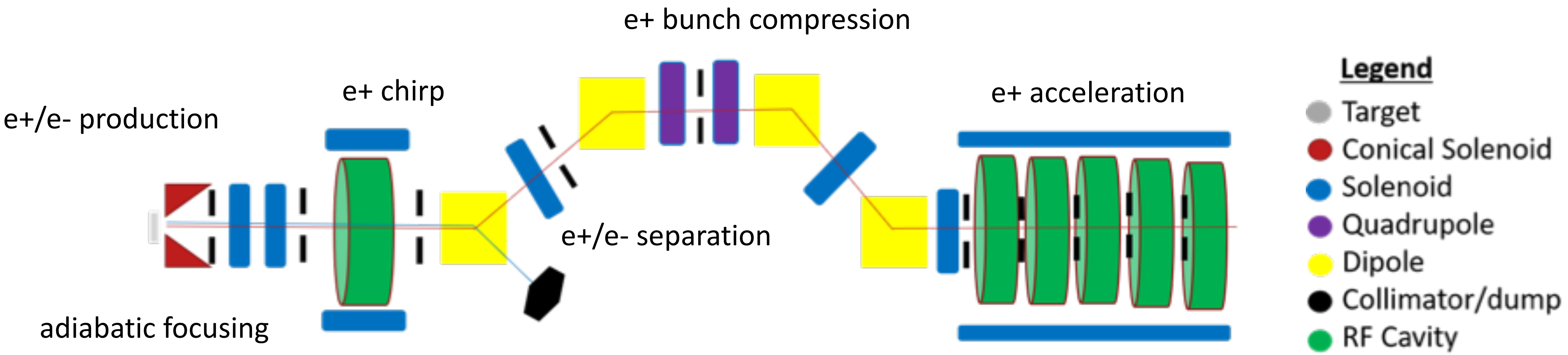
Or send e-beam through a full module if needed



- Radiation Shielding
- Cryogenics
- RF/Magnet controls
- Safety Systems
- Expandability

Being realistic…..LDRD : 123 MeV polarized-e driven PEPPo Injector

Jefferson Lab the Users are asking for e+ beams with **polarized (>60%) intensities >100 nA**.



- Collimation defines normalized emittance
- Dipoles separate particle species
- Dispersion selects final dp/p
- Bunching achieve with R56 chirper/chicane

Parameter	Polarized e^+ Captured	Polarized e^+ at Injection	CEBAF Acceptance
Efficiency	2×10^{-4}	4×10^{-5}	
Mean Energy	63 MeV	123 MeV	123 MeV
$\frac{\Delta P}{P}$	15%	1%	2%
ϵ_n	90 mm-mrad	43 mm-mrad	<40 mm-mrad
Bunch Length	15 ps	3 ps	<4 ps
Transverse rms	4 mm	2 mm	<3 mm
Polarization	$\sim$ 66%	$\sim$ 66%	>60%

A GaAs source source providing 1 mA for a week = 600 Coulombs (4x CEBAF)
We would like to have a charge lifetime >1000 C

Technical and engineering goals

Risks, realities, complications….

- 1 mA polarized e- beam with >**1 kC lifetime** (have 200 C @ 0.2 mA now)
- Target that can survive **>10 kW e-beam**
- **>0.5 T dc solenoid** in high x-ray environment

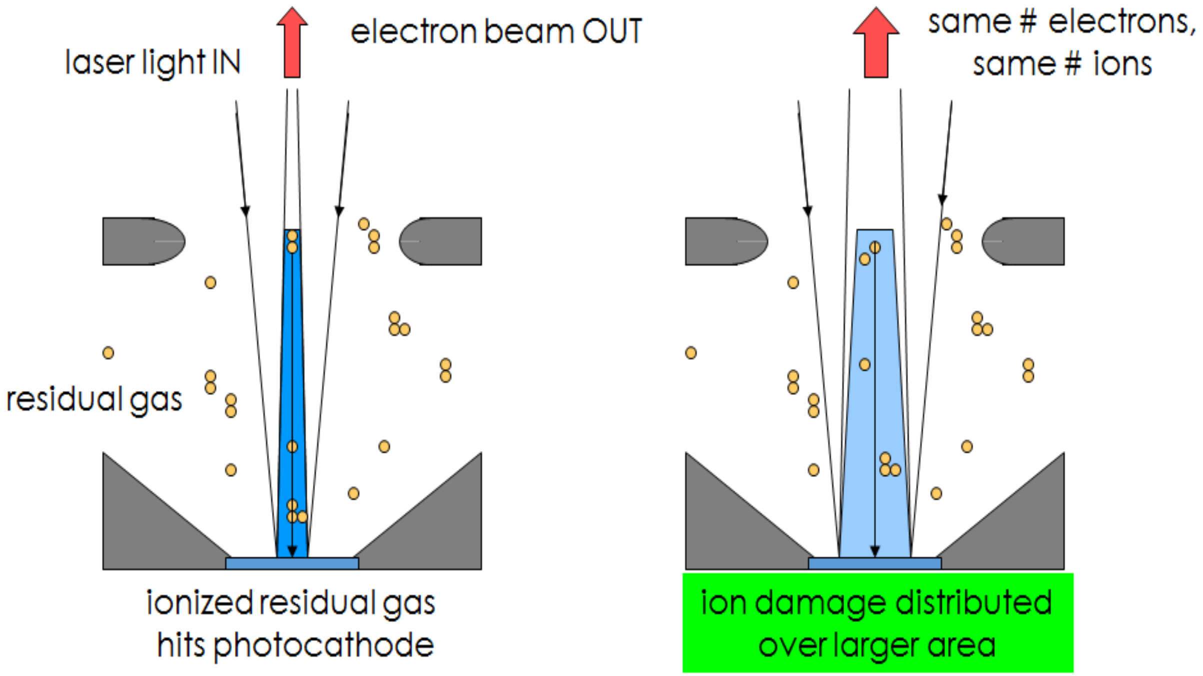
Note, with this approach (8 MeV electron beam), we won't be activating anything

But at the LERF, conversion with higher energy electron beam is a real possibility, <u>that's how we get to higher positron current</u>

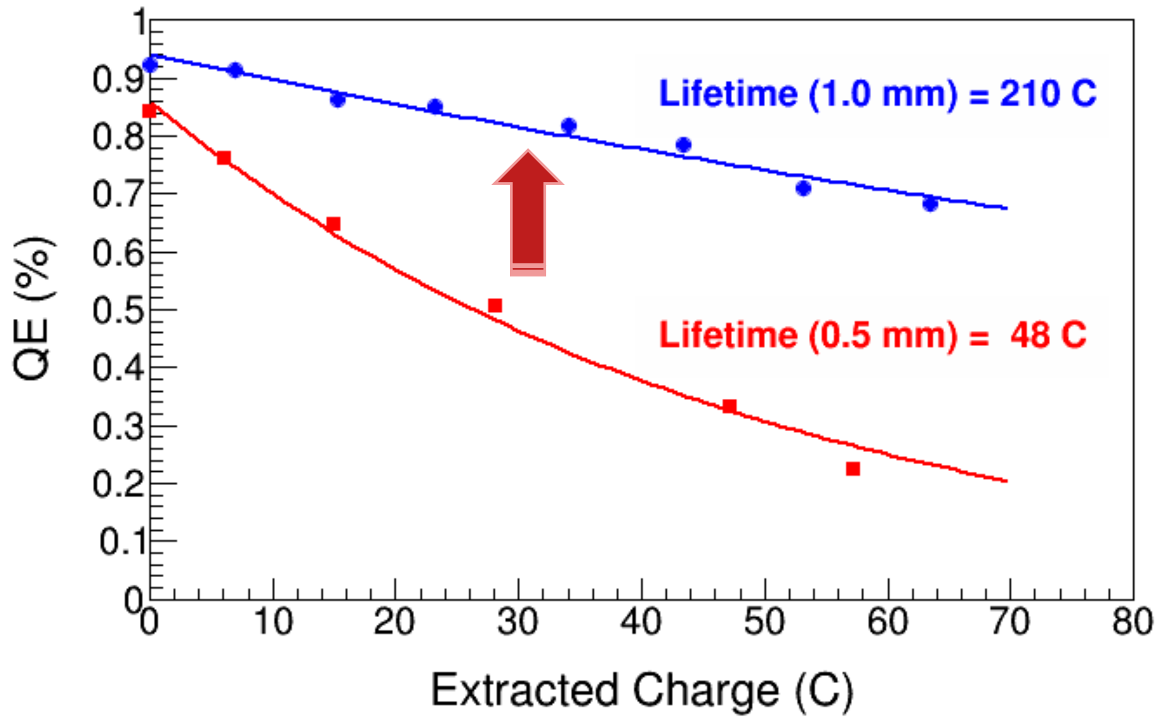
Improving charge lifetime of polarized electron source

Photocathode QE starts high ~1%, but deteriorates via ionized gas bombardment
Distributing ion damage over large area reduces rate of deterioration

Ionized residual gas bombards the photocathode, lowers quantum efficiency, limits charge lifetime.

