RHIC Accelerator R&D

EBIS (Linac-based pre-injector)

RHIC beam cooling R&D (RHIC II)

eRHIC R&D

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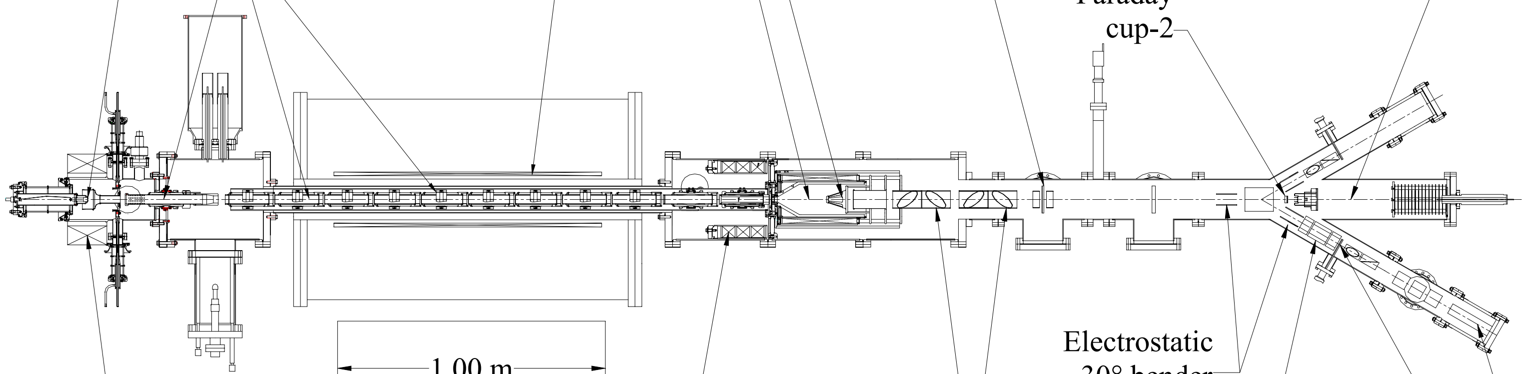
Thomas Roser
DOE NP S&T review
June 30 – July 1, 2004

EBIS/Linac-based RHIC Pre-Injector

- Highly successful development of Electron Beam Ion Source (EBIS) at BNL: achieved ½ of required RHIC performance with ½ of EBIS trap length.
- EBIS allows for a reliable, low maintenance Linac-based pre-injector replacing the Tandem Van de Graaffs
- Greatly reduced operating costs, and avoidance of ~ 9 M$ in reliability-driven investments in the tandems
- Highly flexible to handle the multiple simultaneous needs of RHIC, NSRL, and AGS
- Produces beams of ALL ion species including noble gas ions (NSRL), Uranium (RHIC) and polarized He^3 (eRHIC)
- Ready to start construction; Cost: 18 M$;
  Technically driven construction schedule: FY2005 – 07
  NASA participation under discussion (~ 25 %)

Results from Test EBIS (½ of RHIC EBIS)



	RHIC Requirements	Achieved
E-beam current	**10 A**	**10 A**
Pulse length	**≤ 40 μs**	**20 μs**
Yield of Au^{33+}	**3.4×10^9 (10 A, 1.5 m)**	**1.7×10^9 (8 A, 0.7m)**
Yield of U^{45+}	**2.4×10^9**	

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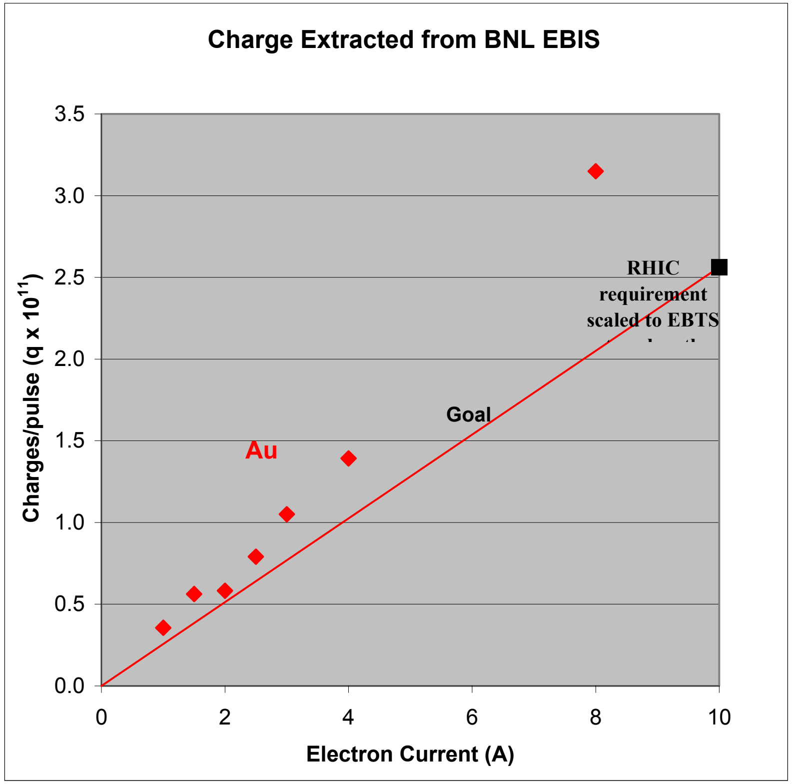
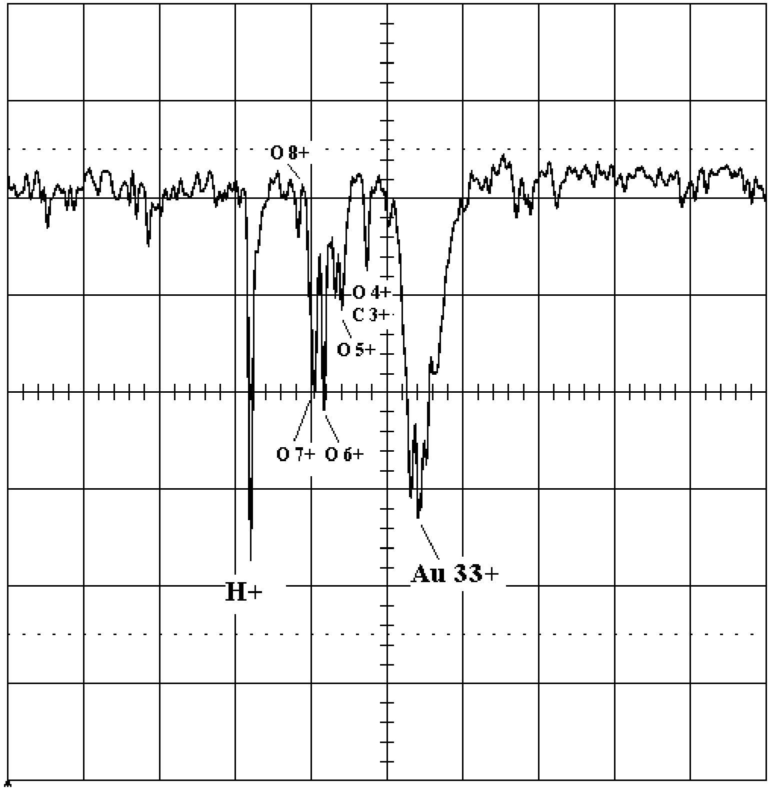
Results from Test EBIS (½ of RHIC EBIS)



Extracted gold ion yield shows more than 50% neutralization



Gold charge state with only 40 ms confinement time.

