The EuCARD-2 Enhanced European Coordination for Accelerator Research & Development project is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453.

This work is part of EuCARD-2 Work Package 5: Extreme Beams (XBEAM).

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Company Overview

Alex Murokh
Vice President and Chief Technology Officer
RadiaBeam Technologies, LLC
Company Background

- RadiaBeam Technologies was founded in 2004, a spin-off from UCLA Particle Beam Physics Laboratory.

Initial business idea was to develop a Radiatron, a high duty cycle FFAG betatron, for industrial applications.
Classic Betatron

- Developed in 1940 by Donald Kerst (U of Illinois)
- Induction acceleration
- A the right injection phase e-beam orbit is contained by changing dipole field
- Shaped poles provide weak focusing (stable orbit)
Classic Betatron

- Betatrons became dominant technology through 40s and 50s
- Major research effort at MURA
- Industrial radiography and radiotherapy (Allis-Chalmers)
Classic Betatron

- Low duty cycle
- Low repetition rate
- Replaced by linacs in 60s
- Fixed-Field Alternating Gradient (FFAG)
- Small radiography market

MURA 50 MeV FFAG betatron
• Technological advances enabling rethink of a classical betatron:
  o Introduction of novel, low cycling loss magnetic materials (i.e. finemet), allowing r.r. over 10 kHz
  o Surge in computational capabilities to model FFAG lattice
  o Development of IGBT power switching electronics
Radiatron vs. Linac

- 6 MeV classic betatron, linac and Radiatron:

  **Betatron:**
  - r.r. ~ 100 Hz
  - Duty cycle ~ 1%
  - Peak current ~ 10 µA
  - E-beam power ~ 1 W
  - Dose ~ 3 cGy/min-m
  - Still in use in a low dose security applications

  **Linac:**
  - r.r. ~ 100 Hz
  - Duty cycle ~ 0.1÷0.3%
  - Peak current ~ 0.03÷1.0 A
  - E-beam power ~ 0.2÷20 kW
  - Dose ~ 0.01÷1 kGy/min-m
  - Replaced betatrons for most applications (competition from Rhodotron above 100 kW)

  **Radiatron:**
  - r.r. ~ 10 kHz
  - Duty cycle ~ 20%
  - Peak current ~ 15 mA
  - E-beam power ~ 20 kW
  - Dose ~ 1 kGy/min-m
  - no RF components
  - less expensive > 10 kW
  - High duty cycle
Radiatron Development

- DOE SBIR grant to develop a prototype system (6 MeV, 10-20 kW average power)
- 2004-2005: beam dynamics design/engineering
- 2006-2007: prototype construction
Radiatron Development

- 2007: ran out of $$
- the biggest unresolved technical challenge was FFAG magnets and extraction
- IBA s.a. became interested in Radiatron
  - Offered access to IBA codes to study extraction
  - Funded magnets redesign (no success)
Products

- 2009: IBA funding ran out, Radiatron development had to stop
- Fortunately since foundation we tried to develop and sell other products (longitudinal and beam profile diagnostics, magnets, RF structures).

1\textsuperscript{st} product sold (2004): THz interferometer for bunch length measurements (licensed from U. of Georgia); delivered to INFN

2\textsuperscript{nd} product sold (2005): quadrupole triplet for low energy beamline; delivered to Accuray

- SBIR Program also offered multiple new opportunities (products/R&D – positive feedback)
Longitudinal Diagnostics

- Spectral measurements are often done with THz interferometer
- RadiaBeam licensed an interferometer design from Uwe Happek (U-Georgia)
- Sold > 10 units, including complete systems
Real Time Interferometer

- Single shot interferometer (DOE SBIR, 2008-2011)

X-band deflecting cavity

- X-band deflector (DOE SBIR grant 2007-2012)
  - Enables ~ 10 fs longitudinal resolution
  - Delivered completed structure to BNL ATF
- Provided a major boost to RF capabilities
Beam Profile Diagnostics

- Scintillating screen are the most useful diagnostics
- At higher beam densities OTR and wire scanner more accurate
- The best approach is to have multiple diagnostics available
IBIS-I

- Integrated beam imaging system (IBIS-I)
- Single position easily replaceable diagnostics, and optical module (attached by kinematic mount)
- Market failure (developed in 2005, sold 8 units, discontinued in 2009)
IBIS-2 (multi-position)

- Multi-position pneumatic actuator system
- Up to 4 diagnostics at the same port
- Modular system with multiple add-ons
- Launched in 2010, sold ~ 70 systems (large orders, i.e. 20 identical units)
New Developments

- COTR discovery introduced a new range of problems for transverse diagnostics at X-FELs
- Wire-scanners work well, but multi-shot
- Developed Cherenkov single-shot “wire scanner” based on fiber mesh (DOE SBIR 2010)
New Developments

- Dielectric Laser Accelerators, although in infancy, require sub-micron diagnostic resolution
- Developed reflective DUV OTR diagnostics
- Initial tests indicated 0.5 µm resolution
Present Status

- In 2012 recorded ~ $7 million in revenue, of which about 30% are product sales
- Currently over 40 employees, including 8 PhD scientists
Facilities

- Machine shop (clean and regular)
- Assembly area
- Magnetic measurements
Facilities

- Hot cell
- Clean room
- Chemical processing
- RF test area
- Laser lab
Capabilities

- Mechanical engineering
- CAD
- Programming
- Prototyping
- Production
Capabilities (RF)

- RF design and engineering
- Production and RF surface processing
- Cell sorting, brazing, tuning, etc.
Capabilities (Magnets)

- Magnetic design and engineering
- Coil winding/ QA
- Magnetic testing
- EMs and PMs
Research Products

- Diagnostics
  - Transverse
  - Longitudinal
  - Charge, emittance, etc.