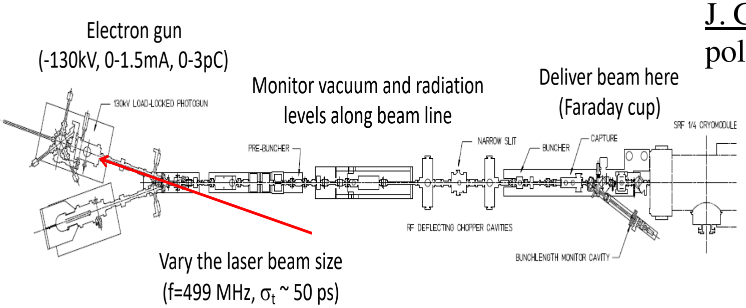


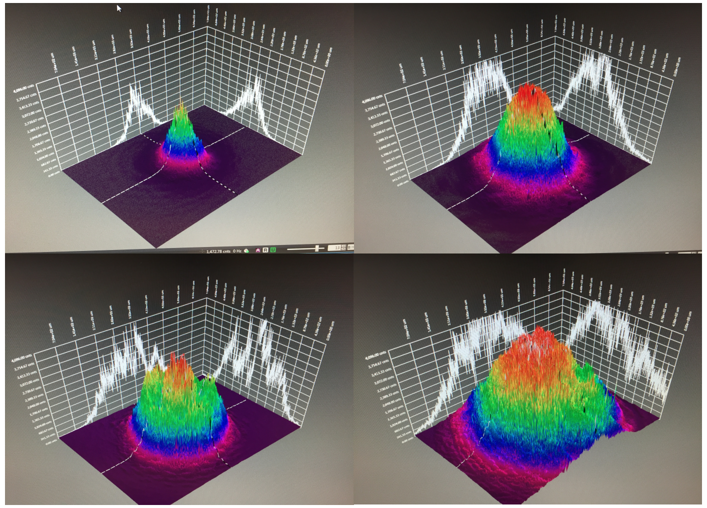
Charge lifetime increased by four when doubling the laser spot size from 0.5 mm to 1.0 mm (fwhm)



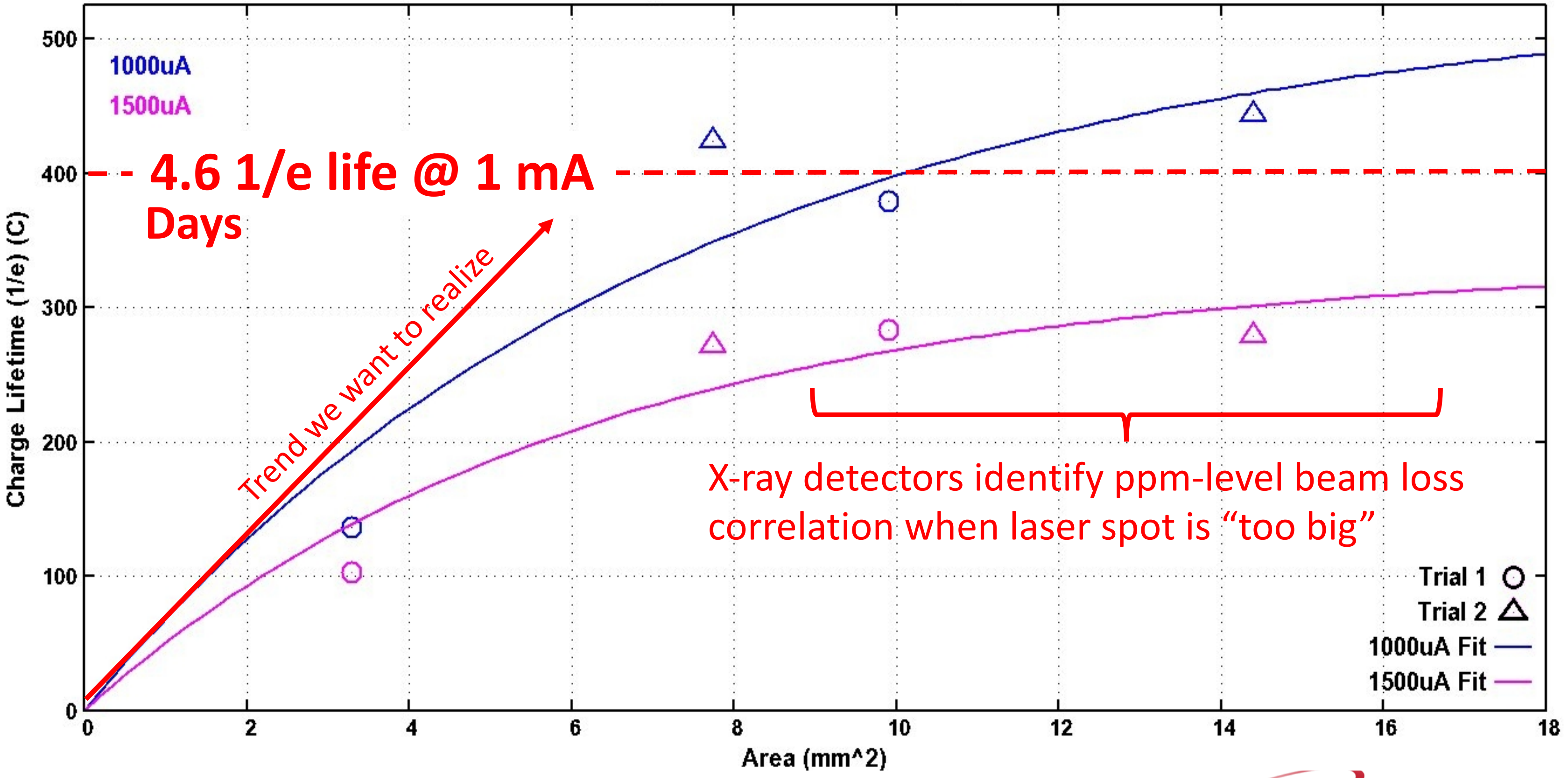
Operating >1 mA for weeks

- By increasing laser size we set our new lifetime record for mA operation (>400 C)
- Eventually size became "too big" for CEBAF gun
- Designing a new photogun to "straighten the curve"





J. Grames, P. Adderley, J. Hansknecht, R. Kazimi, M. Poelker, D. Moser, M. Stutzman, S. Zhang, "Milliampere beam studies using high polarization photocathodes at the CEBAF Photoinjector" Polarized Sources, Targets and Polarimeters Workshop, Dajeon South Korea (2017)



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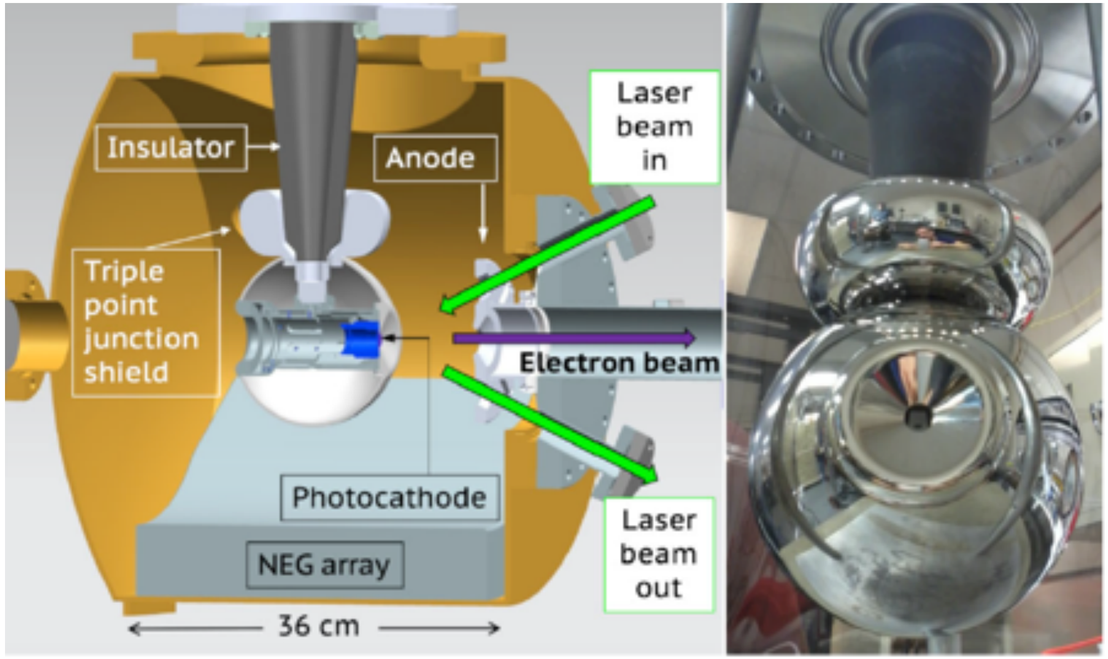
Building a polarized electron source for >1 mA operation

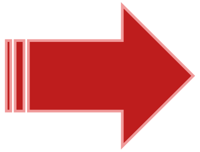
- Applying the experience and lessons learned from the 300 kV ***unpolarized*** photogun to build a 200 kV UHV ***polarized*** electron source for high polarization photocathodes

300 kV Magnetized Beam Electron Source (CsKSb)

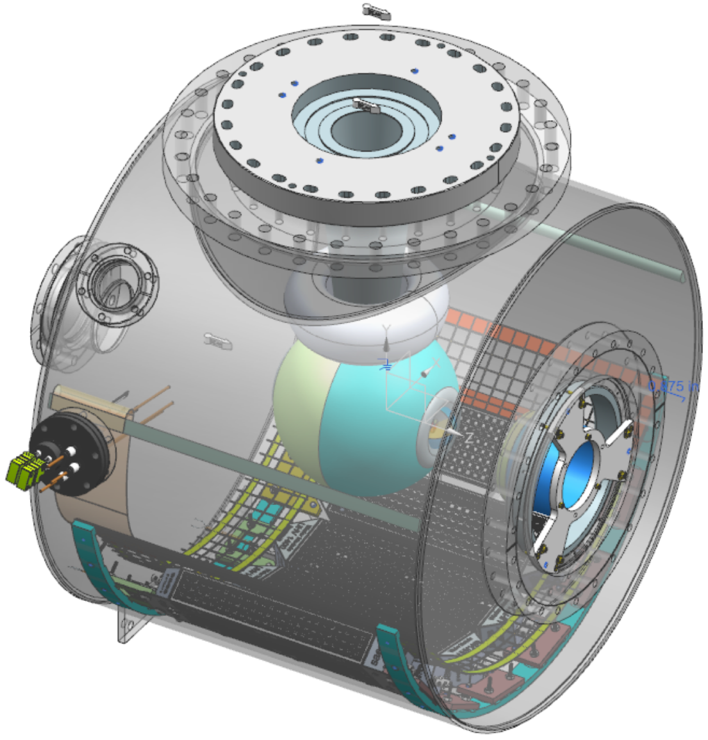


C. Hernandez-Garcia *et al.*, Phys. Rev. Accel. Beams **22**, 113401 (2019)

- R30 inverted geometry ceramic insulator
- Conditioned to 350 kV
- Demonstrated 4.5 mA CW 300 keV