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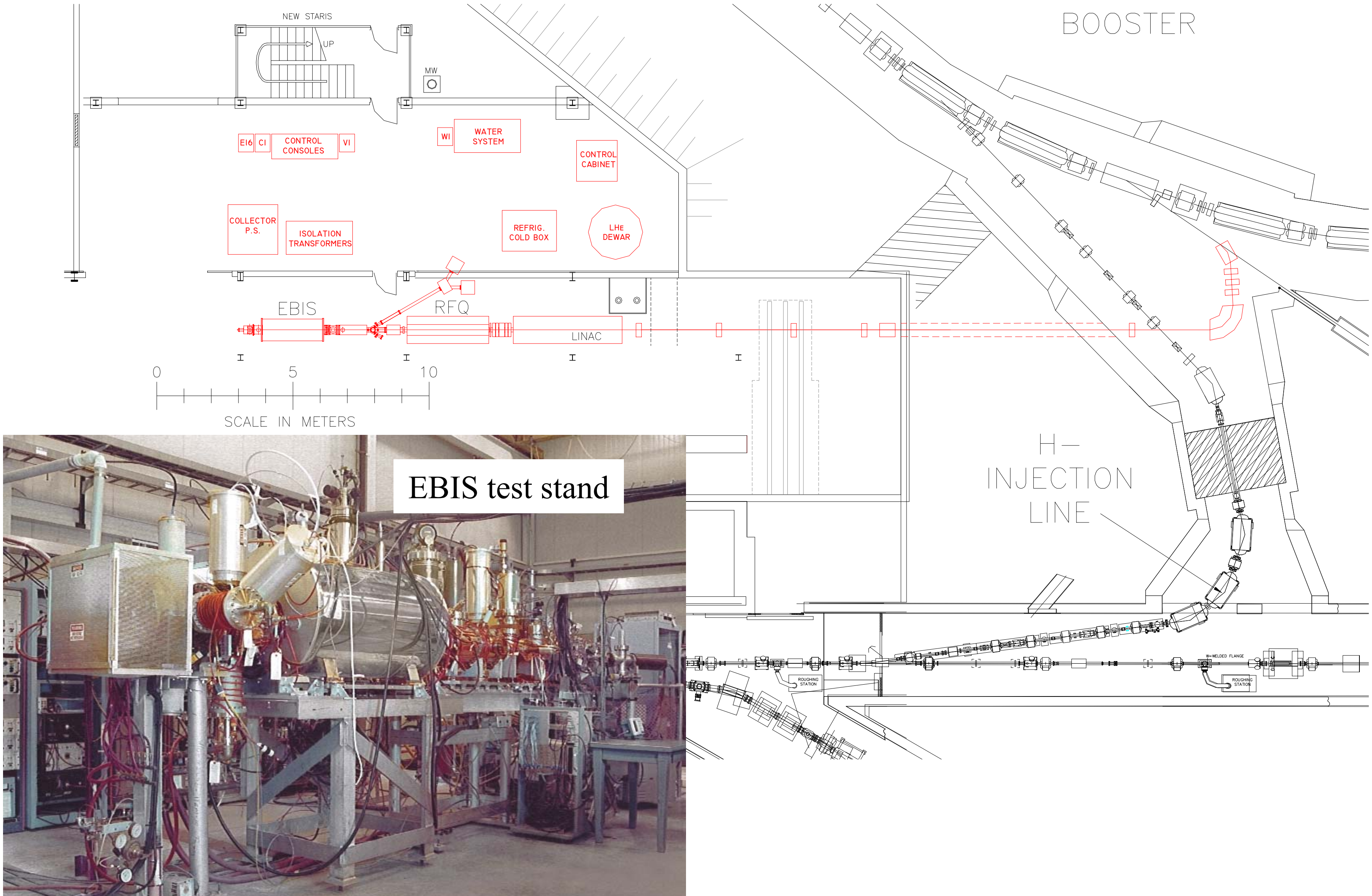
EBIS layout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UP
MW
E16
CI
CONTROL CONSOLES
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WATER SYSTEM
CONTROL CABINET
COLLECTOR P.S.
ISOLATION TRANSFORMERS
REFRIG. COLD BOX
LHe DEWAR
EBIS
RFQ
LINAC
0
5
10
SCALE IN METERS
BOOSTER
H–
INJECTION
LINE
EBIS test stand

RHIC electron cooling

- Au ions in RHIC are 100 times more energetic than in a typical cooler ring. Relativistic factors slow the cooling by a factor of γ^2. Cooling power needs to be a factor of γ^2 higher than typical.
- Bunched electron beam requirements for 100 GeV/u gold beams:
  E = 54 MeV, <I>=100-200 mA, electron beam power: ~ 5-10 MW!
- Requires high brightness, high power, energy recovering superconducting linac, as demonstrated by JLab for IR FEL. (100 MeV, 10 mA)
- First linac based, bunched electron beam cooling system used at a collider
- Cost: ~ 55 M$ (FY03$, updated design study underway)
  Technically driven schedule: 2008 – 2012
  Construction mainly independent of ongoing RHIC operations. Installation possible during ~ 3 months yearly shut-down periods
- Reviewed by C-AD MAC in March 2004 [O. Boine-Frankenheim (GSI), A. Chao (SLAC), J.-P. Delahaye (CERN), D. McGinnes (FNAL), L. Merminga (JLAB), F. Willeke (DESY, Chair)]

RHIC II luminosity upgrade

Eliminate beam blow-up from intra-beam scattering with electron beam cooling at full energy!

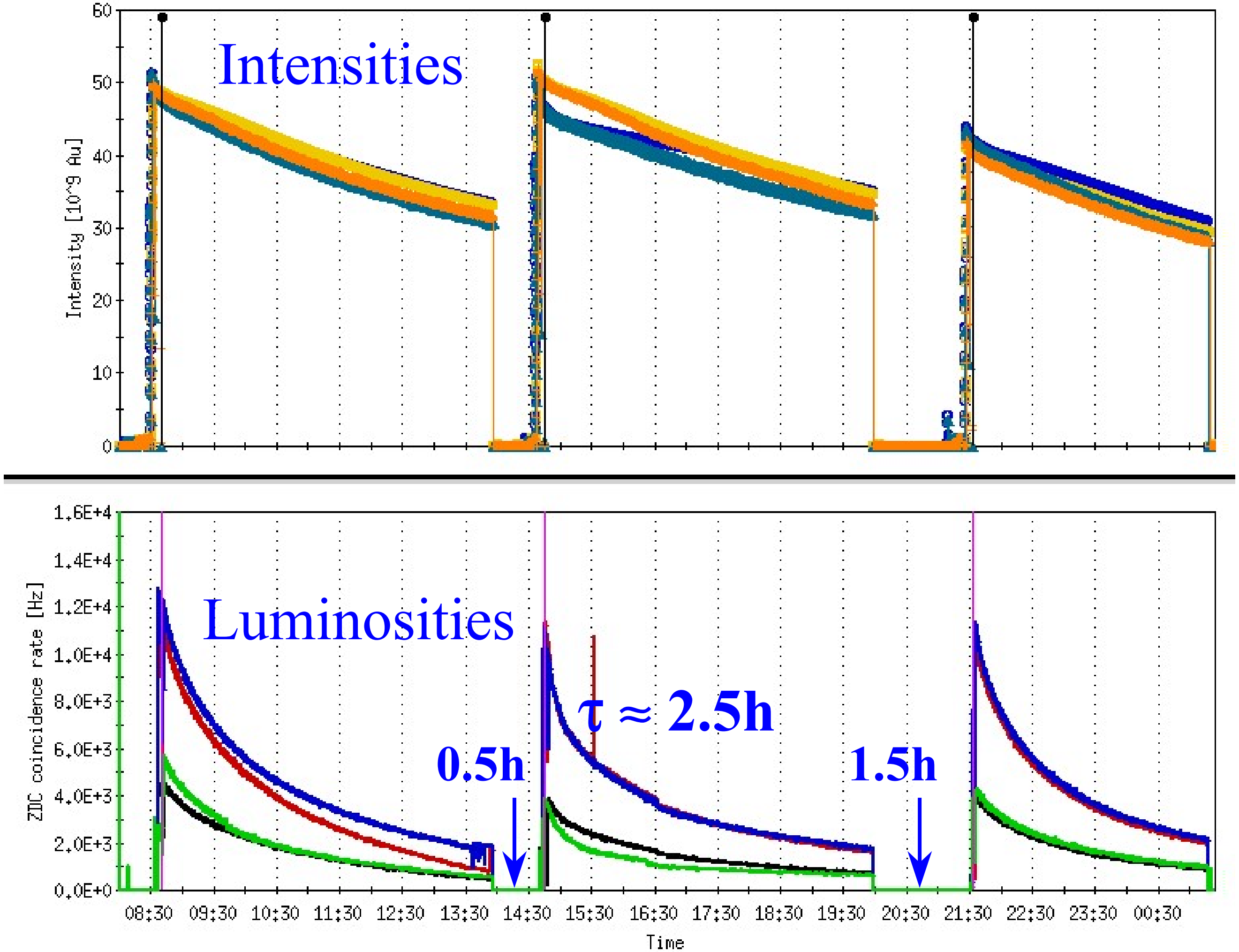
What changes:

- ~ 10 x RHIC average enhanced luminosity (70×10^{26} cm^{-2} s^{-1} at 2 high luminosity IRs)
- 3 x peak luminosity and no luminosity decay
- Store length is limited to ~ 4 hours by "burn-off" due to Au-Au interactions (~ 200 b)
  - Ave. luminosity for complete burn-off in 4 hours: 160×10^{26} cm^{-2} s^{-1} /IR
- Smaller transverse and longitudinal emittance
  - Smaller vertex region

What will remain the same:

- 120 bunch pattern
  - 100 ns collision spacing (~ same data acquisition system)
  - Only one beam collision between DX magnets
- 20 m magnet-free space for detectors
  - No "mini-beta" quadrupoles
- Approx. the same bunch intensity
  - No new vacuum or instability issues
  - Background similar as before upgrade

Luminosity Limit – Intra-Beam Scattering (IBS)



- Debunching requires continuous gap cleaning (tune meter)
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