- RF structures
  - RF photoinjectors
  - Linacs, deflectors

- Magnetic systems
  - Electromagnets
  - Permanent magnets
  - Systems (chicanes, final focus, etc.)
Production Capabilities

- Prototyping and small scale production
- Testing, shipping, installation, support
- Turn key systems
Industrial systems

- Entered into industrial accelerators market in 2012
- Sold two turn-key linac systems
- Potential area of growth, but very competitive
- Very cost-sensitive non-expert customers
Business Development

- **RadiaBeam Technologies** (founded in **2004**)
- **RadiaBeam Systems** (**2010** – industrial accelerators)
- **RadiaBeam Europe** (**2013** – EU subsidiary)
- **RadiaSoft** (**2013** – software development)
Funding agencies

- #1 customer is US funding agencies
- about $3M/year in SBIR funding
- R&D to develop new products and technical solutions
Epilogue

• 2014: received a DOE grant to adapt Radiatron for nuclear resonance fluorescence (NRF) application
• For NRF high duty cycle is the key advantage
• Redesign in progress
• Hopefully we’ll get it to work this time
RF Structures

- Layer-by-layer Manufacturing (copper)
  - Solid free form fabrication enables internal features (i.e. cooling) without additional brazing steps
  - Developed process for copper to achieve full density
  - SFF cathode has been tested at 70 MV/m at UCLA
RF Structures

- Layer-by-layer Manufacturing (niobium)
- There are multiple applications towards superconducting RF cavities, couplers, HOM dampers, etc.
- Started developing SFF process for niobium

<table>
<thead>
<tr>
<th>Parameter \ Material</th>
<th>EBM Niobium</th>
<th>Wrought Reactor Grade Niobium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>8.40 – 8.51</td>
<td>8.57</td>
</tr>
<tr>
<td>RRR</td>
<td>19 – 24.7</td>
<td>~ 40</td>
</tr>
<tr>
<td>Vickers Hardness (GPa)</td>
<td>0.82 – 0.86</td>
<td>0.76 - 0.85</td>
</tr>
</tbody>
</table>
• Carbon Nanotube Cathodes capable of producing good current density with low thermal emittance
• Measured 300 mA field emission current (limited by beam loading)
Nano-patterned cathode

- DOE STTR with UCLA (P. Musumeci)
- Periodic nano-scaled surface patterns (metallic cathodes with enhanced surface plasmon resonance, improve multiphoton emission)
- 3000 times QE enhancement

R. Li et al., *PRL* **110**, 074801 (2013)
Laser Wire Scanner

- Ongoing experiment at Cornell ERL
- Components (laser source, optical transport and transducer, interaction chamber and X-ray detection system)
• Enhancement to RF deflector
• Laser/e-beam interaction
• Sub-fs resolution

G. Andonian et al., PR STAB 14, 072802 (2011)
Textured Dy has saturation inductance > 3 T (below 90°K)

Combination of PrFeB magnets and Tx Dy pole may lead to an ultra short period undulator (~ 7-9 mm), while maintaining normalized field strength, K~1
• Collaboration with Fermilab to develop novel magnetic lattice for storage rings
• 2 m device is split into 20 magnets (prototype in fabrication)
• Ultra Fast Electron Diffraction: Compromise between Conventional and Relativistic UED systems

• Possibility of performing the same type physics of current UED systems but cheaper and more compact (no fs-laser required)
ICS

• Inverse Compton Scattering (ICS) gamma ray source
• High spectral brightness, directionality, tunability
• With the laser re-circulation, $10^{13}$ photons/s is feasible
• Conducted a pilot experiment at ATF-BNL
• Design and build a prototype of a dedicated THz source delivering over 10 W out-coupled power from periodic corrugated radiator

• E-beam spectral structure is formed by alpha magnet rather than photocathode (high average power)
• DARPA funded project (RBT-UCLA-Stanford-PSU-BNL)
• Room size hard X-ray Free Electron Laser
RF structures

- Designed, fabricated, and tested in-house
- L, S, C and X-band / multiple types
Cargo Screening

- ARCIS (Adaptive Rail Cargo Inspection System)
- Novel proprietary detection scheme to enable 100% detection at 45 km/h train speed, and at lower dose.
Spectral analysis of coherent radiative processes allows to monitor longitudinal beam profile on a sub-picosecond time scale.