Model of CEBAF 200 KV Polarized Gun (GaAs/GaAsP)



Operate at >200 kV without field emission
HV conditioning >350 kV (uses R30 inverted ceramic insulator)
Dynamic pressure (during beam delivery) ~ 1×10^{-12} Torr

Target that can survive >10 kW (100 kW) of beam power

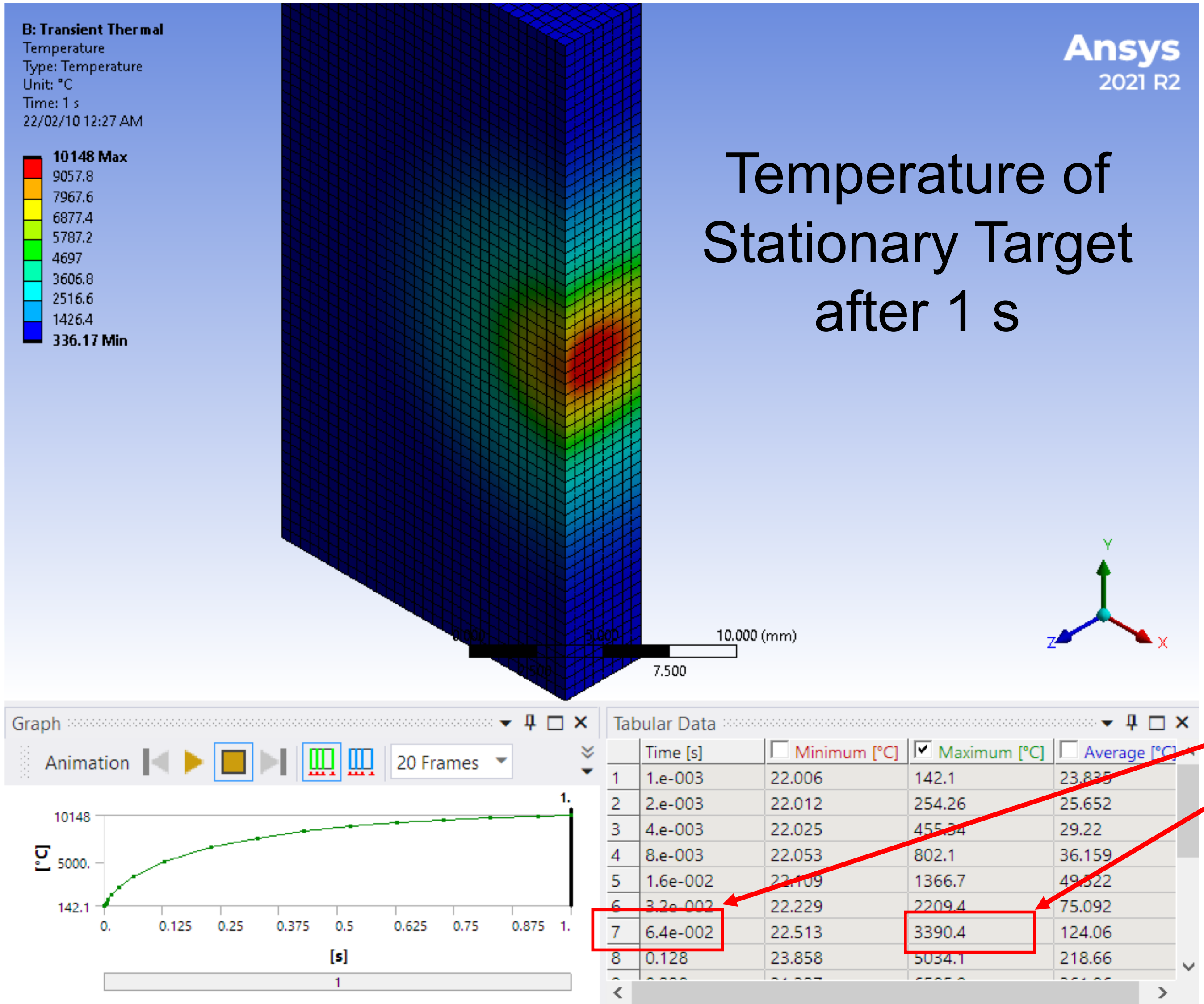
Work of A. Ushakov, IJCLab

Preliminary studies for 120 MeV x 1 milliamp solid *rotating* target

- Beam energy: electron beam with energy of **120 MeV**
- Beam current: **1 mA** (continuous wave, RF frequency of 1497 MHz)
- Beam size on target: beam has a Gaussian distribution with RMS size >150 µm. The biggest beam spot size is limited by aperture size of focusing magnet downstream the target
- Target material: pure **Tungsten**
- Target thickness: **4 mm**
- Average power deposited in target: **17 kW**
- Concept of target cooling: rotating tungsten rim is mounted on water cooled copper disk (could even be fixed target lower power for initial 8 MeV tests)

Managing 100 kW of beam power

Work of A. Ushakov, IJCLab



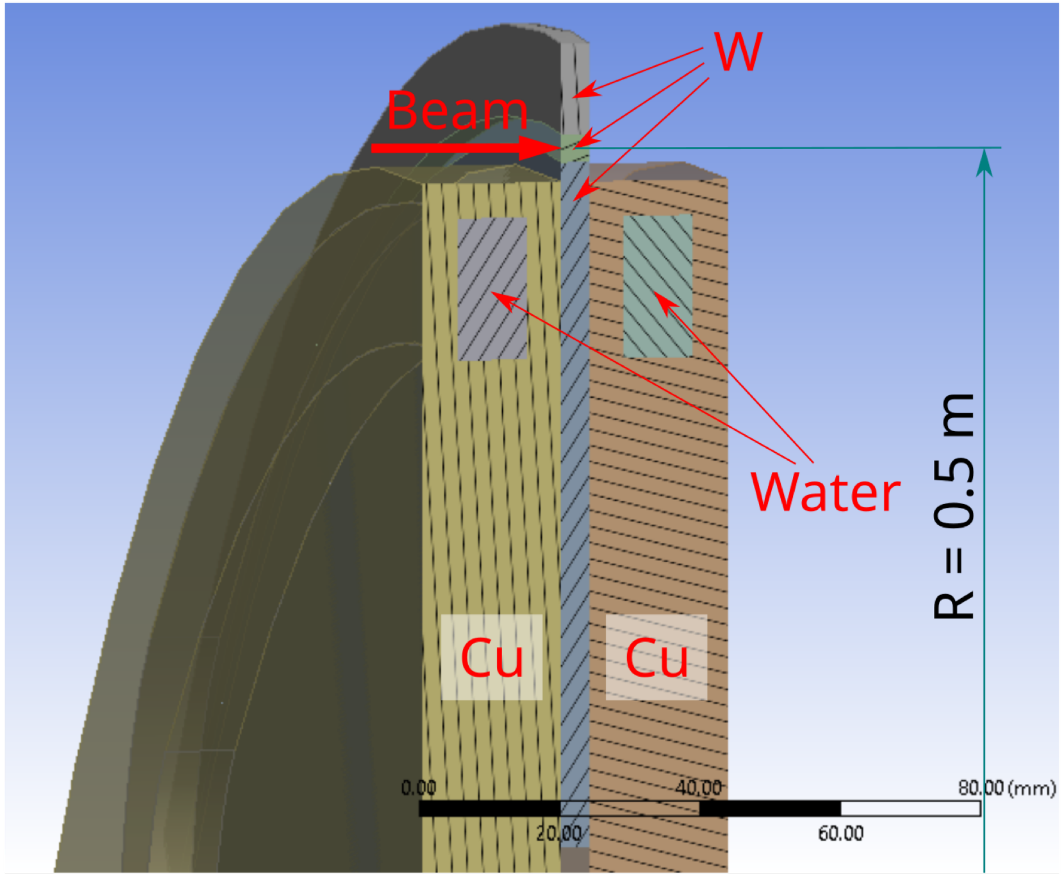
1 mA @ 120 MeV cw electron beam with 1.5 mm RMS size ***melts*** the stationary 4 mm thick tungsten target in 64 ms