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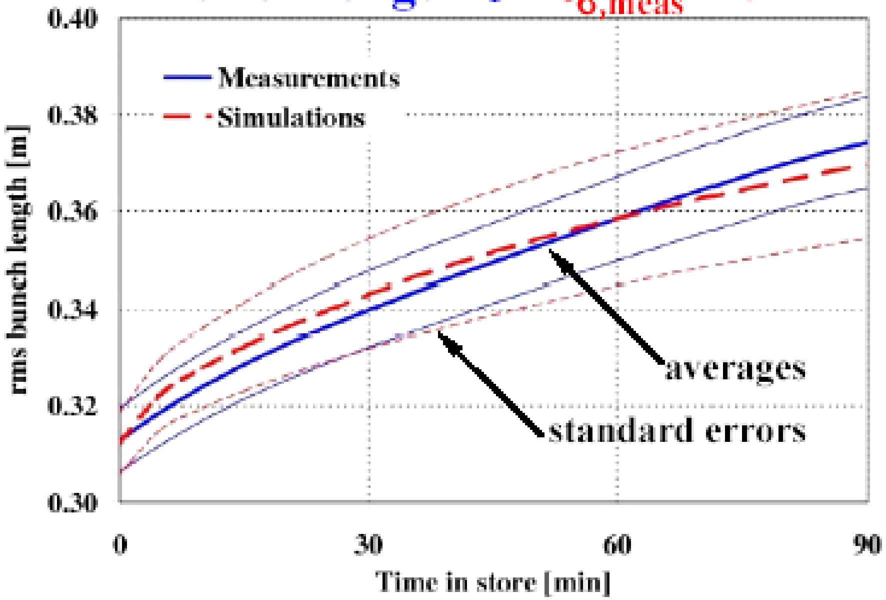
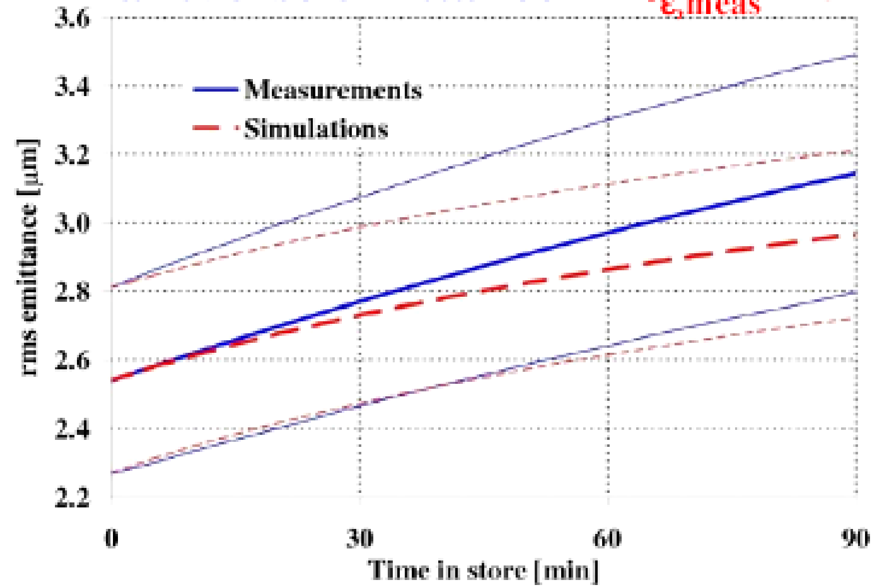
Intra-Beam Scattering (IBS) in RHIC

Bunch length σ $\tau_{\sigma,meas} \approx 8h$



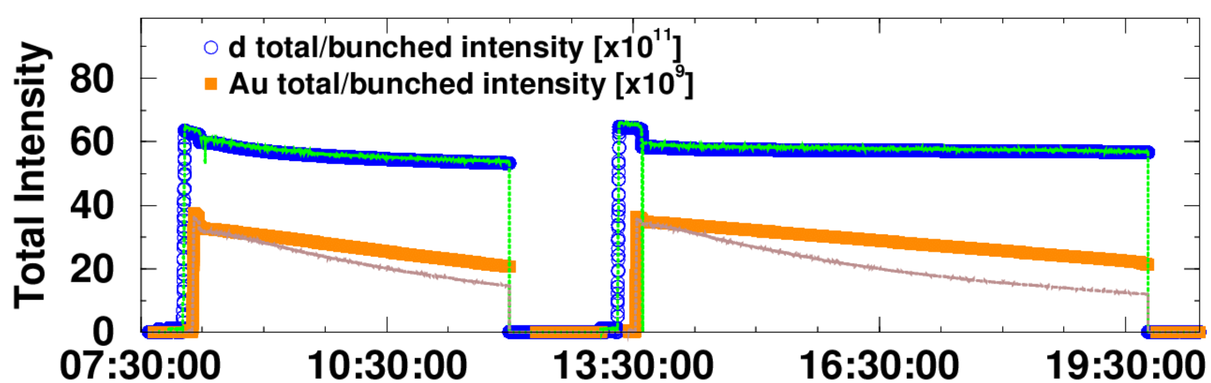
Transverse emittance ε $\tau_{\varepsilon,meas} \approx 6h$



Longitudinal and transverse emittance growth agrees well with model

Some additional source of transverse emittance growth

Deuteron and gold beams are different because of IBS



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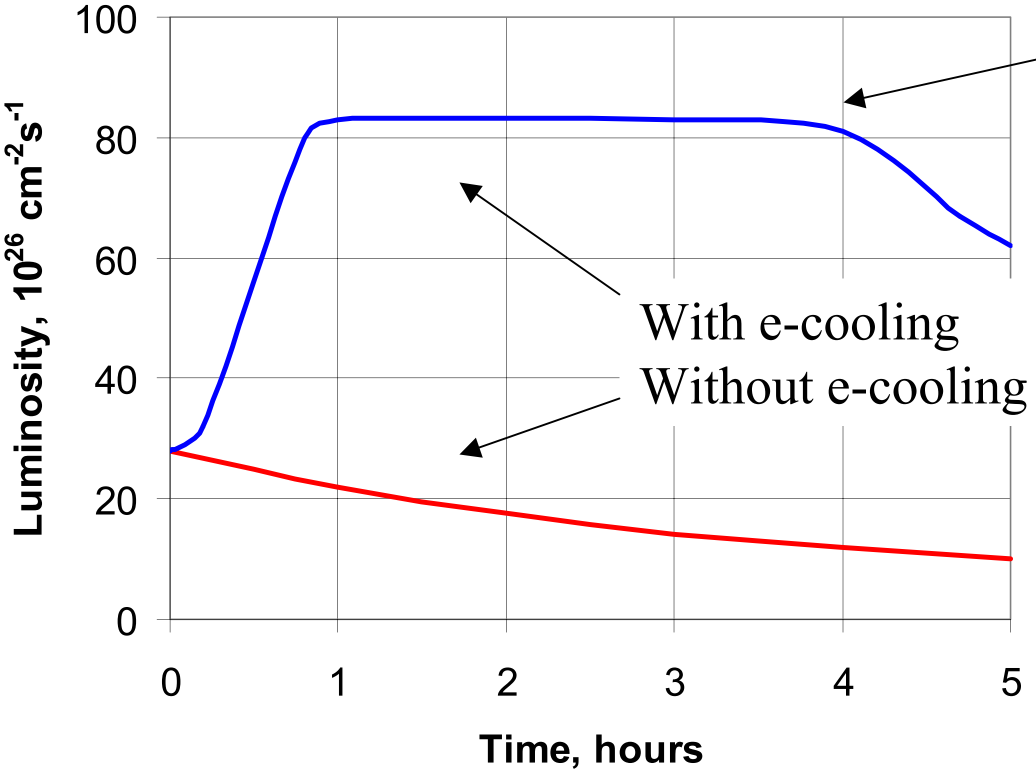
Electron cooling and IBS

Intra-Beam Scattering:
The ions collide with each other, leading to accumulation of random energy (heat) derived from the guide fields and the beam's energy.

Electron cooling:
The high-current high-brightness electron beam from an ERL will cool the RHIC ions in a high-precision, 26 m long superconducting solenoid.

RHIC Luminosity with and without Cooling

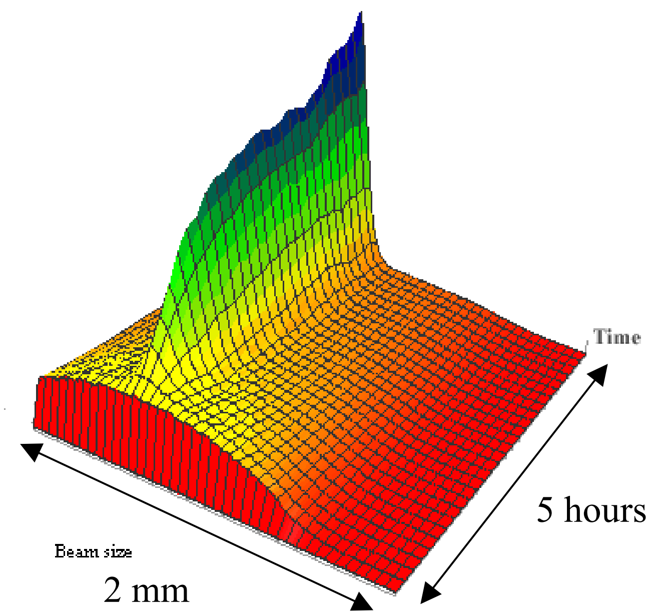


Luminosity leveling through continuously adjusted cooling

Store length limited to 4 hours by "burn-off"

Four IRs with two at high luminosity

Transverse beam profile during store



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RHIC II Luminosities with Electron Cooling