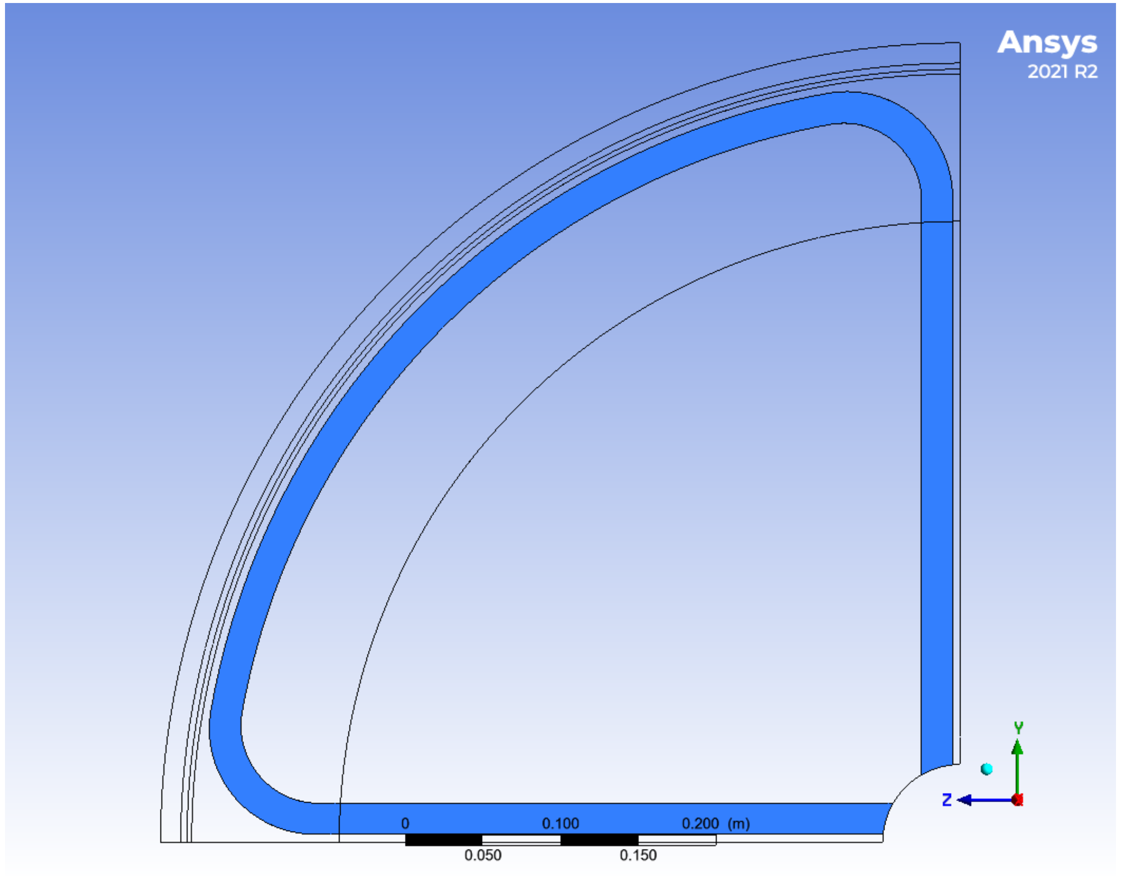
Water cooled rotating tungsten target

Work of A. Ushakov, IJCLab

W Rim Cooled from One Side by Copper Disk with 10mm x 20mm Cross Section of Water Channel and 2 m/s Flow (ANSYS Fluent)

Beam Passing through the Target at Radius of 0.5 m

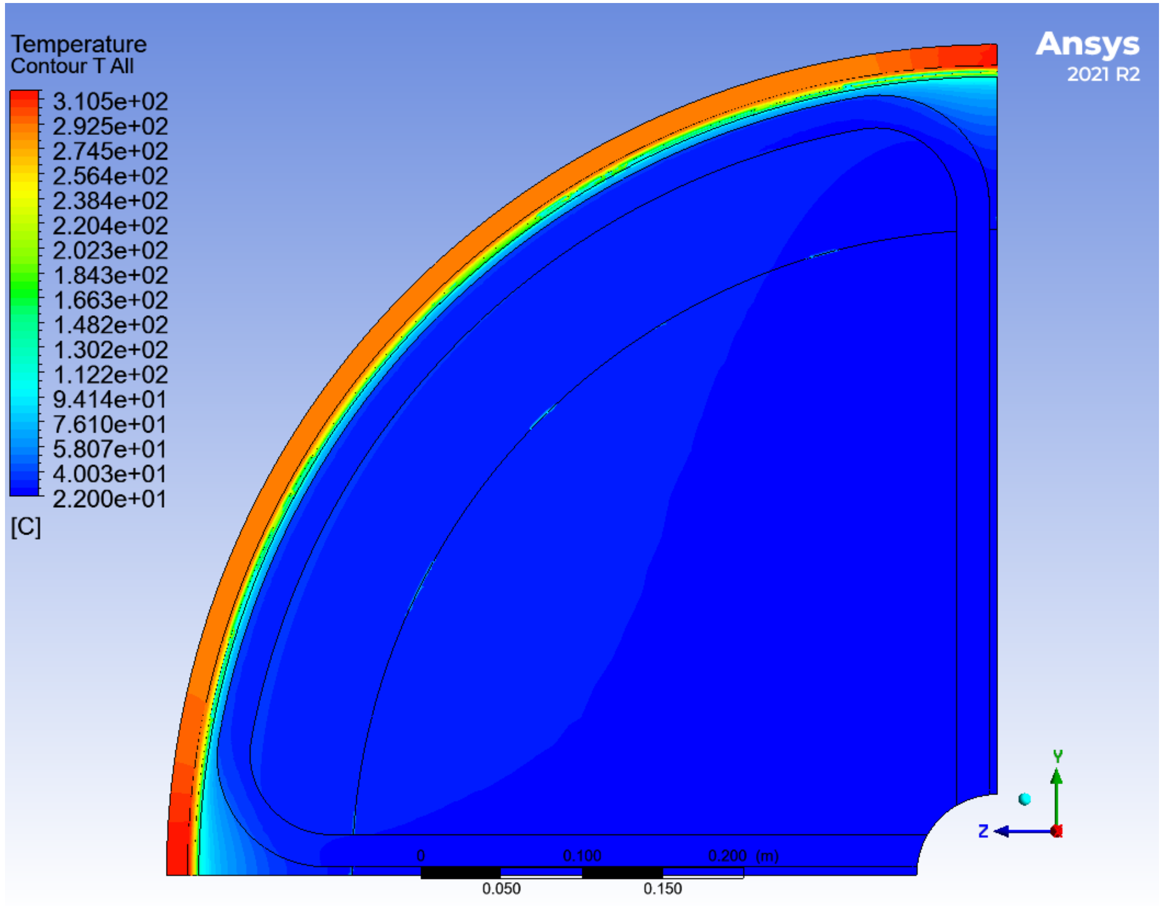


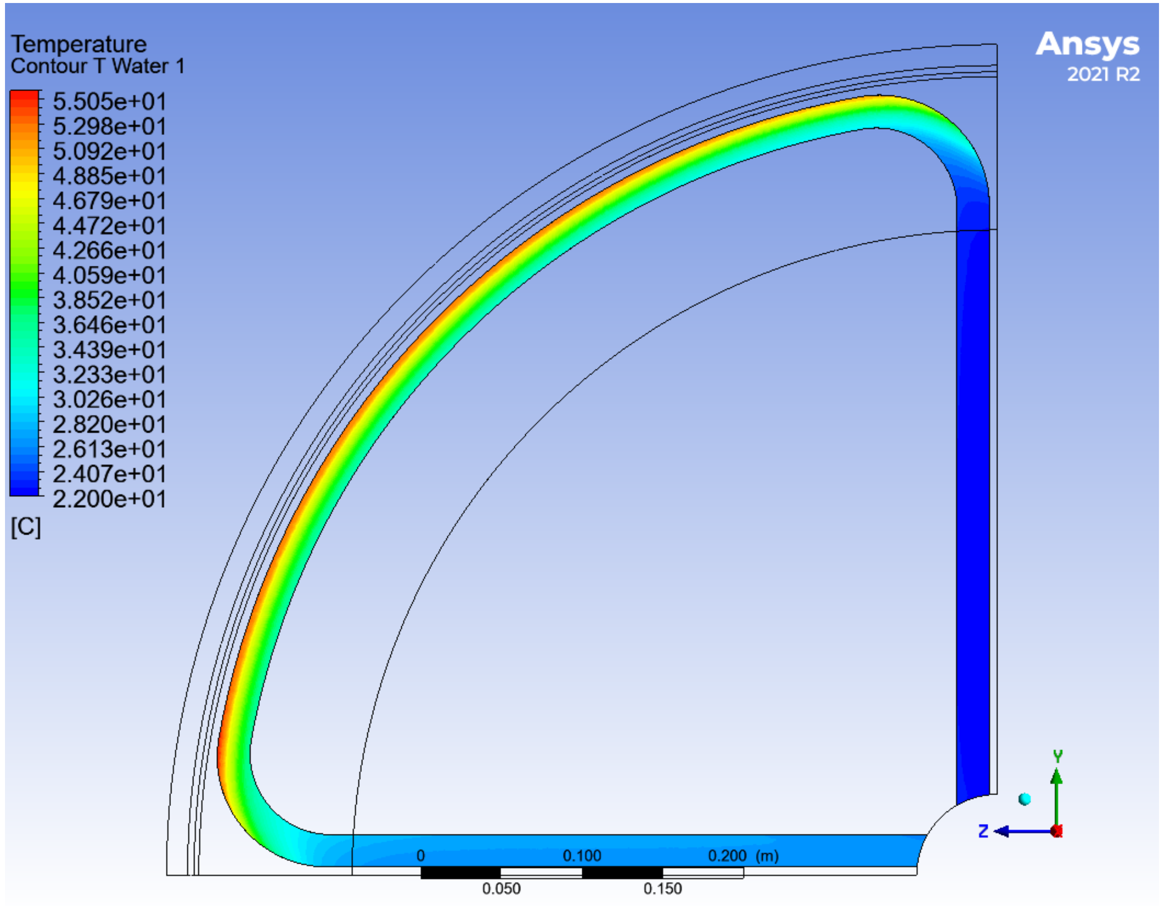


Exploring "DC" thermal load

Work of A. Ushakov, IJCLab

Average Temperature of Tungsten and Copper (left) and Temperature of Water (right)





T_{max} = 310 °C

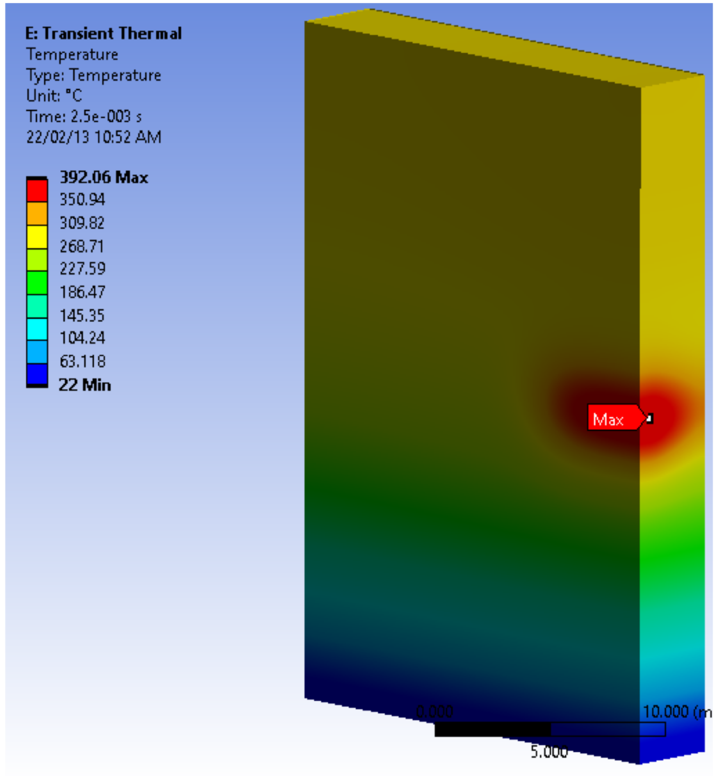
T_{max} = 55 °C

Thermal cycling for a spinning target

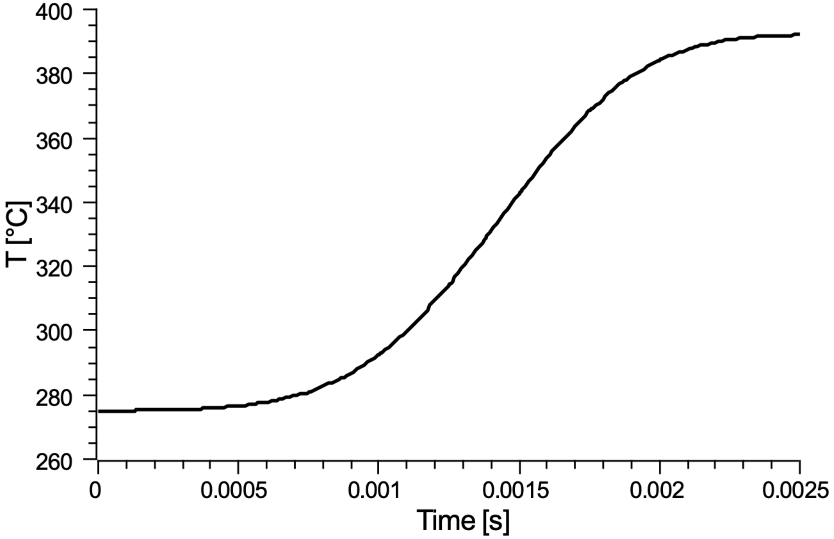
Work of A. Ushakov, IJCLab

Probe of Temperature T vs Time at Selected Point on Target moving with 4 m/s
(R = 50 cm)

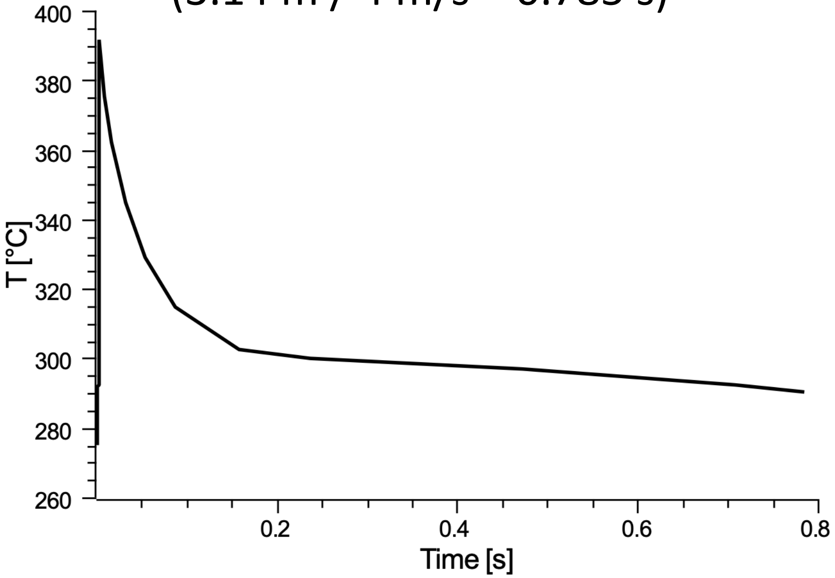
Snapshot of T after 2.5 ms



Temperature vs time t for 0 < t < 2.5 ms
(1.5 mm RMS beam size)



One Thermal Cycle
(3.14 m / 4 m/s = 0.785 s)



$\Delta T_{max} \approx 118$ °C

Temperature rise during one full rotation of JLab positron target on top of average T

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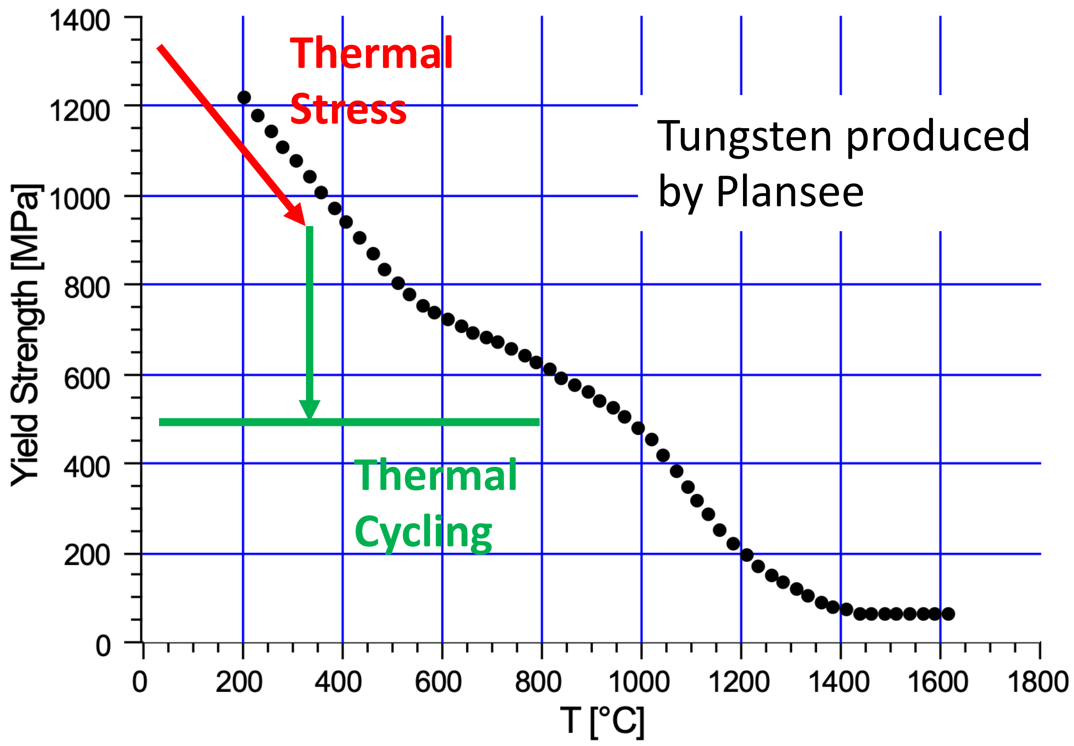
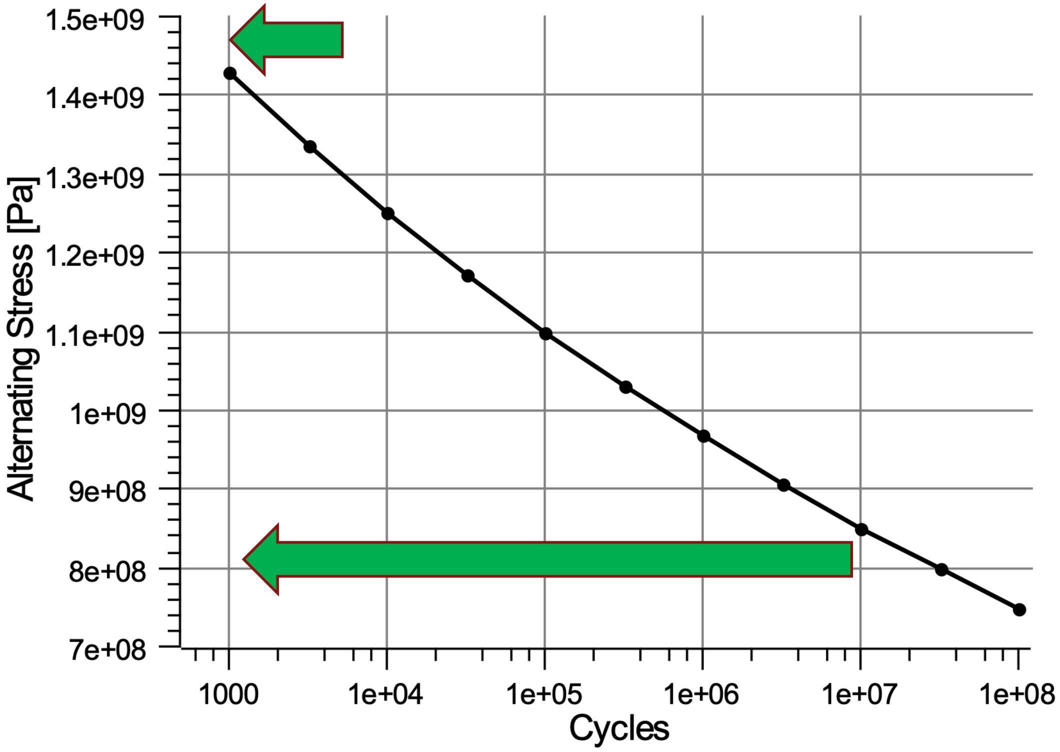
Operating 100 kW target for 1 year