Gold collisions (100 GeV/n × 100 GeV/n):	**w/o e-cooling**	**with e-cooling**
Emittance (95%) πμm	15 → 40	15 → 10
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^9]	1	1 → 0.3
Beam-beam parameter per IR	0.0016	0.004
Peak luminosity [10^{26} cm^{-2} s^{-1}]	32	90
Ave. store luminosity [10^{26} cm^{-2} s^{-1}]	8	70

Pol. Proton Collision (250 GeV × 250 GeV):		
Emittance (95%) πμm	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^{11}]	2	2
Beam-beam parameter per IR	0.007	0.012
Ave. store luminosity [10^{30} cm^{-2} s^{-1}]	150	500

Other species and energies with electron cooling

Polarized proton collisions:

- Pre-cooling at injection energy possible (no IBS)
- Effect of electron beam on proton polarization needs to be studied

Lower energy gold-gold collisions:

- Luminosity still scales with energy^2 (beam-beam limited)
- Strong longitudinal cooling gives as small a vertex distribution as at 100 GeV
- Store length not limited by "burn off"

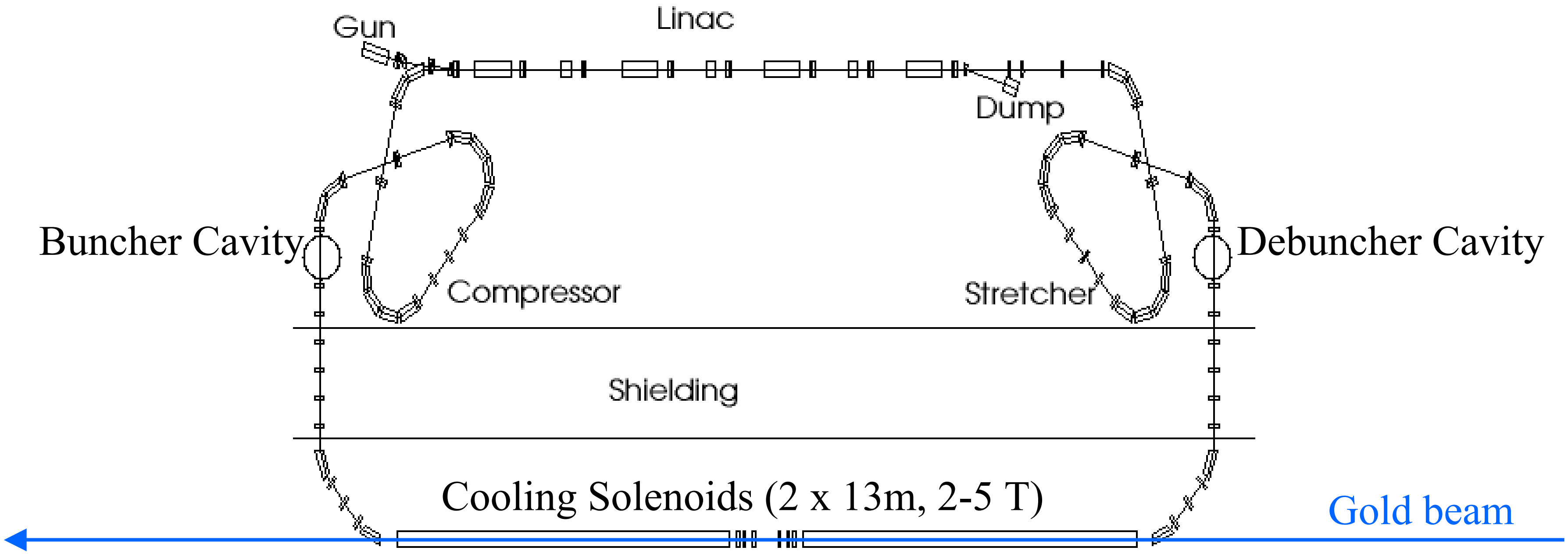
Lighter ions:

- Pre-cooling allows operation at beam-beam limit

pA and dA:

- Cooling of gold beam is limited by beam-beam effect of gold beam on p or d
- Beam-beam limit for dA is twice as large as for pA

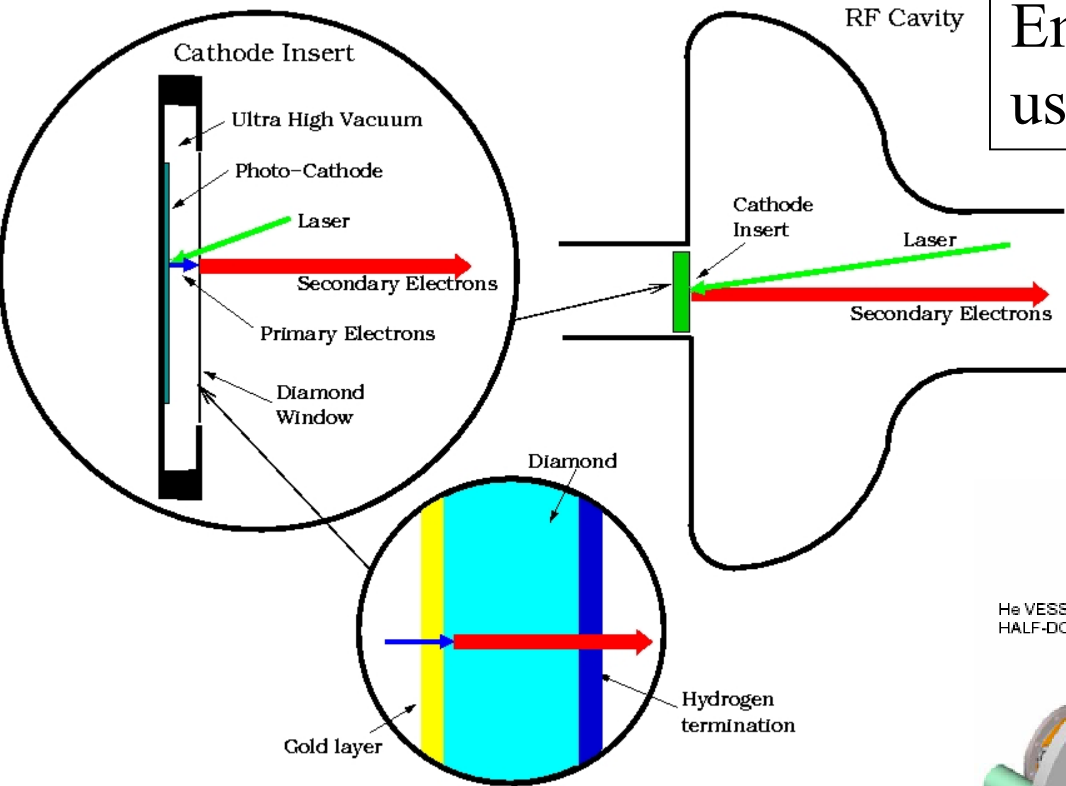
RHIC Electron Cooler R&D

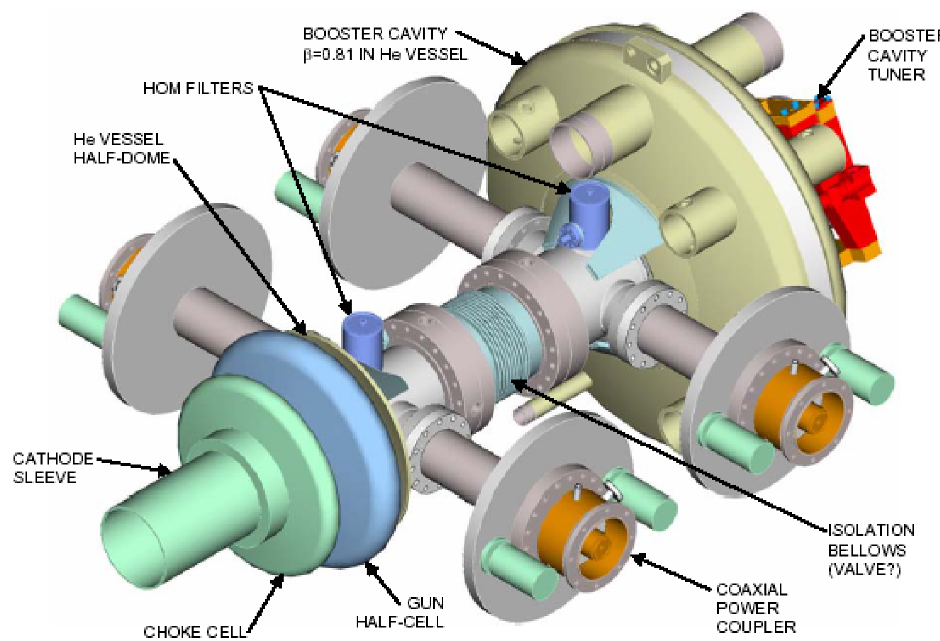


- Simulation and experimental benchmarking of cooling force in RHIC high energy regime (using SIMCOOL, BETACOOL, direct numerical calculations [Vorpal, Tech-X, Colorado], e-coolers at GSI, COSY, CELSIUS, collaboration with INTAS)
- Demonstrate high precision (<10 ppm) solenoid
- Demonstrate 20 nC, 100 – 200 mA 703.8 MHz CW superconducting rf photo-cathode electron gun (collab. with AES)
- Develop 703.8 MHz CW superconducting cavity for high intensity beams (collab. with Jlab, AES)
- Build R&D Energy Recovering Linac