Work of A. Ushakov, IJCLab

Average Thermal Stress (Equivalent von-Mises Stress, left) and
Yield Strength of Tungsten vs Temperature (right) for Two Cooling Channels



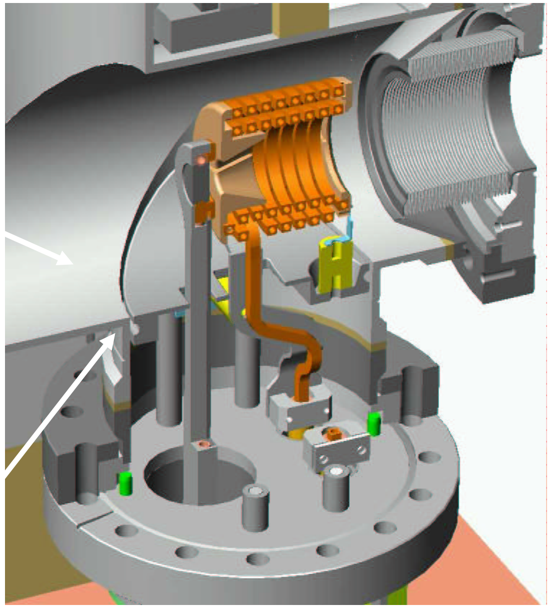


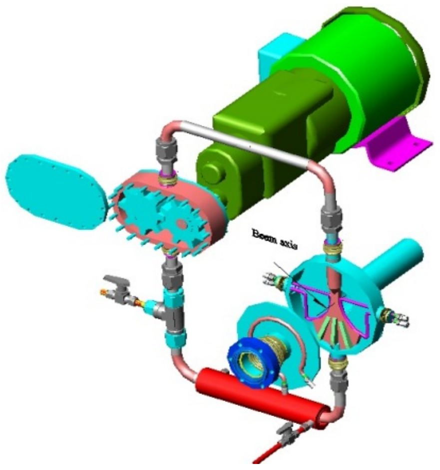
For 5000 h of source operation and 0.875 s cycles: 2.3E+7 of thermal cycles limit the tolerable alternating stress.

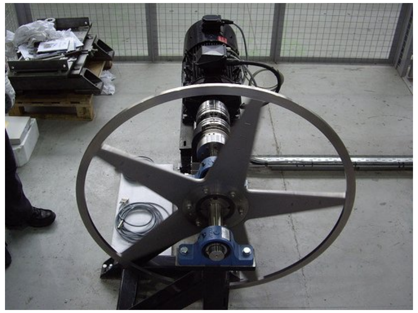
e+ collection technology for ~8 MeV, and then 100 MeV…

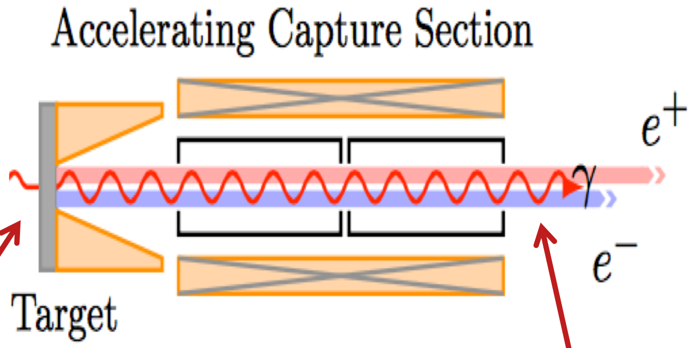
- DC collection magnet (high rad, 0.5 -> 1.5 Tesla)
- Large acceptance collection cavity
- Managing magnetized e+ beams

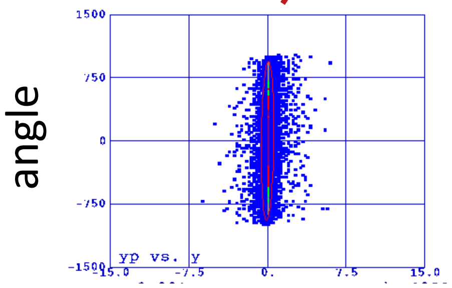
J. Barley, V. Medjidzade, A. Mikhailichenko
“New Positron Source for CESR”

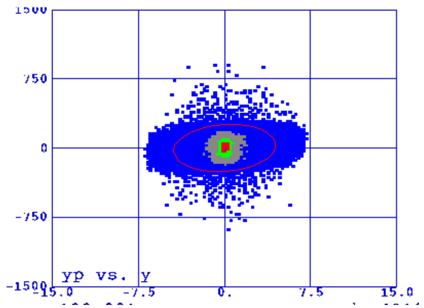












Positron R&D extends further…

Positron R&D goes beyond the gun group….CASA, ENG, INJ, SRF

Not covered today … but opportunities for future talks:

- Reversing polarity of CEBAF magnets
- Transport of e+ to 12 GeV
- High energy spin rotators
- High power GaInSn liquid metal target (proposed by Xelera)
- Integration to CEBAF injector

Good news, our positron R&D is NOT in conflict with 20+ GeV CEBAF

- What we learn at LERF is broadly applicable to CEBAF (cw beams, polarization from electrons)
- Meshes nicely with future-of-JLab options (variants for 100 MeV, 650 MeV, etc.)

Conclusions

Host a positron workshop at JLab with goal of determining the level of interest for our three options: GeV, MeV and keV polarized positrons, this could happen in the fall this year. And then in parallel…

Finish the CEBAF injector upgrade, this frees up labor associated to these projects

After installing the new booster at CEBAF, we move existing CEBAF ¼ CM to the LERF

Install a 350 kV load locked gun at LERF, making 8 MeV polarized electron beam 1 mA

Design and build a 10 kW prototype target, 0.5 Tesla magnet and the e-/e+ beam lines

In five years we make >100 nA positron beams, this means with good beam quality, suitable for acceleration

Acknowledgments

I would like to thank those who have contributed or participated to our positron R&D.

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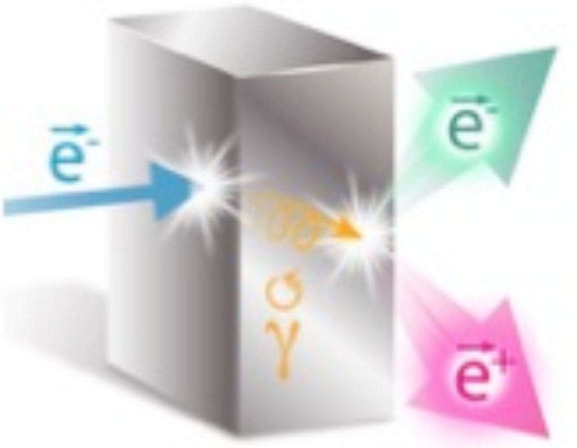
- Dennis Turner, JLab
- Eric Voutier, IJCLab-Orsay
- Fanglei Lin, ORNL
- Jay Benesch, JLab
- Karl Smolenski, Xelera
- Larry Cardman, JLab
- Reza Kazimi, JLab
- Ryan Bodenstein
- Ryan Richards, Univ. of Virginia
- Sami Habet, IJCLab-Orsay
- Stephen Brooks, BNL
- Matt Poelker, JLab
- Val Kolstrum, Xelera
- Yuhong Zhang, JLab
- Yves Roblin, JLab

Backup Slides

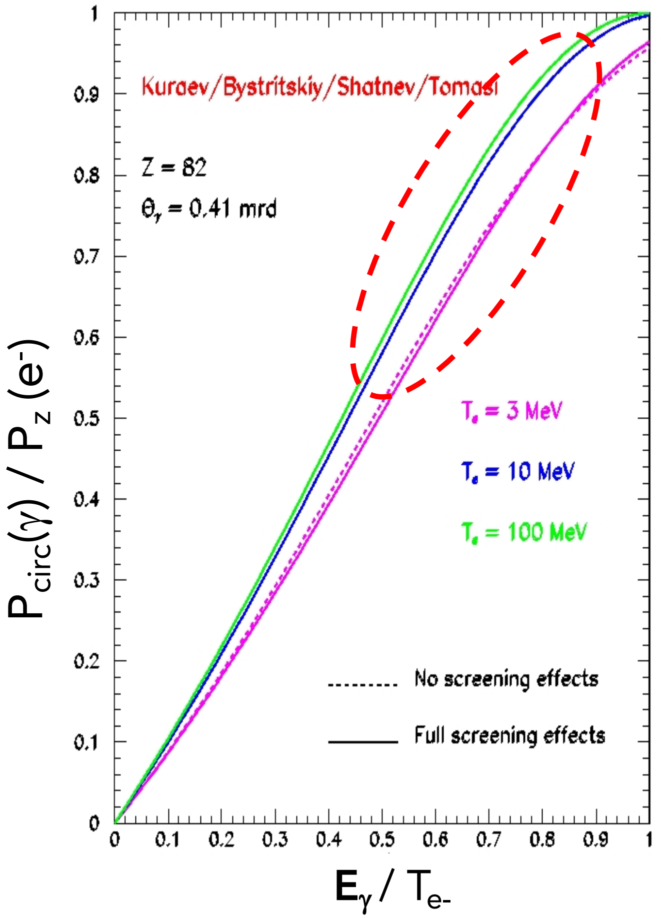
Exploit electron spin polarization to produce polarized positrons

$\vec{e}^- \rightarrow \overset{\circlearrowright}{\gamma} \rightarrow \vec{e}^+ \; (+ \, \vec{e}^-)$