CW Photo-cathode and Superconducting rf Gun R&D

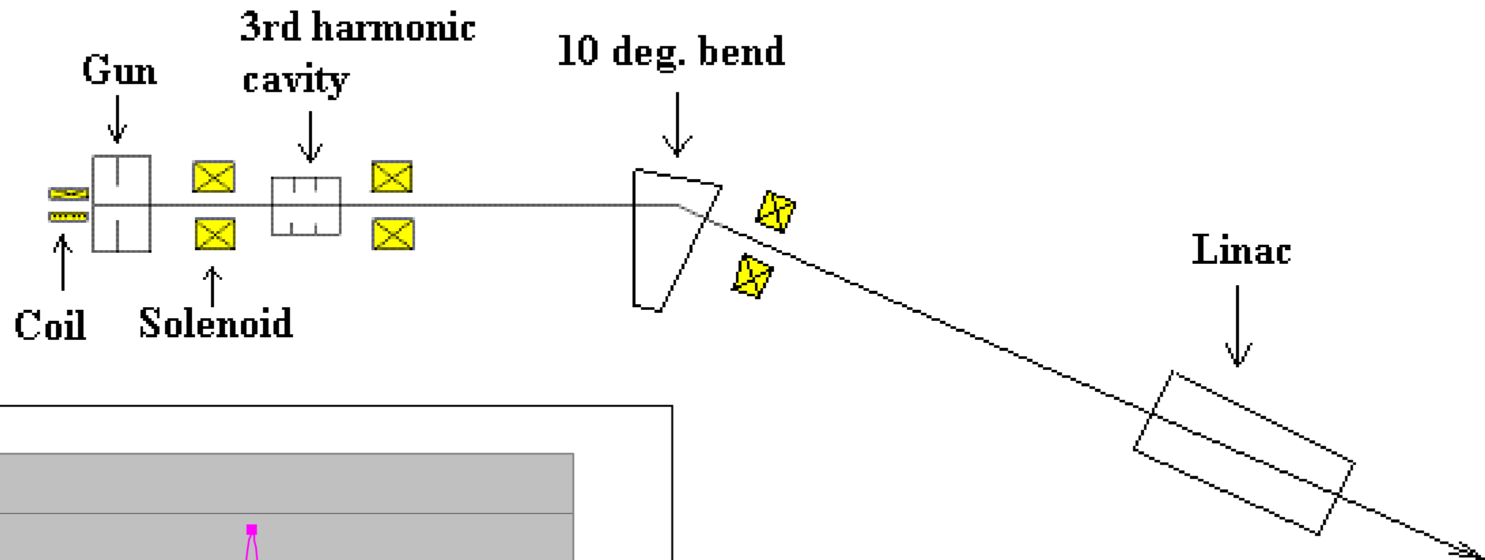
Emission enhancement (x 30-80) using a diamond window

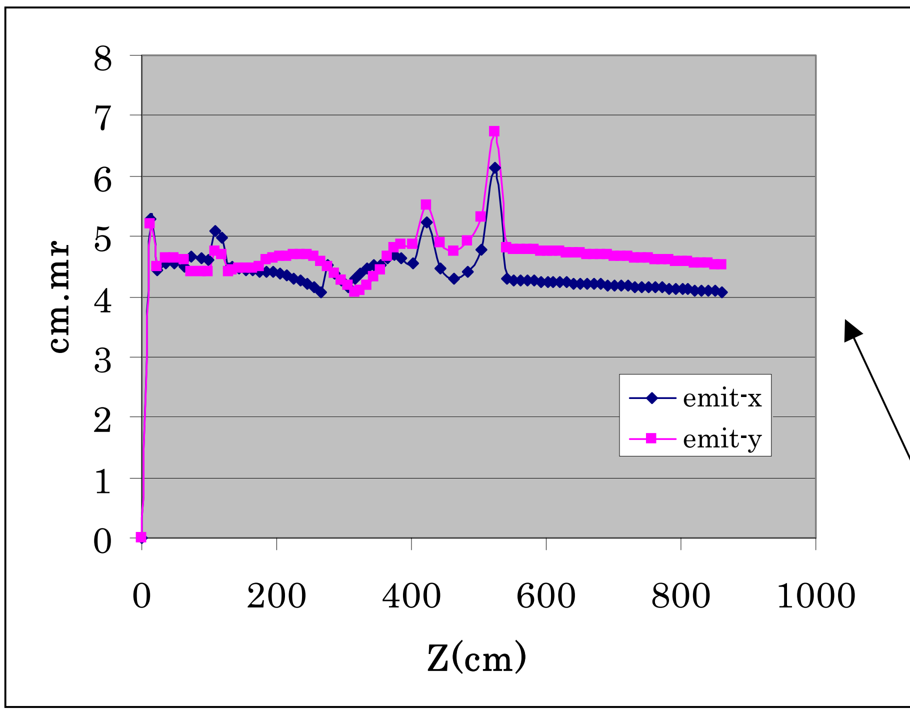




Initial conceptual design for a superconducting gun with high quantum efficiency cathode.

Magnetized Beam Dynamics for Gun and Linac





Charge: 20nC/bunch
Spot radius on cathode: 10mm
Magnet field on cathode: 200G
Energy at gun exit: 4.9MeV

Emittance (calculated in a rotating frame) as a function of path length.

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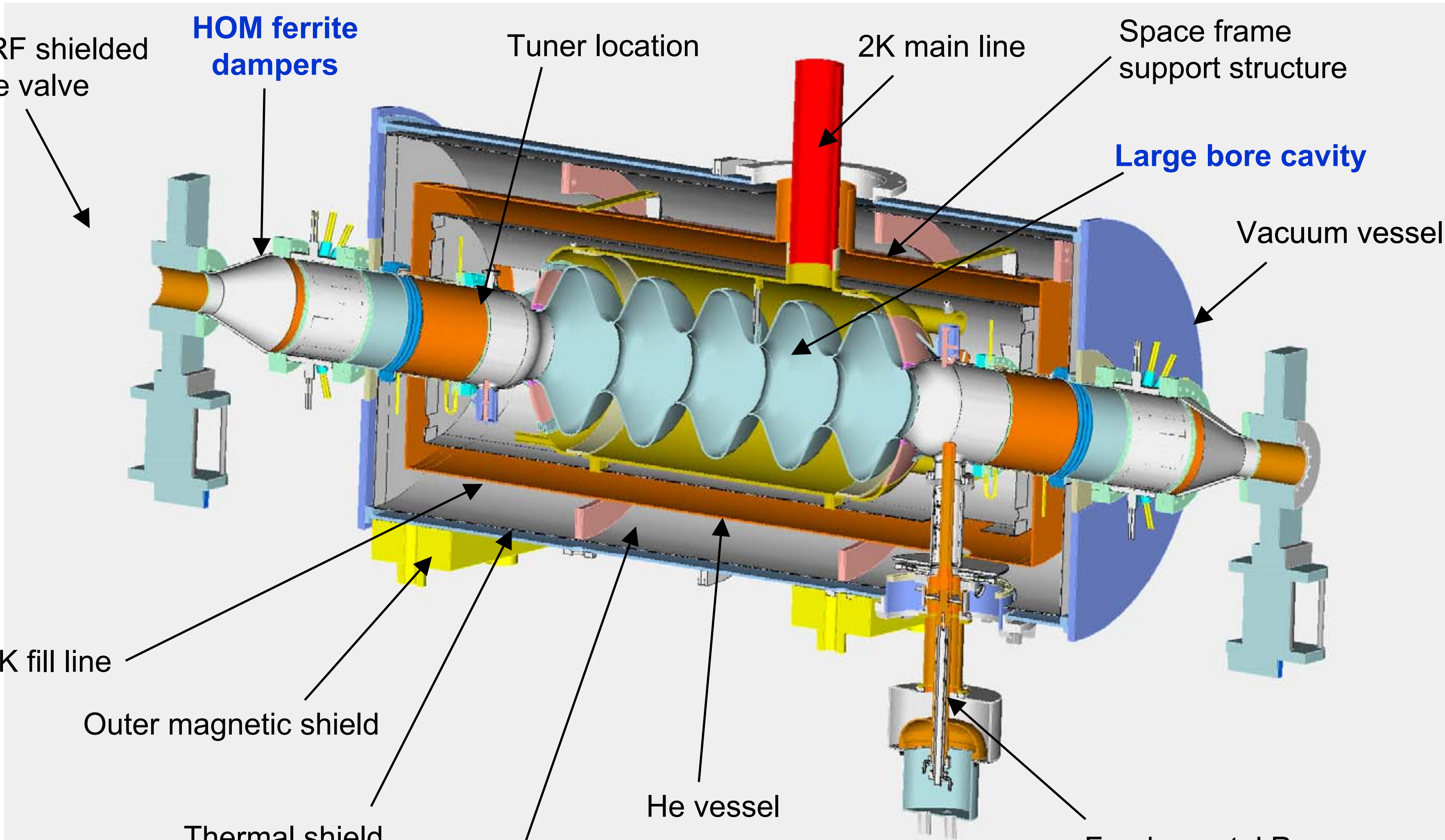
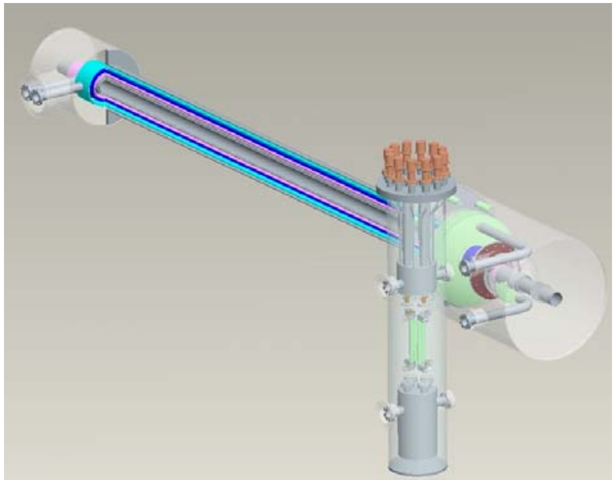
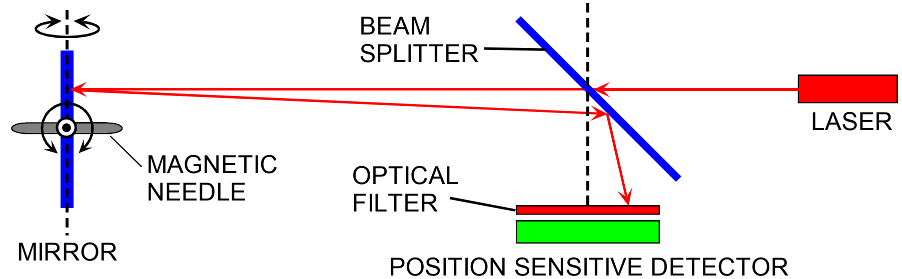
703.8 MHz CW Superconducting Cavity for High Intensity Beams