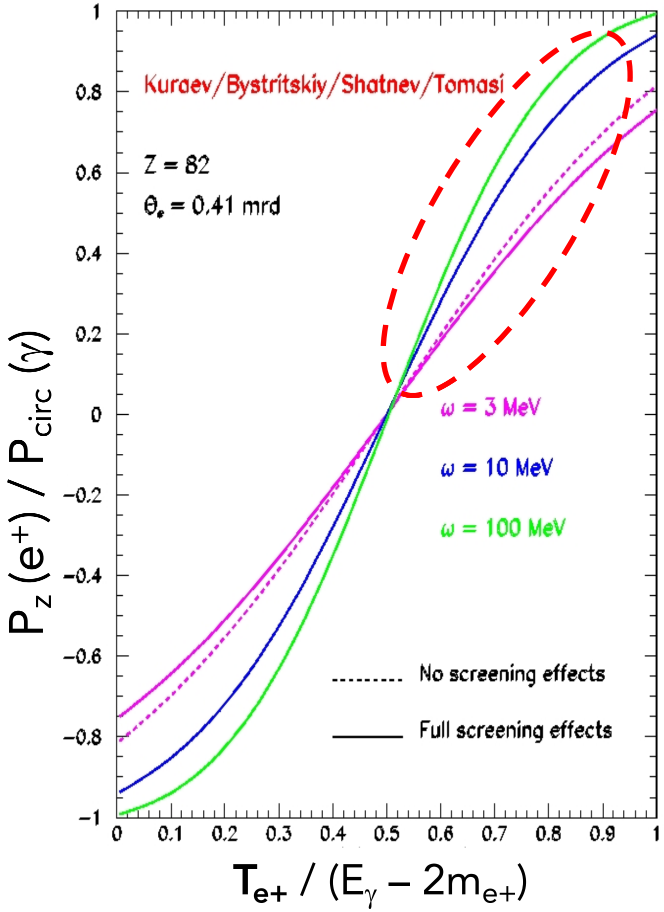


Longitudinal spin polarization passes from incident electrons to outgoing pair-produced positrons in the electromagnetic shower, when incident on a target, e.g. high-Z material useful.

Polarized Bremsstrahlung



Polarized Pair Creation



E.A. Kuraev, Y.M. Bystritskiy, M. Shatnev, E.Tomasi-Gustafsson, PRC 81 (2010) 055208

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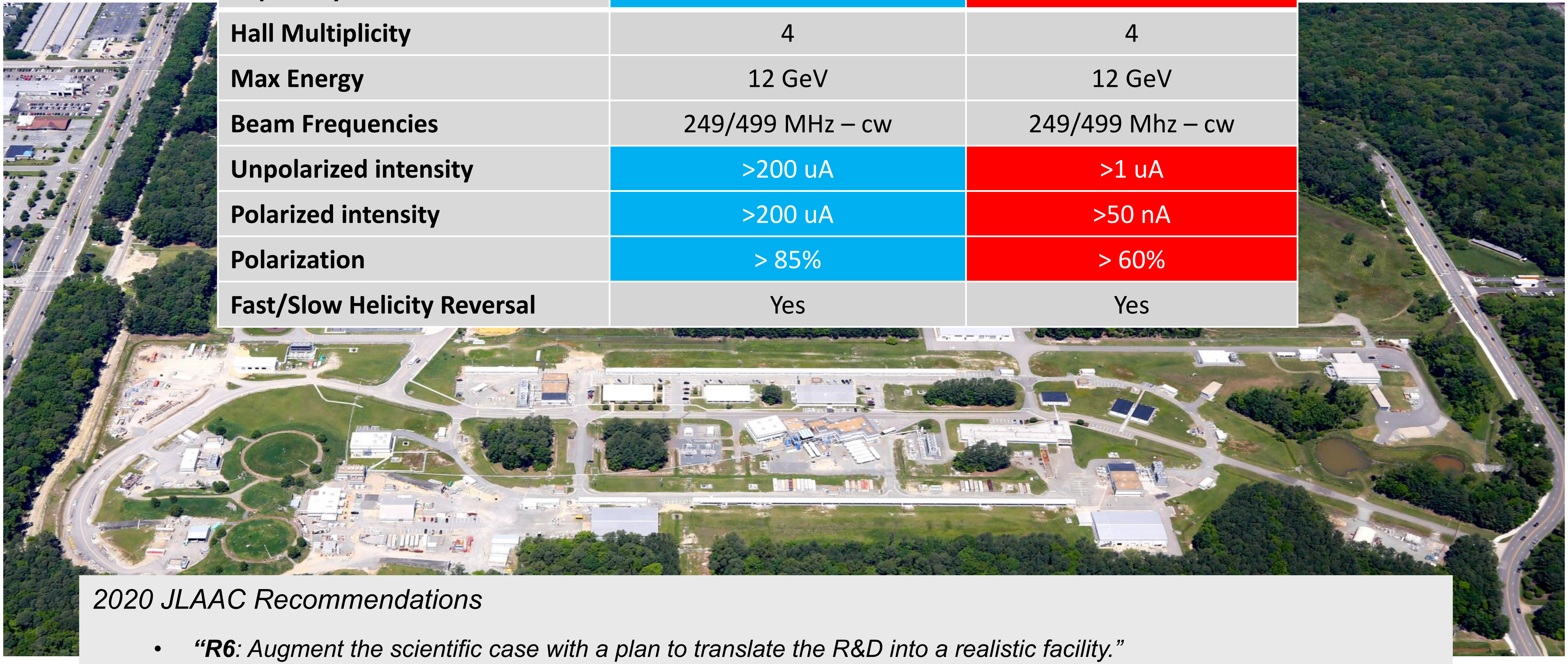
12 GeV CEBAF : Polarized Electron or Polarized Positron Beams

Capability	Electrons	Positrons
Hall Multiplicity	4	4
Max Energy	12 GeV	12 GeV
Beam Frequencies	249/499 MHz – cw	249/499 Mhz – cw
Unpolarized intensity	>200 uA	>1 uA
Polarized intensity	>200 uA	>50 nA
Polarization	> 85%	> 60%
Fast/Slow Helicity Reversal	Yes	Yes

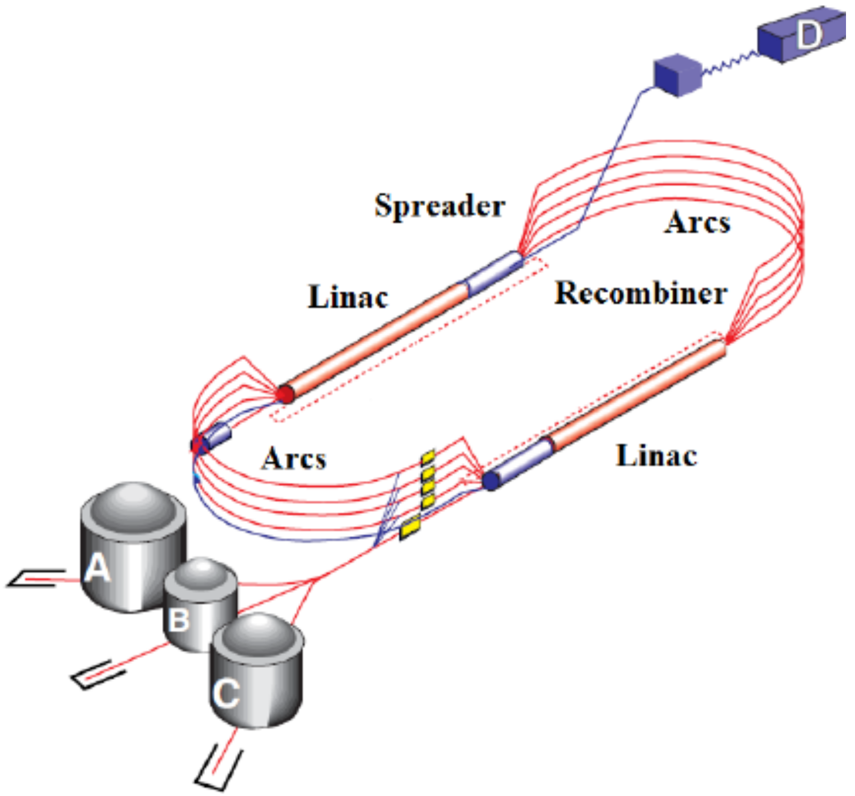


2020 JLAAC Recommendations

- *“**R6**: Augment the scientific case with a plan to translate the R&D into a realistic facility.”*
- *“**R7**: Include radiation protection considerations into the evaluation of the electron beam energy choice.”*

CEBAF 12 GeV : Transverse Emittance* and Energy Spread†

- Large e+ initial dp/p and emittance damped adiabatically unitl SR in upper arcs
- Whereas e- parameters grow, e+ parameters improve to 10-12 GeV (sim to e-)



electron beam

Area	$\delta p/p$ [x10^{-3}]	ε_x [nm]	ε_y [nm]
Chicane	0.5	4.00	4.00
Arc 1	0.05	0.41	0.41
Arc 2	0.03	0.26	0.23
Arc 3	0.035	0.22	0.21
Arc 4	0.044	0.21	0.24
Arc 5	0.060	0.33	0.25
Arc 6	0.090	0.58	0.31
Arc 7	0.104	0.79	0.44
Arc 8	0.133	1.21	0.57
Arc 9	0.167	2.09	0.64
Arc 10	0.194	2.97	0.95
Hall D	0.18	2.70	1.03

(Damping: Chicane – Arc 4; SR: Arc 5 – Hall D)

positron beam

Area	$\delta p/p$ [x10^{-3}]	ε_x [nm]	ε_y [nm]
Chicane	10	500	500
Arc 1	1	50	50
Arc 2	0.53	26.8	26.6
Arc 3	0.36	19	18.6
Arc 4	0.27	14.5	13.8
Arc 5	0.22	12	11.2
Arc 6	0.19	10	9.5
Arc 7	0.17	8.9	8.35
Arc 8	0.16	8.36	7.38
Arc 9	0.16	8.4	6.8
MYAAT01	0.18	9.13	6.19

(Damping: Chicane – Arc 8; SR: Arc 9 – MYAAT01)

Values are provided at the end of each segment. For positron this is up to pass 5 extraction, for electrons it goes all the way to hall D.

* Emittances are geometric

† Quantities are rms

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CEBAF 12 GeV : Magnetic Transport System

Reversing polarity of 2100 CEBAF magnets – S. Philips (DC Power)

- >1900 (correctors & quads) already bipolar operation
- 39 (recirculation/transport dipoles) will require engineered solution
  - 21 recirculation & dog-leg
  - 12 extraction units
  - 6 end-station transport/dump
- $1M – Remote PS switches, shunt modules, firmware, PSS integration
- Hall D is only permanent magnet – would have to be rotated

Magnetic Field Integrity – M. Tiefenback (Magnet Integrator)

- Unipolar dipoles would need to be deliberately tested
  - demonstrate field restores after polarity inversion
  - quantify possible systematic effects
- Soft iron steel are expected to perform well under polarity reversal
- Two decades of operation suggest remnant fields <20 G tolerable
  - Sudden power supply trips introduce uncontrolled flux
  - Modifications to power supplies or field maps

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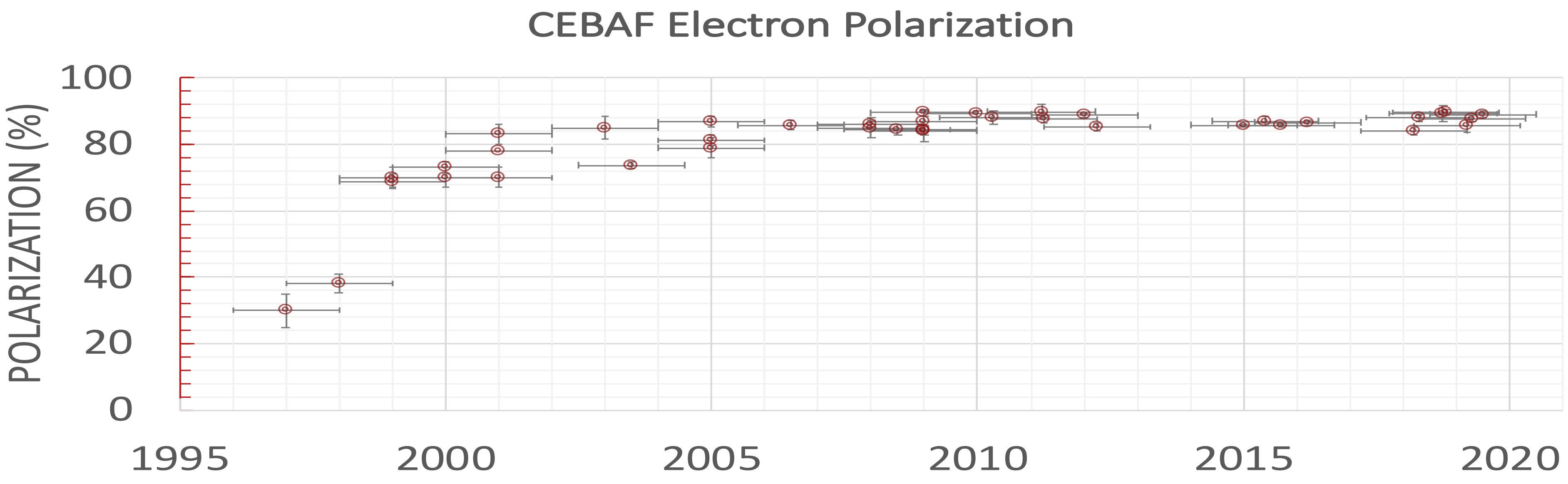
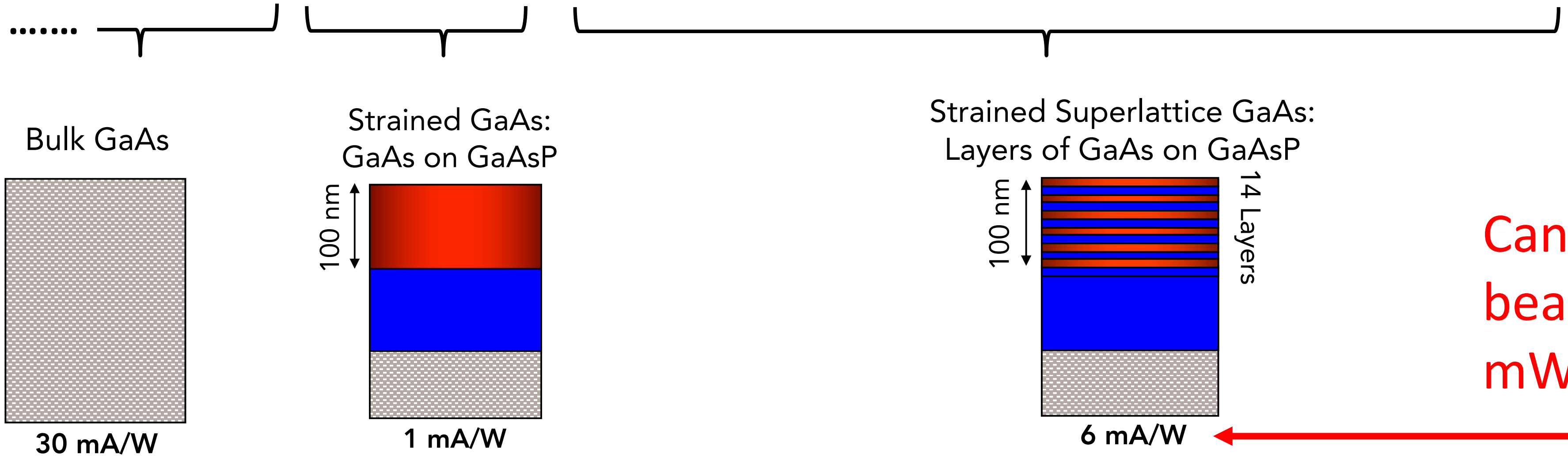
Spin polarization from GaAs/GaAsP



Represents expectation for User facilities proposed today



Can make mA's of beam with 100s of mW of "red" light

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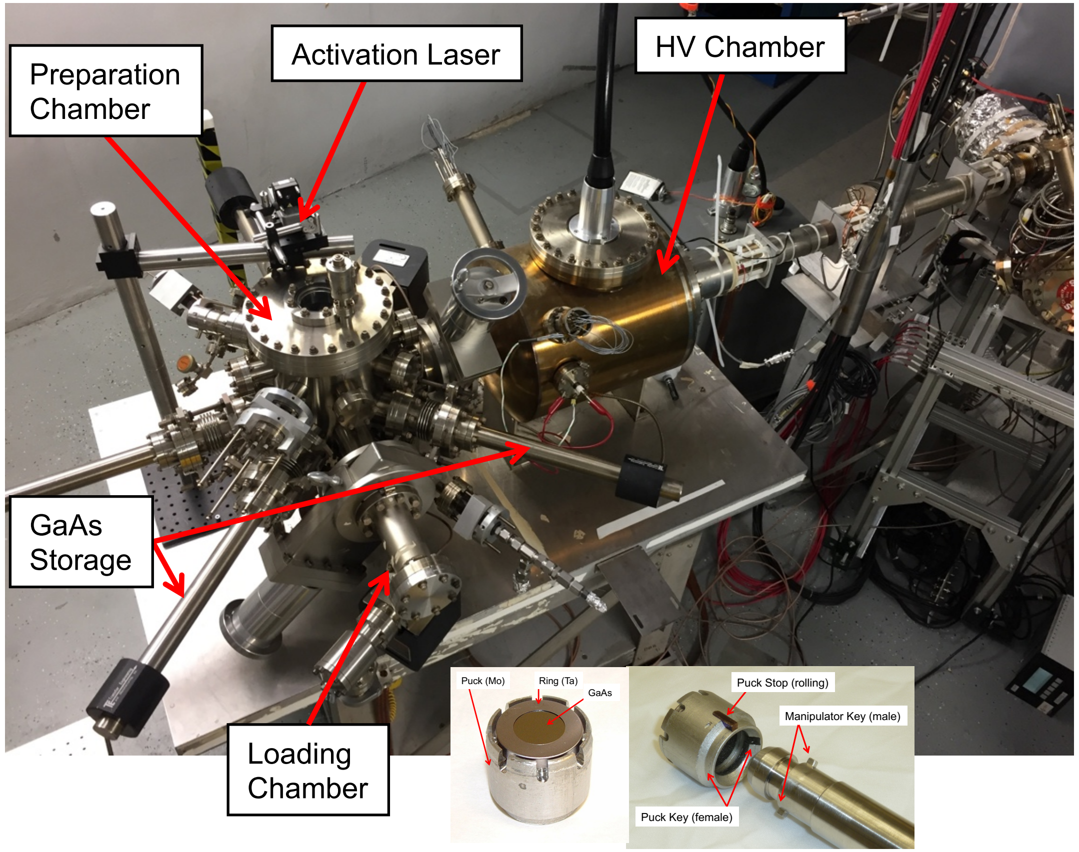
CEBAF: an example of e-driven polarized source



P. Adderley *et al.,* Phys. Rev. Accel. Beams **13**, 010101 (2010)

Gun2 Photocathode (Fall 2016 – Spring 2017)

- **Lifetime ~200 C** (σ_{4D} ~ 1mm) with intensity **@ 200 µA**