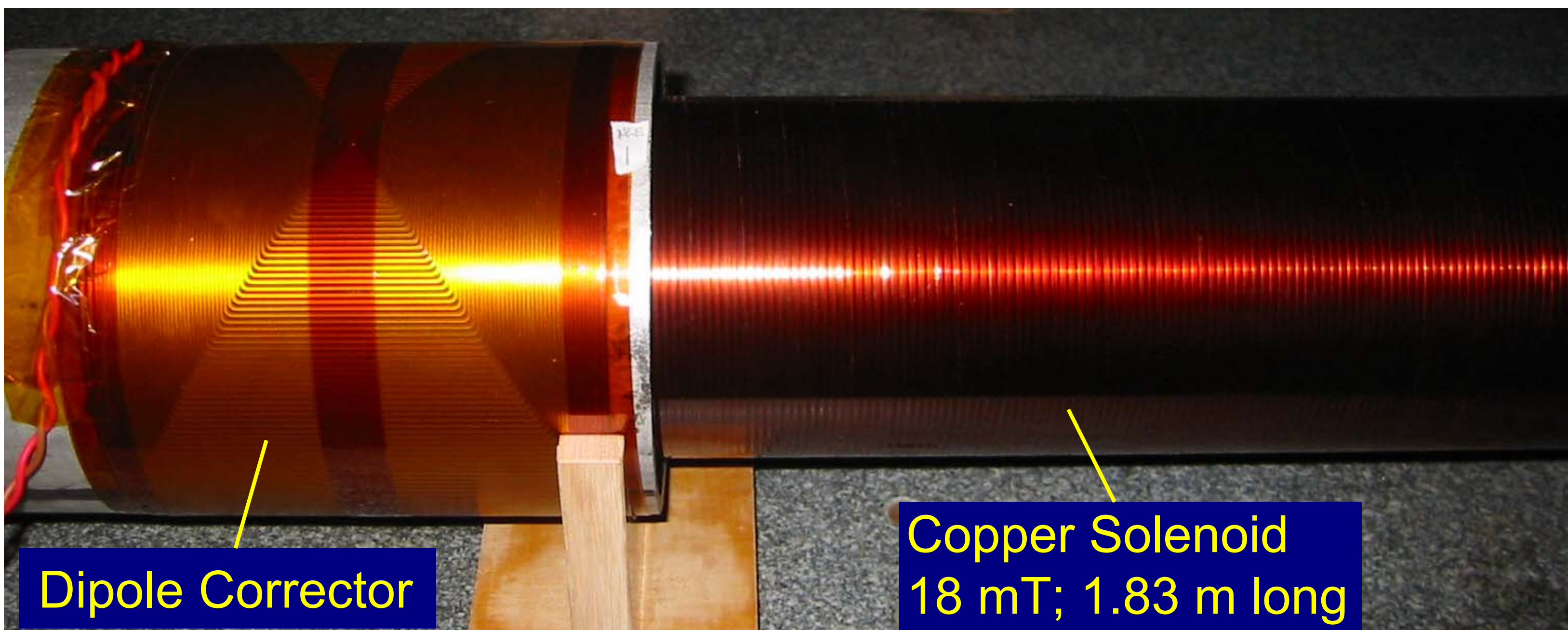


Cold model to be tested soon

Solenoid R&D: <10 ppm Directional Uniformity







5 T design started

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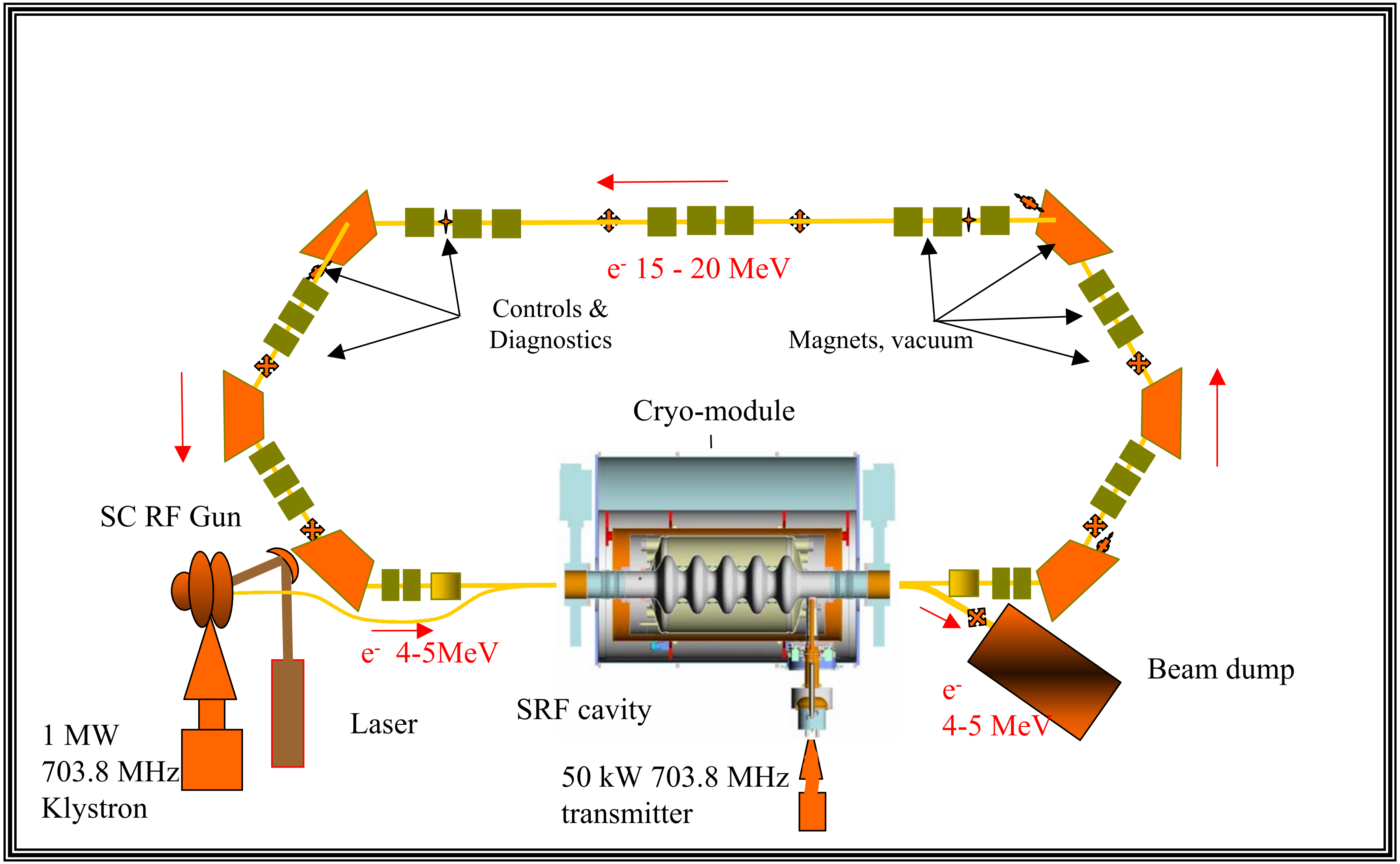
R&D Energy Recovery Linac *in Bldg. 912*



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ERL beam parameters

ERL	e-Cooler	Prototype
ERL circumference [m]	~ 120	~ 20
Number of passes	1	1 to 2
Beam rep-rate [MHz]	9.38 -28.15	9.38 - ?
for tuning		1 Hz – 1 kHz
Beam energy [MeV]	54.677	20 - 40
Electrons per bunch (max)	10^{11}	10^{11}
Normalized emittance [μm rad]	~ 50	~ 50
RMS Bunch length [m]	0.03 – 0.2	0.05
Charge per bunch [nC]	10+	10+
Average e-beam current [A]	0.1+	0.01 – 0.1+
Efficiency of energy recovery	99.9…%	> 99.95%
Efficiency of current recovery	99.999….%	> 99.9995%

Electron Cooling R&D Timeline

Theory, simulations and benchmarking experiments	
• Codes completed,	
▪ initial cooling calculations	June 2004
▪ Definition of cooler parameters	July 2004
• Start-to-end beam dynamics of e-beam	March 2005
• Initial benchmarking experiments	December 2005 *
• Simulations of cooler and RHIC dynamics	December 2005 *
• Final simulations and adjustments	September 2006
Electron source	
• Photocathode	
▪ R&D complete	July 2005
▪ System ready for ERL	March 2006
• Superconducting gun	
▪ Design complete	September 2005
▪ Gun ready for testing	September 2006
Superconducting 5-cell cavity	
• Copper prototype	June 2004
• Cavity and cryostat ready for processing at JLAB	January 2005
• Test of cavity at BNL complete	June 2005
Solenoid	
• Measurement system ready	October 2005
• Prototype ready	March 2006
• Prototype testing complete	September 2006
Energy Recovery Linac	
• Infrastructure ready	September 2005
• Commissioning	March 2007

* e-cooling feasibility demonstration

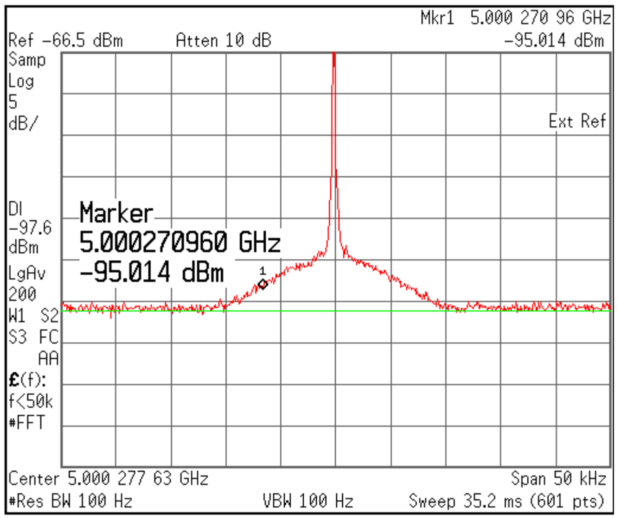
Sources of Funding, k$

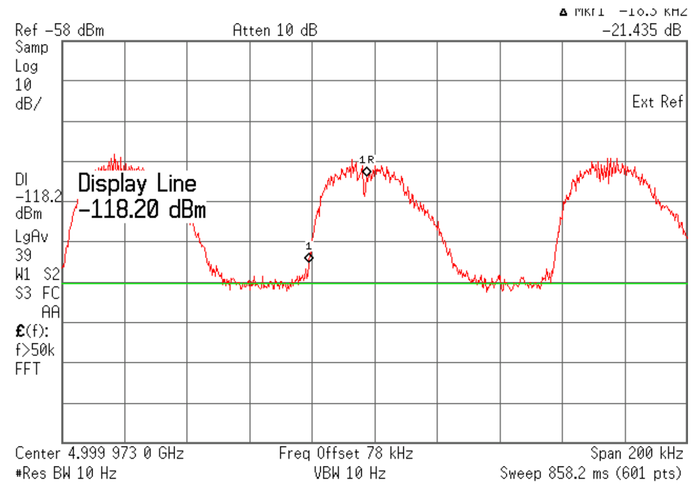
	FY03	FY04	FY05(Exp./Req.)	FY06 (Exp./Req.)
DOE Nuclear Physics	900	2000	2000	2000
BNL Prog. Dev/GPP	600	1200	1200	600
SBIR Tech-X	100	750	500	
JTO Cryo-module	350	300	100	
ONR Photo-cathode		490	490	
JTO ERL			300	300
JTO Photoinj.			600	600
Total	1950	4740	5190	3500

Stochastic Beam Cooling at RHIC

Microwave stochastic cooling (4-8 GHz) should work for longitudinal cooling and avoid beam debunching due to IBS during store (→ AIP)

Longitudinal bunched-beam Schottky spectra during store (100 GeV):





Protons: persistent coherence interferes with cooling

Gold: no persistent coherence (IBS) debunched beam visible

Optical stochastic cooling (~ 30 THz) has great potential for the long term future. Proof-of-principle R&D proceeding

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Electron-Ion Collider at RHIC: eRHIC

- 10 GeV, 0.5 A e-ring with 1/3 of RHIC circumference (similar to PEP II HER)
- 10 GeV electron beam $\rightarrow s^{1/2}$ for e-A : 63 GeV/u; $s^{1/2}$ for $e\uparrow$-$p\uparrow$: 100 GeV
- Existing RHIC interaction region allows for typical asymmetric detector
- Luminosity: up to 1×10^{33} cm^{-2}s^{-1} per nucleon
- ZDR completed (http://www.agsrhichome.bnl.gov/eRHIC/eRHIC_ZDR.htm)

eRHIC R&D:

- Electron cooling of 100 GeV/A gold beams in RHIC (see RHIC II above)
- Development of the design for eRHIC for both ring-ring and linac-ring options (with MIT Bates)
- Development of a high intensity polarized He3 source (with MIT Bates and Caltech)
  - polarized electron-polarized neutron collisions (Bjorken sum rule, $\alpha_s(Q^2)$)
- Development of a high-current polarized electron source (with Jlab and MIT Bates, mainly for linac-ring option)
- Study of high intensity beams in RHIC (electron clouds, pressure rise, beam tube heating, ...)
  - The beam intensity in RHIC is presently limited by beam induced pressure rise.

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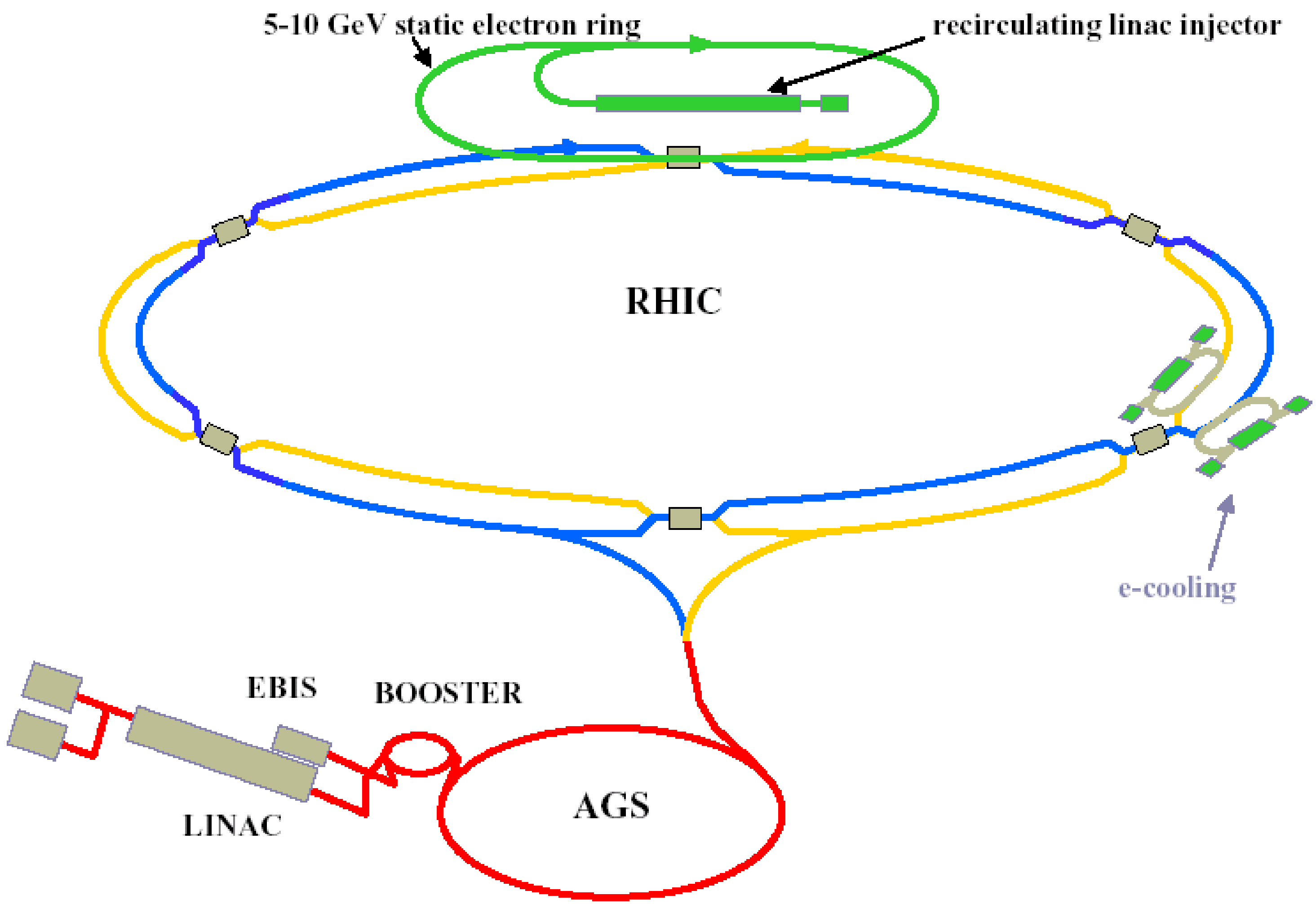
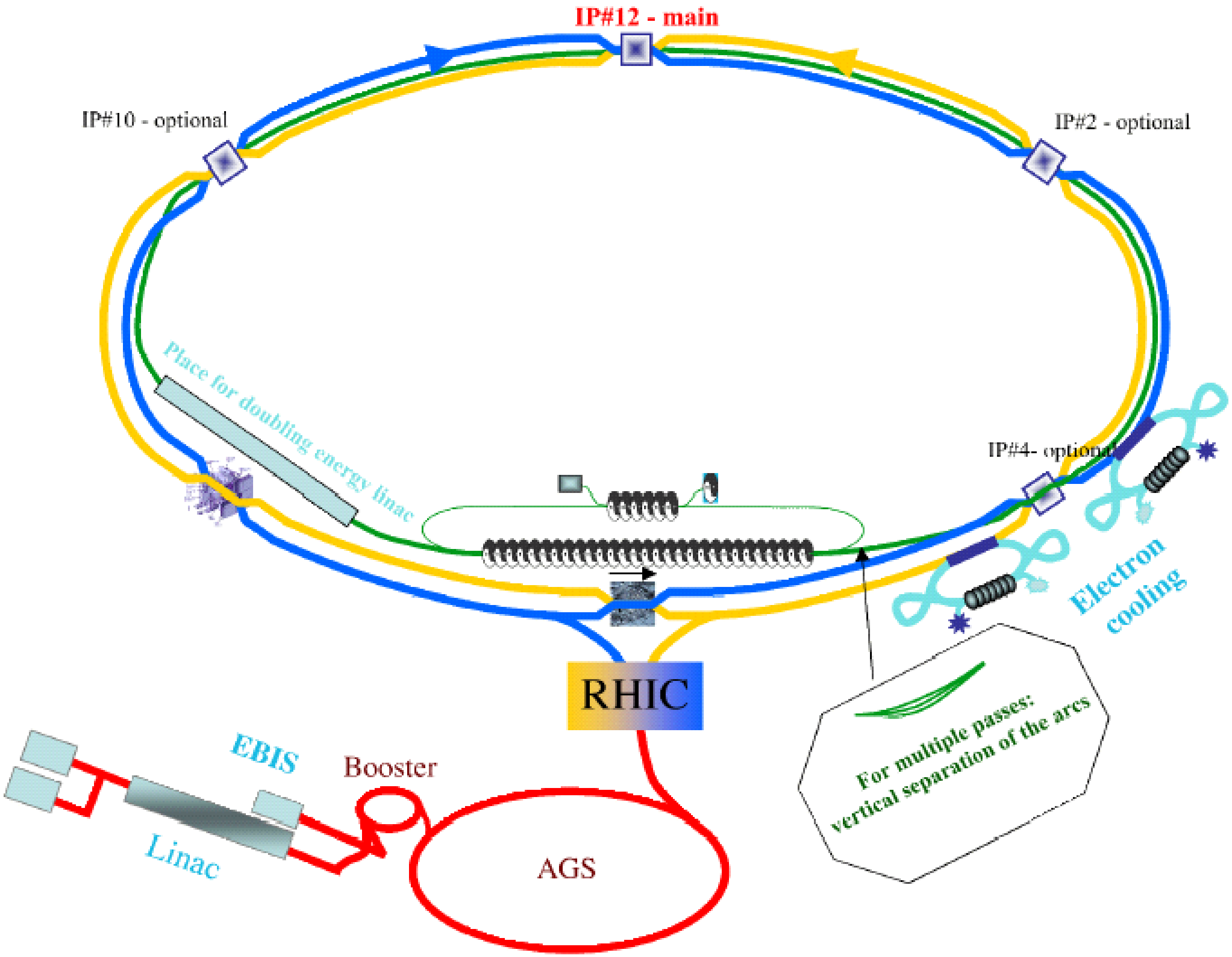
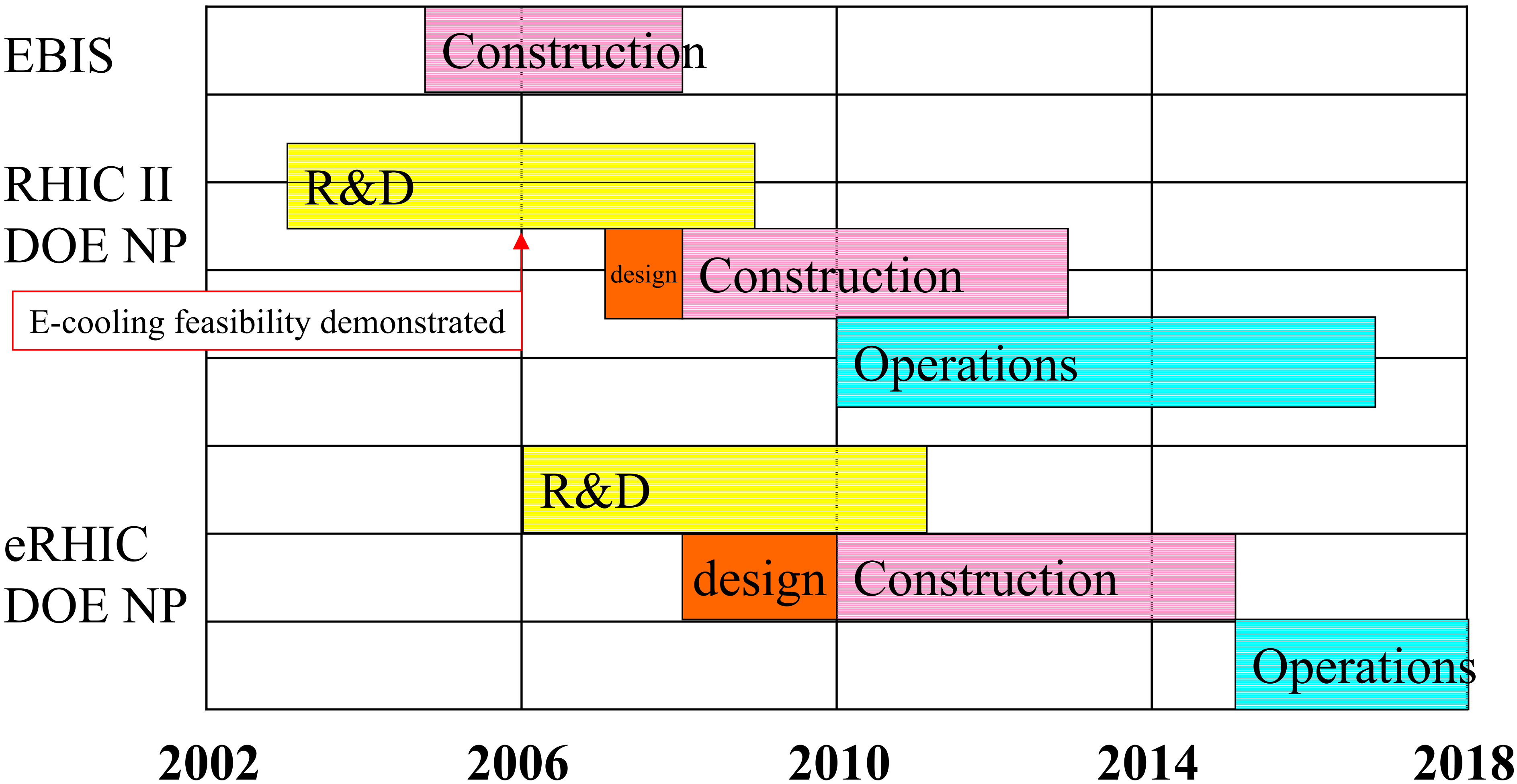
Ring-ring eRHIC (base design)



Linac-ring eRHIC



Technically Driven Schedule (in Fiscal Years)



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Summary

- R&D for Linac-based RHIC pre-injector (EBIS) successful
  Ready for construction.
- Plan for "enhanced luminosity" (x 4 design) over next 4 years
- R&D for full energy RHIC beam cooling underway to support RHIC II luminosity upgrade (x 40 design)
- ZDR for eRHIC completed
  - R&D on design continues
  - R&D on challenging components is planned